Application of Vertical Inclusions as Ground Improvement Techniques in Foundations of Transportation Infrastructure

By Yashar Salehi

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Under the supervision of Professor Hadi Khabbaz and A/Prof Sanjay Nimbalkar

University of Technology Sydney

Faculty of Engineering and Information Technology

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Yashar Salehi, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney, is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.
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Abstract

This research thesis investigates the application of vertical inclusions in the foundations of transportation structures, with a specific focus on Vibro Stone Columns (VSC), Controlled Modulus Columns (CMC), and an innovative technique known as Bi-modulus Columns (BMC). The study begins with a comprehensive literature review, critically analysing previous investigations to identify significant gaps in the current understanding of these techniques. By examining past research, the study highlights the need for further exploration into the performance and optimization of vertical inclusions in various soil conditions and loading scenarios.

A major contribution of this thesis is the extensive numerical analysis conducted using the PLAXIS 3D software package. Numerous scenarios are modelled to simulate the behaviour of shallow clayey soils under static and cyclic loading conditions. This detailed analysis aims to elucidate the mechanisms by which vertical inclusions mitigate settlement in embankments constructed on shallow clayey soils. The results provide a deeper understanding of soil-structure interaction and the effectiveness of each type of inclusion in enhancing the stability and performance of transportation infrastructure.

Additionally, the thesis incorporates a global perspective through interviews with renowned experts in the field of geotechnical engineering. Specialists from various regions share their extensive experience and insights, offering a comparative analysis of the techniques based on practical applications. These interviews reveal regional preferences, specific advantages, and potential drawbacks of each method, contributing to a more comprehensive understanding of their suitability in different geological and environmental contexts.

A practical cost analysis of the vertical inclusion techniques is also conducted, evaluating their economic feasibility and cost-effectiveness. This analysis provides a detailed comparison of the initial investment, maintenance costs, and long-term benefits associated with each technique, assisting engineers and decision-makers in selecting the most appropriate and cost-efficient solution for their specific projects.

The findings of this thesis underscore the critical importance of site-specific analysis in the selection and design of vertical inclusions for transportation structures. The research highlights the need for tailored solutions that consider both technical performance and economic viability. The concluding remarks summarize the key insights gained from the study and

propose recommendations for future research to address the identified gaps and further advance the field of ground improvement in geotechnical engineering.

In brief, this thesis sheds lights on evaluation of VSC, CMC, and BMC, offering valuable contributions to the understanding and application of vertical inclusions in the foundation of transportation infrastructures. The integration of numerical analysis, expert insights, and cost considerations provides a holistic approach to optimizing foundation solutions for weak ground, ultimately aiming to enhance their durability, stability, and cost-effectiveness.

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A_p/A = Area of the Column Per Square Meter

BMC = Bi-Modulus Column

CMC = Controlled Modulus Column

c' = Effective Cohesion

D = Diameter

e = Void Ratio

E = Young's Modulus

E_p = Moduli of Deformation for the CMC

E_S = Moduli of Deformation for the Soil

E_S^* = Apparent Deformation

f = Loading Frequency

F_n = Resultant Negative Skin Friction

F_p = Resultant Positive Skin Friction

FEM = Finite Element Models

H = Soil Thickness

L_v = Vehicle Length

LTP = Load Transfer Platform

M = Slope of the Critical Sate Line

MCC = Modified Cam Clay

m_v = Coefficient of Volume Change

N = Specific Volume of Normal Compression Line

OCR = Over Consolidated Ratio

PLT = Plate Load Test

Q = Vertical Load

Q_p = Tip Resistance in the Anchorage Layer

S = Spacing

SRR = Stress Reduction Ratio

v = Vehicle Speed

VSC = Vibro Stone Column

γ = Unit Weight

κ = Slope of the Swelling Line

λ = Slope of the Normal Consolidation Line

μ = Coefficient of Friction

v = Poisson's Ratio

σ_g = Vertical Stress

φ = Friction Angle

ψ = Dilatancy Angle

1

Introduction

1.1 Background

Significant time and financial resources could be conserved if constructions could maintain stability on a natural foundation. However, in many cases, the soft soil found in natural grounds lacks the necessary bearing capacity and fails to meet the serviceability standards during the construction of new infrastructure. According to Indraratna et al. (1992), employing appropriate ground improvement techniques is essential to circumvent these challenges.

The selected ground improvement methods must satisfy diverse requirements, including site conditions, structural types, and financial limitations. As outlined by Sivakumar et al. (2004), there are presently five frequently utilized approaches in real-world scenarios:

1) Implementing pile installation, while expensive, proves highly effective and generally leads to time savings.
2) Vertical drains associated with embankments or vacuum preloading can expedite consolidation, albeit they consistently take up a significant amount of time.

3) Chemical stabilization, which entails adding lime, cement, or other chemicals to heavily waterlogged soft clay, is not environmentally sustainable and can sometimes lead to adverse environmental effects that may impede construction decisions.
4) Stone columns, which are semi-rigid vertical inclusions, improve the overall stiffness and shear strength of soft ground. According to Hughes and Withers (1974) and Black et al. (2007), these columns are frequently utilized in scenarios where loads are relatively light to moderate.
5) Controlled Modulus Columns (CMC) are stiff vertical inclusions comprising concrete columns arranged in a grid pattern. They effectively distribute substantial loads from the structure above, both to the ground and the CMC grid. As per Masse et al. (2017), the initial development of CMC rigid inclusions was directly prompted by the shortcomings of stone columns in extremely soft or organic soils.

Despite limitations in their application, stone columns, as semi-rigid vertical inclusions, generally present a relatively cost-effective and environmentally friendly alternative compared to various other ground improvement methods. On the other hand, CMC, as rigid vertical inclusions, can also be regarded as a highly reliable and inexpensive solution for the majority of ground conditions.

The fundamental idea behind stone columns involves substituting a portion of the initial soft clay with a series of compacted columns composed of coarse granular materials like gravel or sand. Stone columns, to a certain degree, function akin to piles by supporting the load from the surrounding soil and serve as vertical drains, facilitating the dissipation of excess pore pressure. Based on Hu (1995), Guetif et al. (2007), and McCabe et al. (2009), this approach enhances bearing capacity, diminishes overall and differential settlements, expedites consolidation, improves stability, and fortifies control over liquefaction.

Nevertheless, in highly compressible and organic soils where stone columns may not be effective due to a lack of lateral confinement, Controlled Modulus Columns (CMC) were developed by Menard over three decades ago. CMC are currently employed in various soil types, whether cohesive or granular. These columns aim to enhance the mass properties of compressible soils and reduce their compressibility by utilizing a grid of rigid inclusions. The installation of these rigid inclusions is carried out through a straightforward and efficient process, with or without soil displacement during drilling. Grout or concrete is introduced at low pressure through the hollow stem of the drilling tool. Subsequently, a load transfer platform (LTP) is constructed on top of the CMCs to distribute structural loads uniformly, reduce differential settlements, and enhance stability. It serves as a stiffened platform, improving load-bearing capacity and supporting construction loads on soft soils. This entire process is vibration-free and generates minimal surface spoil, promoting a cleaner work environment and limiting the risk of contamination. Additionally, as outlined by the Menard Oceania website, the adoption of rigid inclusion ground improvement allows for cost reduction in the structure by decreasing concrete thickness and steel reinforcement.

An innovative approach known as the bi-modulus columns technique was created in the early 2000s. These columns consist of vertical soil reinforcement elements comprising rigid inclusions that are capped with compacted granular material. Bi-modulus columns offer the benefits of traditional stone columns (ease of excavation of the footings) while addressing the constraints present in extremely soft soils. In situations where the use of stone columns is not advisable due to insufficient lateral confinement and the potential for bulging, bi-modulus columns provide a suitable solution. Based on Menard Oceania website, bi-modulus columns prove highly efficient, especially in scenarios involving deep cut-offs, where the goal is to prevent undesired moments in slabs on backfill or in seismic zones. The attributes of this approach have resulted in a significant increase in its adoption since its inception.

The global demand for highways and high-speed rails in coastal areas has been consistently rising, driven by the growing requirements of modern transportation. However, these infrastructures cannot be built on shallow grounds, and reinforcement of the ground is highly necessary before construction of highways or rail tracks. No matter which vertical inclusion is chosen and utilized, the challenge lies in enhancing the substantial deposits of soft soil to ensure the safe and proper construction of transportation infrastructure is achieved. Typically, the traffic load exerted by highways or railways is relatively low when compared to the loads induced by high-rise buildings, and as mentioned earlier, stone columns have proven effective under low to medium loads. Therefore, the installation of stone columns appears to be a suitable option for reinforcing the soft ground beneath transportation infrastructure. In addition, in situations where embankments are built on very shallow soils (e.g., organic soils such as peat) or near the bridge approaches, CMC are the better alternative to be used in order to increase the bearing capacity and hence, mitigate the settlement as much as possible. Bi-modulus columns also can be extremely advantageous in specific conditions, particularly where there are LTP-related issues and concerns.

1.2 Statement of the Problem

When incorporating vertical inclusions (either semi-rigid or rigid) to enhance the ground beneath transportation infrastructure, it is crucial to account for both static and cyclic loading conditions, as these vertical inclusions endure static overburden as well as cyclic stress caused by traffic loads.

This thesis employs numerical analysis to address four specific concerns related to shallow ground transportation infrastructure enhanced with rigid and semi-rigid vertical inclusions:

1) Assessing the impact of speed on shallow ground with and without improvement.
2) Analysing the behaviour of shallow ground enhanced with vertical inclusions under static and dynamic loading.
3) Conducting an extensive parametric study on vertical inclusion ground improvement techniques, considering numerous design aspects and possible scenarios affecting their overall effectiveness.
4) Evaluating the effectiveness of bi-modulus columns in eliminating mushroom effects and reducing LTP thickness.

Furthermore, incorporating vertical inclusion ground improvement techniques into construction projects entails considerations of both expenses and timeframes. These techniques, whether employing stone columns, Controlled Modulus Columns (CMC), or bi-modulus columns, can add to the overall project cost due to the materials required and the specialized equipment and labour involved in their installation. Additionally, the timeframe for implementing these techniques can vary depending on the scope of the project, the soil conditions, and the chosen method. While some techniques, like CMC, may offer relatively quicker installation times compared to others, such as stone columns, the overall timeframe must account for factors like site preparation, drilling, and curing times.

On the other hand, when assessing the safety and durability of vertical inclusion ground improvement techniques, it is essential to consider their effectiveness in providing stable foundations for transportation infrastructure. Stone columns, for instance, have demonstrated effectiveness in enhancing soil stability under low to medium loads, but their performance may vary depending on soil characteristics and loading conditions. CMC offer a more rigid solution and are suitable for various soil types, providing increased bearing capacity and stability, particularly in soft or organic soils. Bi-modulus columns, with their innovative design combining rigid inclusions and compacted granular material, offer promising benefits in deep cut-off scenarios and where lateral confinement is a concern. In terms of durability, these techniques are typically designed to withstand the expected lifespan of the transportation infrastructure they support. Properly installed and maintained, vertical inclusion ground improvement techniques can contribute to the long-term stability and performance of highways, railways, and other transportation systems. However, ongoing monitoring and maintenance are essential to ensure their continued effectiveness over time, particularly in regions prone to seismic activity or environmental changes. Overall, while vertical inclusion ground improvement techniques may involve initial investment and careful planning, their potential to enhance safety and durability can justify their use in critical infrastructure projects.

Given the significance of these topics, this thesis compiles insights from numerous industry experts worldwide through interviews. Their extensive expertise regarding the costs, duration of construction, and evaluations of safety and durability for these methods are collected.

1.3 Objectives and Scopes

In this thesis, the performance of soft ground enhanced with vertical inclusions (rigid, semi-rigid, and bi-modulus) under static and cyclic loading is evaluated. PLAXID 3D finite element software is employed to analyse the behaviour of the shallow ground before and after improvement in various circumstances and scenarios. Furthermore, industry experts worldwide are interviewed to gain insights into the advantages and drawbacks of these ground improvement techniques. Since the cost-effectiveness of the ground improvement project is of paramount importance, a comparison of costs between rigid and semi-rigid techniques is also conducted.

The detailed objectives of this thesis are summarized below:

1. Conducting a thorough literature review on previous numerical and experimental investigations to understand the behaviour of vertical inclusions for soft soil improvement.
2. Performing a three-dimensional finite element analysis using PLAXIS 3D to create an exact 3D model of the real-world ground improvement project to validate the numerical investigation.
3. Developing a highly complex numerical model to enable the investigation of the behaviour of shallow ground enhanced with semi-rigid, rigid, and bi-modulus vertical inclusions under static and cyclic loading.
4. Interviewing numerous industry experts worldwide to capture their insights regarding the advantages and drawbacks of vertical inclusions.

5. Undertaking a cost-related comparison between vibro stone columns, controlled modulus columns, and bi-modulus columns to assess their advantages and drawbacks and provide recommendations.

1.4 Thesis Outline

This thesis is divided into seven chapters, organized as follows:

Chapter 1 introduces the research background, the statement of the problem, and objectives and scopes.

Chapter 2 provides a comprehensive literature review on the application of vertical inclusions in ground improvement techniques. It briefly introduces vibro stone columns (VSC), Controlled Modulus Columns (CMC), and the innovative technique called bi-modulus columns. The chapter covers a wide range of factors affecting the performance of these vertical inclusions, including column geometry, area replacement ratio, spacing, stress level, the significance of Load Transfer Platform (LTP), and development of column deformation. Furthermore, the chapter examines previous laboratory tests and numerical investigations, as well as the cyclic effect, particularly focusing on their application in the foundation of transportation structures.

Chapter 3 presents a comprehensive numerical model of shallow clayey ground under static and cyclic loading, reinforced with rigid, semi-rigid, and bi-modulus vertical inclusions as ground improvement methods. An extensive parametric study on vertical inclusion ground improvement techniques is conducted, considering numerous design aspects and possible scenarios affecting their overall effectiveness.

Chapter 4 consists of insights, knowledgeable information, and experiences of industry experts from around the world who were interviewed regarding vertical inclusions.

Chapter 5 presents a cost-related comparison between vibro stone columns (VSC), Controlled Modulus Columns (CMC), and bi-modulus columns.

Chapter 6 provides the Conclusions and Recommendations, followed by a list of References cited in the body of the thesis.

2

Literature Review

2.1 Introduction

The main objective of this chapter is to review the literature, the current state of the art and to show that further theoretical, numerical and experimental research on application of vertical inclusions as ground improvement techniques are necessary. This involves discussing the evolution of ground improvement using vertical inclusions, as well as the research conducted by previous investigators regarding the behaviour of such inclusions and their perspectives on the matter.

This chapter provides an overview of the advantages associated with incorporating vertical inclusions in ground improvement, serving as a comprehensive review. It encompasses a presentation of conclusions drawn from prior studies and conducts a comparative analysis between rigid and semi-rigid inclusions. In addition, this chapter briefly introduces the features of the bi-modulus columns as an innovative alternative. The recommendations for optimizing vertical inclusions and exploring their potential future advancements are provided in this chapter as well.

2.2 Structure of the Literature Review

This chapter is segmented into six sections. The initial section provides an overview of vertical inclusions (both rigid and semi-rigid) utilized for ground improvement. The second section focuses on the introduction of stone columns and their application, drawing upon insights from prior researchers. The third section delves into controlled modulus columns (CMC) and unveils previous investigations. The fourth section outlines a comparison between stone columns and controlled modulus columns. In the fifth section, a pioneering method known as bi-modulus columns is introduced and explained. Lastly, the concluding section offers key insights and recommendations for prospective research endeavours.

2.3 Overview of vertical inclusions

The idea of using vertical inclusions to strengthen a soil mass is relatively old. It has been hundreds of years that deep foundations have been utilized in various construction projects for support. Over the years, rigid inclusions, such as controlled modulus columns (CMC), also known as concrete injected columns (CIC), or semi-rigid inclusions, such as vibro stone columns (VSC), have been extensively employed by geotechnical engineers to provide essential support for structures above.

The basic principle of these techniques is to alleviate the load on soft soils without significantly altering the soil structure. By absorbing and thereby reducing the applied external loading on the shallow ground, such vertical inclusions are employed to mitigate differential and total settlements by 60 to 90% (depending on site conditions and design requirements). Therefore, soils reinforced with rigid/semi-rigid inclusions are sometimes denoted as composite foundations with increased shear strength and bearing capacity and less compressibility. Irrespective of the rigidity of the inclusions, the Load Transfer Platform (LTP) situated atop them serves a vital function in dispersing forces and minimizing uneven settling at ground level. In the CMC foundation system, due to the high rigidity of CMC, the LTP holds paramount significance, necessitating meticulous design. Conversely, in the VSC technique, where columns are partially rigid, there is less sensitivity, but the existence of LTP remains essential. Furthermore, since the majority of column-type ground improvement structures, especially stone columns, act as vertical drains, the consolidation of soft soil can also be accelerated considerably because of the presence of vertical inclusions.

In today's world, due to population growth, urbanization, and the development of new suburbs and towns, the construction of roads and embankments on soft ground is a prevalent problem. Such soft soils often undergo excessive deformation under external loads and require improvement to withstand applied loading. Vertical inclusion systems present promising solutions for constructing transportation infrastructure such as roads and railway tracks overlying soft soils. Therefore, in the construction of road and railway embankments in poor soil conditions, column-type techniques are increasingly utilized worldwide for the purpose of ground improvement.

In recent years, CMC have gained popularity as a viable ground improvement technique for roads and rail projects. Additionally, the use of geosynthetic encasements has been widely preferred by geotechnical engineers to overcome issues associated with stone columns in very soft clays, making them another feasible solution. The recently developed method known as bi-modulus columns, which integrates stone column material at the upper portion and rigid inclusions at the lower part within a unified element, offers an innovative solution to assist ground improvement endeavours, especially when confronted with challenges related to Load Transfer Platform.

2.3.1 Rigid and Semi-Rigid Vertical Inclusions

As previously mentioned, vertical inclusions can be divided into two separate groups: rigid inclusions (such as steel, concrete, and auger-cast piles) and deformable or semi-rigid inclusions (such as stone columns). Rigid inclusions operate on a principle similar to piles. They have direct contact with surface loads and function by transmitting these loads through skin friction, end-bearing resistance, or both combined, designed to carry the load with minimal settlement. The stiffness and strength of rigid inclusions are typically much greater than deformable inclusions. The distribution of stress among the inclusions and the soil determines the extent of settlement resulting from loading the improved ground.

On the other hand, stone columns, serving as semi-rigid inclusions, are recognized as a deformable foundation system. In this scenario, the materials used for constructing the columns, such as sand, crushed rock, or granular pit run, do not possess inherent self-support. Consequently, without lateral soil support, these columns are unable to sustain themselves, potentially resulting in bulging or even failure.

Since significant settlements resulting from the construction of transportation structures on shallow ground composed of soft soil deposits pose a challenging geotechnical problem, the selection of appropriate treatment is crucial. Reinforcing the weak ground with geosynthetics proves to be an effective method for reducing differential settlement, while vertical inclusions are indispensable for mitigating total settlement. Depending on ground conditions, cost considerations, project requirements, and technological availability, vertical inclusions with or without basal reinforcements are chosen to address the geotechnical challenges associated with weak ground. Figure 2.1 illustrates the potential options wherein vertical inclusions can be employed for ground improvement.

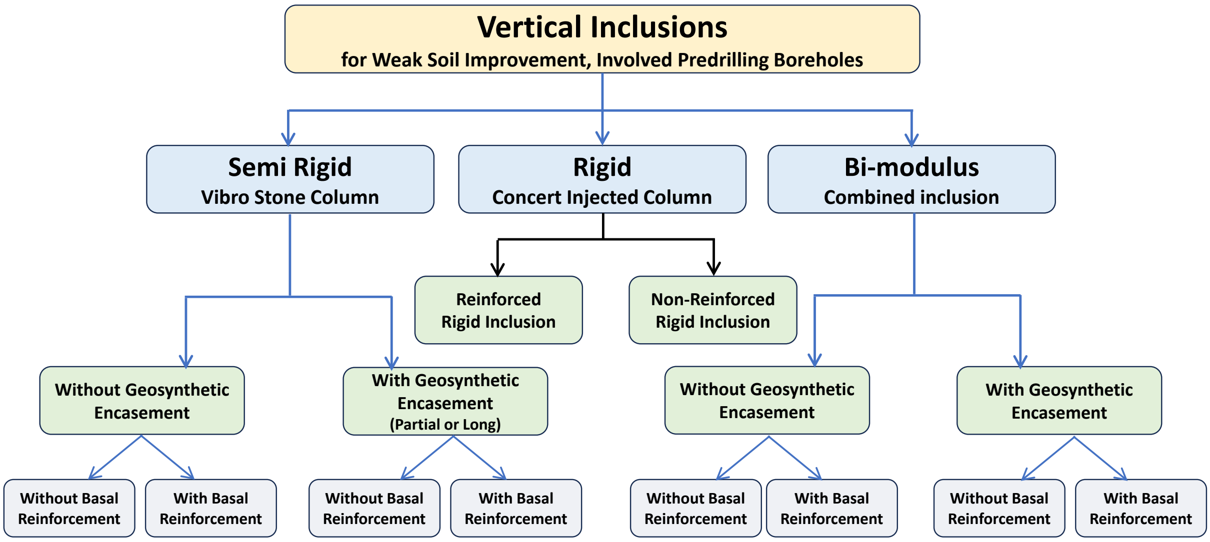

Figure 2.1: Vertical inclusions used in ground improvement of weak soils, involved predrilling boreholes

Possible options for semi-rigid inclusions include those without geosynthetics or with geosynthetics, where either partial encasement (2D to 3D) or long encasement (5D or more) can be utilized, with D representing the diameter of the stone column. Figure 2.2 illustrates the construction of a partially encased stone column using geogrids during construction.

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Figure 2.2: Inserting a geogrid net into a pre-bored and partially constructed stone column (after Lee et al. 2008)

The aim of this study is to briefly describe the vibro stone column (VSC), controlled modulus columns (CMC), and bi-modulus column methods, along with their applications as sustainable ground improvement techniques in various transportation projects worldwide. Case histories, numerical investigations, and experimental achievements conducted by previous researchers are also compiled to compare the efficacy of these two methods and identify any gaps in research that have yet to be explored.

2.4 Introduction of Stone Columns and Their Applications

Ground improvement is the enhancement of foundation soils to provide improved performance under different loading circumstances. Various techniques for ground improvement, such as stone columns, soil cement columns, vertical drains, lime treatment, and vacuum pre-consolidation, have been utilized to improve soil properties. As stated by Bora and Dash (2012), among these methods, one of the most multipurpose and cost-effective solutions is stone columns, particularly for soft clays when there is a need for a reduction in post-construction settlement and a moderate increase in bearing capacity. Stone columns have been used extensively over the past decades in numerous projects and are gaining more attraction, as they are applicable to various soil strengths and soil conditions.

According to Withers and Hughes (1974), stone columns were first used in 1830 by engineers of the French army to support the weighty foundations of ironworks. Stone columns were then rediscovered in the 1930s with vibro-flotation of granular soils. From the early 1960s until the present, the use of stone columns has become very popular as an efficient technique to improve the properties of cohesive soil. In general, stone columns consist of an array of crushed stone or gravel placed with a vibrating tool into holes opened up in the soil below a proposed structure. The diameter, length, and spacing between the opened-up holes in the shallow ground are some important parameters in the design of stone columns.

In developing countries, where only indigenous equipment and tools are available, compacted stone columns are cost-effective substitutes for vibrator compaction, as they do not require advanced technology. Such techniques increase the carrying capacity and soil drainage, while reducing the total and differential settlement of the proposed structure and mitigating the liquefaction potential. Guetif et al. (2007), identified that improving soft soil using stone columns is mainly influenced by three aspects. The first factor is stiffer material inclusion, such as gravel or crushed rock. The second is related to the densification of the soft adjacent soils during the installation process of stone columns, and the final aspect is associated with groups of stone columns acting as vertical drains. With the goals of densification, reinforcement, homogenization, load transfer, and drainage, the stone columns are placed across the area to be enhanced in a rectangular or triangular grid pattern.

In this part of the chapter, the aim is to review previous theoretical, experimental, and numerical investigations regarding the stone column ground improvement technique, providing thorough evaluations associated with its applications, advantages, and limitations. Additionally, (i) column design aspects such as the estimation of depth, diameter, spacing, and settlement of columns, as well as (ii) construction aspects including installation techniques, cost-effectiveness, and the combination of geotextiles with stone columns are discussed.

2.4.1 Feasibility Evaluation for the Use of Stone Columns

Clayey soils and most silts are not readily improved just by the installation of stone columns. Instead, soil improvement in these situations is significantly affected by the amount of soft soil displaced and replaced by the stone columns, geotextile encased columns, vibro concrete columns, or geo-piers. Therefore, the feasibility analysis for stone columns must primarily evaluate the installation of stone columns and their long-term functionality.

Factors affecting the feasibility of utilizing stone columns in weak and soft ground sites differ. Based on IS 15284 Part 1, (2003), the allowable design loading on a group of stone columns should be relatively uniform and limited to a maximum of 500 kN per column if sufficient lateral support by the in-situ soil can be developed. According to Hu (1995), the most cost-effective site improvement can be achieved in compressible clays and silts occurring within 10 m of the surface, where the variation of shear strength is between 15 kPa and 50 kPa. Some columns installed to greater depths are possible, but problems and delays related to hole collapse and aggregate placement become more likely. Sites that may require a large amount of pre-boring of holes to provide access to underlying soft soils may become cost-prohibitive.

Furthermore, based on the Geotechnical Design Manual, Chapter 14, Ground Improvement Technology (2013), ground improvement with stone columns typically reduces settlements anticipated in low-strength soils by 30% to 50% and decreases the amount of anticipated differential settlement by 5% to 15%. Referring to the same reference, it can be inferred that stone columns have been employed in clayey soils with localized, minimum (i.e., not average) undrained shear strengths as low as 7 kPa. However, this level of strength should not be considered as the allowable minimum when contemplating the use of stone columns. Instead, the average minimum shear strength at a site should be around 14 kPa, and caution should be exercised when constructing any stone column in grounds with shear strengths of less than 20 kPa. This caution is warranted due to the high probability of hole collapse and the intrusion of soft soil into the clean aggregate column. Economic considerations and the development of extreme resistance to the vibrator's penetration establish a practical upper limit of the soil undrained shear strength, which varies from 50 to 100 kPa.

Stone columns have been extensively and effectively utilized to improve the stability of slopes and embankments, particularly when any possible failure surface is located less than 9 m from the ground surface. It is important to note that slope stability design typically relies on wedge analysis or conventional slip circle methods, which utilize composite (i.e., averaged) shear strengths. For the operation of cranes on or near the slope, a relatively flat workbench with a width of at least 7.5 m is required. Additionally, stone columns can be used to reduce seepage or artesian forces that promote slope movement. To prevent soil piping into the stone column's aggregates, the following relationship is recommended:

$$20\, D_{S15} < D_{G15} < 9\, D_{S85} \tag{2.1}$$

where D_{S15} and D_{G15} represent the diameters of soil passing 15% for the adjacent soil and stone (gravel) materials, respectively, and D_{S85} is considered as the diameter of the nearby soil passing 85%. The selected gradation for design should adhere to a pattern that is economically and readily available, and it should be coarse enough to settle rapidly in water to the base of the probe.

2.4.2 Design Aspects

Stone column design involves estimating stone column properties, identifying stone column failure modes, and calculating shear strengths, bearing capacities, and settlements. Stone columns should be designed to resist failure modes during service, while also being economical and constructible. The efficiency of stone column design should be assessed by improvements in settlement reductions, shear strengths, and load-bearing capacities of the improved ground.

Nowadays, there are various design guidelines for dynamic compaction and vibro compaction techniques, which share similarities in basics. Gouw (2018), has presented one of the most recent design strategies for practicing engineers. Nevertheless, the initial stage of stone column design involves determining the column's diameter, required spacing, critical length, and the stone's angle of internal friction. After obtaining these parameters, a comprehensive analysis should be performed to determine settlement ratios, load-carrying capacity, and shear strengths of the improved ground.

2.4.2.1 Stone Column Diameter

Determination of an appropriate column diameter is based on the desired level of improvement, the stone size, method of installation, and the in-situ soil strength. Generally, the softer the soil, the larger the diameter of the formed column should be. According to the Menard website (http://www.vibromenard.co.uk), the stone column's final diameter depends on the properties of the adjacent soils and might vary with depth in non-homogeneous soils. The Keller Group (2017), suggests that, in general, a cylindrical soil body of up to 5 m diameter is considered the column's diameter in the vibro compaction process, and the diameter of columns in the vibro replacement process is between 750 mm and 1100 mm. Farrell company (http://www.farrellinc.com) declares that compacted stone columns are generally constructed in diameters varying from 600 mm to 900 mm. Apart from the vibro compaction process, column diameters used for ground improvement could range from 0.5 m to 1.2 m. The graphical correlation between the column diameter and the undrained shear strength of soils developed by Besancon (1984), can be found in Figure 2.3.

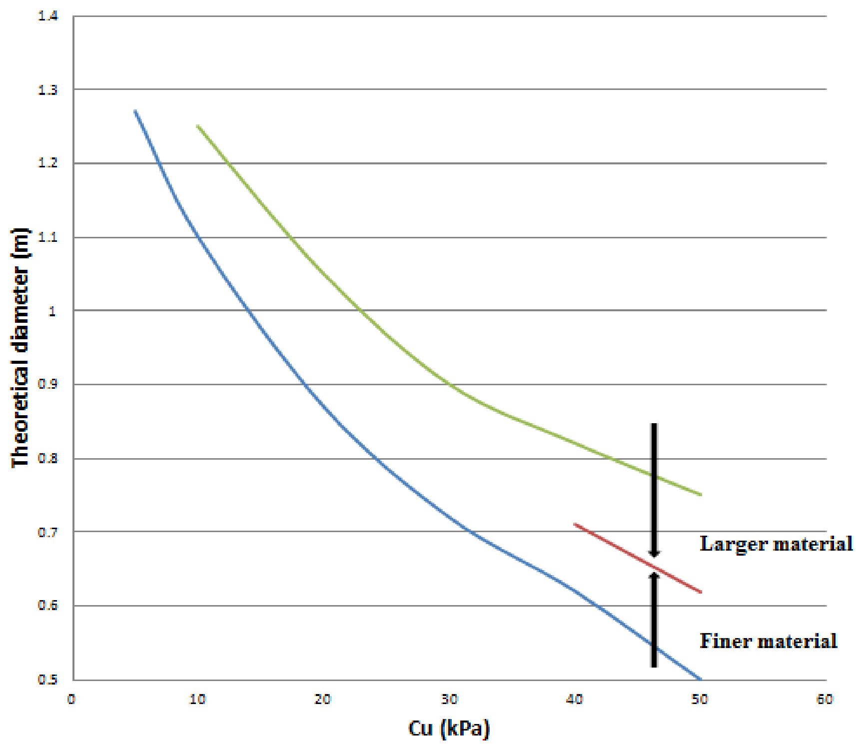

Figure 2.3: Determination of column diameter according to soil strength (modified after Besancon, 1984)

According to the graph, the lower the value of undrained shear strength of the soil, the larger column diameter shall be considered for the design. Furthermore, the fineness of the soil material is another governing factor to estimate the theoretical diameter of the columns where soils with larger material constituents require larger diameter stone columns. In the case of finer materials, since there are fewer voids between the soil particles, less compaction and densification is required, and hence, smaller column diameters could be sufficient for ground improvement.

Rani and Kumar (2015), carried out an experimental study to decipher the behavior of stone columns with various diameters (50, 60, 75, 90 mm) for ground improvement and stabilization of soil. Based on the test results, it was concluded that by increasing the diameter of the columns, the bearing capacity of the columns increases as well. After load application on the soil-column composite, results also revealed that although the original length of columns with different diameters deformed in all cases, the largest diameter column had minimal deformation. This proves that stone column diameter is a significant parameter in the design of stone columns.

2.4.2.2 Critical Length

Numerous researchers such as Tan et al. (2014), Ng (2014), and Remadna et al. (2020), have suggested that the critical length of a column can be a key factor in defining the overall stone column performance mechanism, although there are some differences among their conclusions on this matter. Mattes and Poulos (1969), indicated that the critical length of a stone column is usually 4D, where D is the column diameter. Reddy et al. (2015), found that the most desirable L/D ratio of a stone column could be a function of the liquidity index and liquid limit of the soil mass, whereas it is almost independent of the soil type. Hughes (1974), reported the critical length to be 4.1 times the column diameter, while Dash and Bora (2012), stated that the stone column's ultimate length for supreme performance is approximately 5 times the column diameter. Beyond that length, the stone column does not contribute to an increased bearing capacity, but it continues to reduce settlement by penetrating to a firmer layer. In other words, the shortest column capable of carrying the ultimate load, irrespective of the settlement, is called the critical column length. Remadna et al. (2020), through numerical analysis, concluded that increasing the lateral earth pressure of the soil leads not only to a reduction in the settlement of the footing but also to a reduction in the optimum length of the stone columns.

According to Keller's guidelines (Keller, Ground Engineering Pty Ltd, 2008), the total length of a stone column can reach up to 20 m in vibro replacement technique, while in vibro compaction process, the compaction depth might reach up to 50 m. In compacted stone columns, the depth for which these columns are designed typically ranges from 2 m to 9 m. These columns are constructed by drilling and ramming crushed rock in 300 mm lifts.

2.4.2.3 Spacing

For the design of column spacing, no exact recommendations may be assumed on the minimum and maximum spacing between columns as this is entirely site-specific. However, from past ground improvement projects, it can be identified that for square or rectangular grid patterns, the center-to-center column spacing is usually between 1.5 m and 3.5 m. For larger projects, field trials must be implemented to find the optimal spacing of the stone columns. According to the EarthTech website, in general, column spacing varies from 1.2 m to 2.0 m beneath main load-bearing foundations and up to 3 m beneath floor slabs. An experimental investigation conducted by Dash and Bora (2012) on a clayey bed improved by floating stone columns proved that the ideal spacing between stone columns was approximately 2.5D, where D is the diameter of the column. Based on Welsh (1987), the column spacing is a function of the desired improvement, the sensitivity of the in-situ soil, and the construction process. Balaam and Booker (1981) indicated that once stone columns are spaced closely to each other, the most noteworthy correlations to the elastic settlement occur.

2.4.2.4 Stone Column Properties

The stone's angle of internal friction depends on the installation process, the shape and size of the stone, as well as the infiltration of the native soil between stone particles. In general, a friction value ranging from 35° to 45° can be used. Greenwood and Kirsch (1984), concluded that the results of parametric studies of stone column applications indicated that approximately 5 degrees variation of friction angle had minimal to no influence on the total settlement and ultimate bearing capacity of the columns. However, the friction angle will have a significant impact on the horizontal shear resistance of the stone column-reinforced soil. Balaam and Booker (1981), reported that the modular ratio (ratio between the Young's modulus of the stone column and the surrounding soil) and the dilatancy angle of stones play a crucial role in the settlement of stone columns. Table 2.1 outlines typical stone column material properties that have been used in various sites.

Table 2.1: A summary of stone column properties used in various sites (i.e. in field projects)

Reference	Stone Column Properties				
	Unit weight (γ), (kN/m^3)	**Young's modulus (E), (kPa)**	**Friction angle (φ°)**	**Dilatancy angle (ψ°)**	**Poisson's ratio (ν)**
Poorooshasb and Meyerhof (1997)	N/A	1000	44 (well compacted) 38 (less compacted)	N/A	0.2
Ambily and Gandhi (2004)	N/A	48000	42	N/A	0.3
Malarvizhi and Ilamparuthi (2004)	12	2500	46	20	0.35
Ambily and Gandhi (2007)	16.62	55000	43	10	0.3
Aza-Gnandji and Kalumba (2014)	16	2500	48	16	0.3
Ng and Chew (2019)	17	40000	38	N/A	0.3
Singh and Kumar (2021)	22.78	55000	42	14	0.3

2.4.3 Settlement Analysis of Stone Column Improved Ground

Analysis methods for stone columns range from semi-empirical and experience-based estimates to complicated finite element analysis. Semi-empirical methods such as Priebe's method, the Equilibrium method, and Balaam and Brooker's method could be utilized to calculate the settlements of stone column-improved ground. It should be noted that these settlement prediction techniques are based on the unit cell concept and area replacement ratio. Regardless of the method used, generally, the key factor for the design of vibro replacement technique is the ability to meet absolute settlement criteria, and therefore, researchers mostly concentrate on the settlement response of stone columns and then on bearing capacity. The settlement performance of stone column-improved ground is expressed as the settlement improvement factor (n), which is defined as:

$$n = \frac{S_{untreated}}{S_{treated}} \tag{2.2}$$

where $S_{untreated}$ is the settlement without the presence of stone columns, and $S_{treated}$ is the resultant settlement when the ground is reinforced with stone columns. Clearly, in a larger group of stone columns, since more columns work as a group, a stiffer response is achieved, resulting in the group experiencing a lesser degree of deformation. This enhanced rigidity of the column group is due to increased confining action. The consolidation settlement of the composite treated soil is given by:

$$S = m_v \sigma_g H \tag{2.3}$$

where, m_v is the coefficient of volume change, σ_g denotes the vertical stress in the nearby soil and H is the thickness of the treated soil.

Computer-based finite element simulation is the most popular and accurate method for assessing deformations and settlement of stone columns. Referring to Aza-Gnandji & Kalumba's (2014), numerical analysis, Mohr-Coulomb and modified Drucker-Prager models were used to understand the behaviour of the columns and soil material, respectively. Results of this parametric analysis made it clear that the greater the diameter, the higher the loading capacity of the columns. Increasing the column diameter, D, by 1.5, 2, and 3 times its initial size generally led to an improvement in the load-carrying capacity by approximately 2, 4, and 10 times the initial strength, respectively. The radial expansion of the columns was prominent in their upper parts, with the highest value being experienced at a depth of approximately 0.5D from the ground surface. The settlement response for various diameters (50, 75, 100, 150 mm) within the unit cell can be seen in Figures 2.4a and 2.4b, indicating the load-carrying capacity ratio.

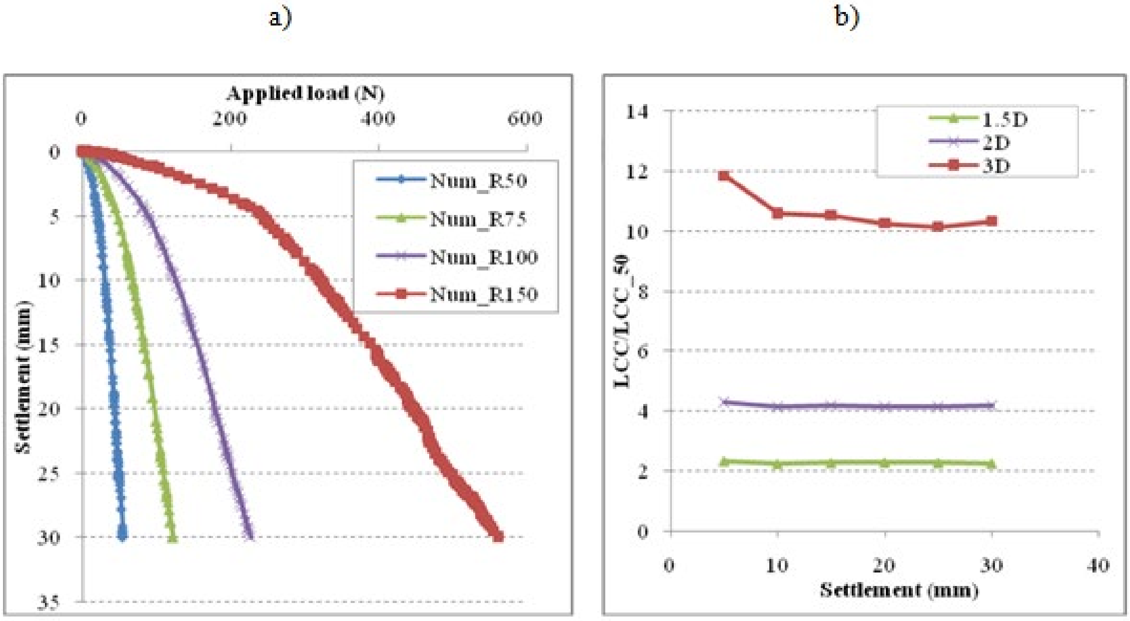

Figure 2.4: Behaviour of the columns with various diameters a) Load settlement response within the unit cell, b) Load carrying capacity ratio (after Aza-Gnandji & Kalumba 2014)

Tandel et al. (2016), used PLAXIS 3D to perform a finite element analysis and decipher the effectiveness of stone column-treated soil, both with and without geosynthetic encasement, in comparison with untreated soft clay soil. The soil-stone column finite element mesh, created using PLAXIS 3D, can be seen in Figure 2.5.

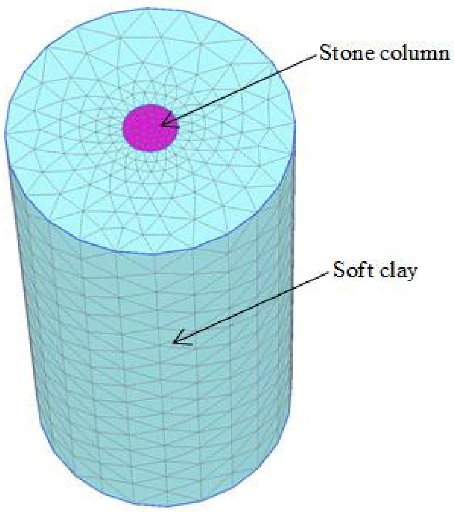

Figure 2.5: Soil-stone column finite element mesh, using Plaxis 3D (after Tandel et al. 2016)

The bottom boundary of the model was restricted in both horizontal and vertical directions, while the vertical boundaries were only allowed to settle vertically. Properties of the soft clay and stone column materials used in that study can be found in Table 2.2.

Table 2.2: Clay and stones properties used in the research conducted by Tandel et al. (2016)

Properties of Clay		**Properties of Stone**	
Unit weight (kN/m^3)	17	Unit weight (kN/m^3)	16
Undrained cohesion (kPa)	9	Undrained cohesion (kPa)	N/A
Angle of internal friction (degree)	N/A	Angle of internal friction (degree)	30
Elastic modulus (kPa)	106	Elastic modulus (kPa)	1886
Poisson's ratio	0.49	Poisson's ratio	0.30
Dilatancy angle (degree)	N/A	Dilatancy angle (degree)	0

Figure 2.6 illustrates the stress-settlement response of the geosynthetic reinforced stone column (GRSC), ordinary stone column (OSC), and the soft clay obtained from PLAXIS 3D finite element analysis, compared with experimental results reported by Tandel et al. (2016).

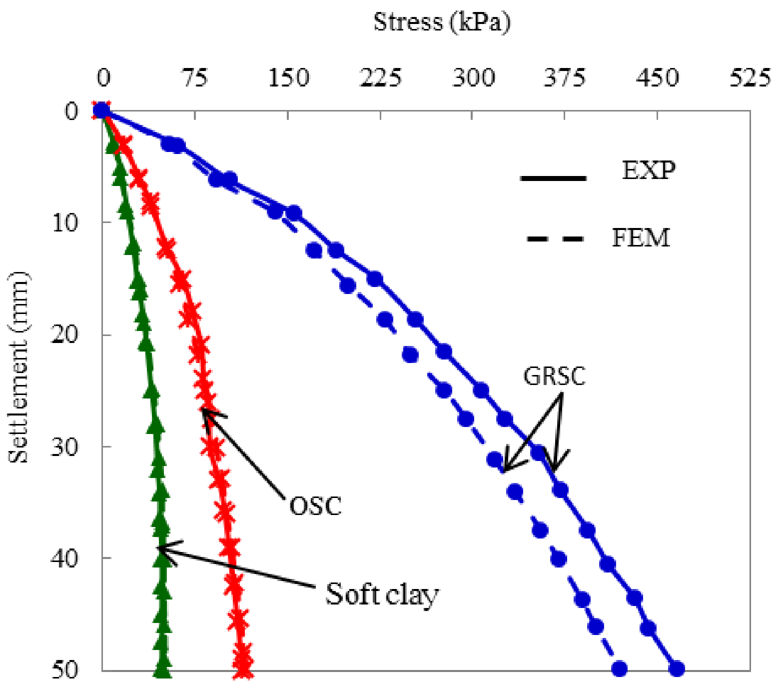

Figure 2.6: Settlement-stress response of soft clay, ordinary stone columns (OSC) and geosynthetic reinforced stone columns (GRSC) (after Tandel et al. 2016)

As can be observed, the stress-settlement curve and the ultimate load attained from finite element analysis match well with experimental results, indicating that PLAXIS software can be confidently utilized for the design of stone columns, provided appropriate input data are implemented in the numerical models. Furthermore, through the application of geosynthetic reinforcement, the settlement of the ground can be reduced extensively compared to soft clay and ordinary stone columns.

Ambily and Gandhi (2004), utilized boundary conditions and an axisymmetric finite element mesh to represent individual load tests for stone columns. They employed 15-noded triangular elements for meshing. Settlement was allowed, but radial deformation along the periphery was fixed. In the model test, both radial deformation and settlement were restricted along the bottom of the tank. The column length was 450 mm with a diameter of 50 mm. Figure 2.7 validates PLAXIS predictions based on physical model test results reported by Ambily and Gandhi (2004).

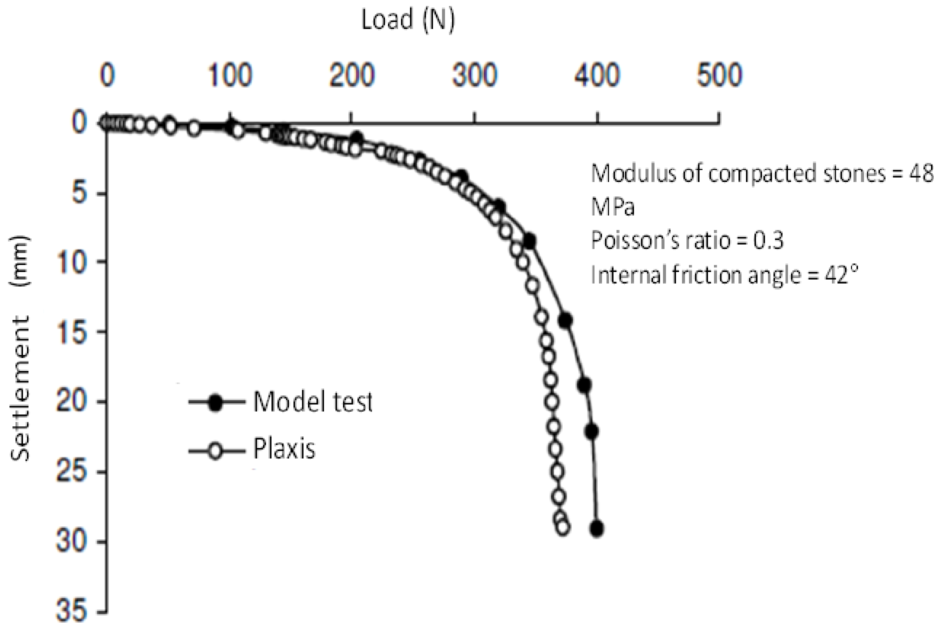

Figure 2.7: Validation of PLAXIS predictions based on physical model test results (after Ambily and Gandhi 2004)

The load-settlement curve, presented in Figure 2.7, further demonstrates the advantage of PLAXIS software for settlement calculations of soil-stone column composites, provided accurate input data are used. As seen, results obtained from PLAXIS and the model test are quite similar, with PLAXIS analysis being more conservative, indicating the same settlement created by slightly lesser loading compared to results from the model test.

In addition, Ambily and Gandhi (2004) conducted a parametric study in which the entire area was loaded, and the results were validated using finite element analysis. Initially, the influence of load intensity on the settlement of the loaded area was investigated. In the model test, failure did not occur due to the confining effect from the tank's wall and because the full area was loaded. Curves from the finite element analysis also followed the same pattern. The load-settlement curves from finite element analysis and model tests for different shear strengths and the same s/d ratio of 2 were compared and can be found in Figure 2.8.

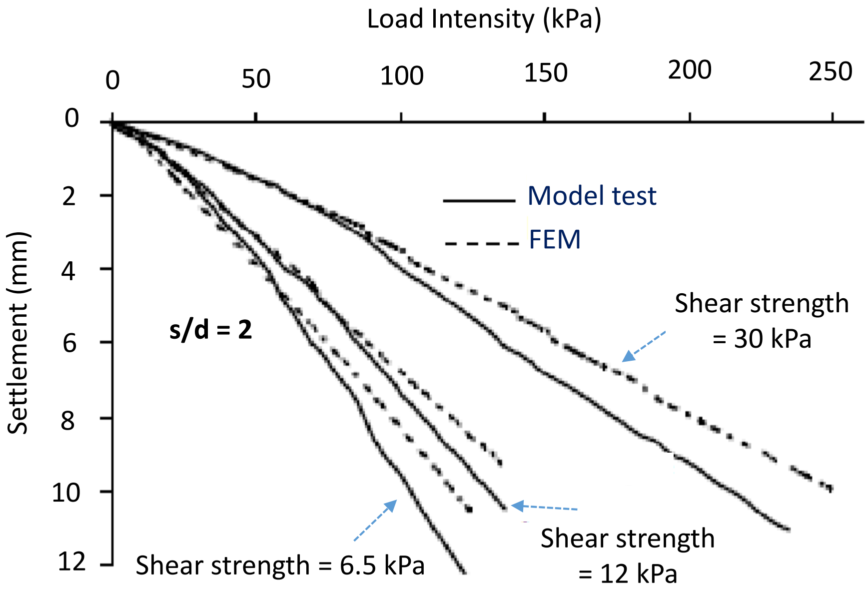

Figure 2.8: Load-settlement test curves for various shear strength (modified after Ambily and Gandhi 2004)

The graph clearly shows that soil-stone column composites with higher shear strengths can tolerate greater load intensities with minimal settlements, while the s/d ratio of 2 remains constant. A summary of the results gathered from this graph is provided in Table 2.3.

Table 2.3: The effects of same spacing to diameter (s/d = 2) and different shear strength on settlement (after Ambily and Gandhi, 2004)

Shear Strength	**6.5 kPa**		**12 kPa**		**30 kPa**	
	Model test	FEM	Model test	FEM	Model test	FEM
Maximum Settlement (mm)	12 mm @ 120 kPa	10.2 mm @ 120 kPa	10.2 mm @ 130 kPa	9.5 mm @ 135 kPa	11 mm @ 230 kPa	10 mm @ 250 kPa

The effects of various spacing-to-diameter (s/d) ratios, with the same shear strength of 12 kPa, on settlement were the next stage of the parametric study conducted by Ambily and Gandhi (2004). Figure 2.9 compares the load-settlement curves obtained from model tests and finite element analysis for different s/d ratios.

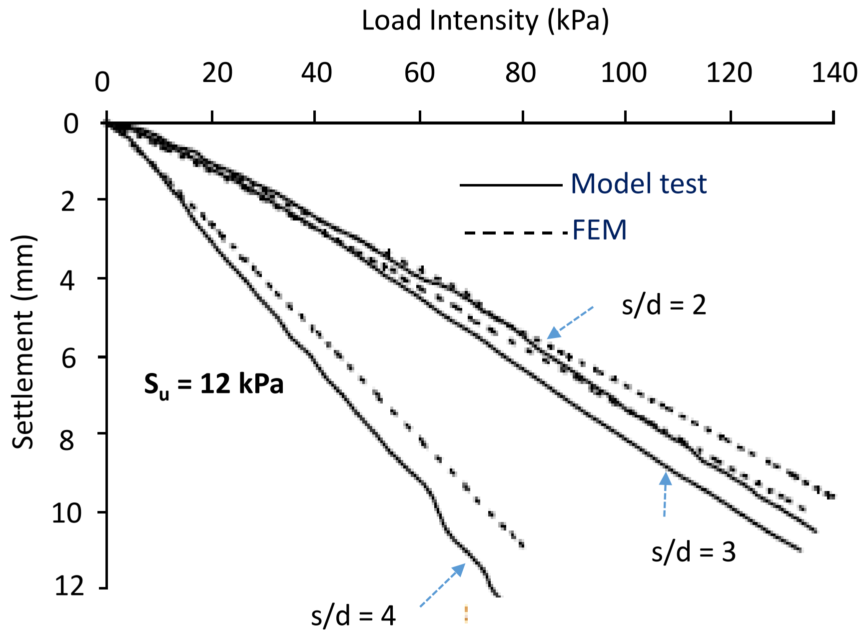

Figure 2.9: Load-settlement curves for different (s/d) ratios (modified after Ambily and Gandhi 2004)

It is evident that the s/d ratio plays a significant role in the load-settlement behaviour of the soil-stone column composite, with a lower s/d ratio leading to greater load tolerance and minimal settlement. The summary of results is provided in Table 2.4.

Table 2.4: The effects of different spacing to diameter (s/d) and same shear strength on settlement (after Ambily and Gandhi, 2004)

s/d ratio	s/d=2		s/d=3		s/d=4	
	Model test	FEM	Model test	FEM	Model test	FEM
Maximum Settlement (mm)	10.4 mm @ 138 kPa	9.8 mm @ 140 kPa	11 mm @ 130 kPa	10 mm @ 135 kPa	12 mm @ 78 kPa	11 mm @ 80 kPa

Previous investigations have not clearly identified which parameters are the most significant and which ones are less sensitive in the design of stone columns. However, as a general consideration, it can be stated that settlements of soil-stone column systems can be substantially reduced by increasing the stone column's diameter and decreasing the spacing. Using spacing greater than approximately 3 times the diameter is not efficient in reducing settlement, and stone columns with such large spacing can only serve as sand drains to accelerate the consolidation process of the soft clay. The stiffness of both soil and stone columns greatly impacts the performance of soil-stone column systems. An increase in the stiffness of either material can significantly reduce settlement. However, it should be noted that an increase in stone column stiffness will result in more load being carried by the stone column, which may lead to yielding. It is acceptable to assume that Poisson's ratio of both materials, within common ranges, has only a minor effect on the settlement of the system.

2.4.4 Failure Mechanism of Stone Columns

When it comes to a single stone column loaded over its own area, the failure mechanism considerably depends on the column's length. Withers and Hughes (1974), examined the mechanism of stone column failure and reported that approximately 4 diameters of the column were significantly strained at failure. The ultimate lateral reaction of the soil around the bulging zone of the column predominantly governs the maximum strength of an isolated column loaded at its top. If the length-to-diameter ratio is less than 4, then columns would fail in end bearing before bulging. Stone columns transmit some load to the surrounding soil through end bearing-induced shear stresses. Apart from short columns, the major load transfer mechanism is lateral bulging into the adjacent soil. Shivshankar et al. (2010), examined the performance of stone columns installed in layered soil. They concluded that the maximum bulging occurred at a depth of one times the column diameter from the top, and the total length of the stone column subjected to bulging was found to be 2-3 times the column diameter. Also, bulging was predominantly observed in the weak layer zone. McKelvey et al. (2004), found that bulging was not prominent in short columns, while in long columns, the bulging was much more significant. However, in long columns, the bottom region appeared not to have undergone significant deformation. Various researchers have effectively used X-ray techniques to examine a deformed isolated column and its adjacent soil. However, this method is costly and raises different health and safety issues when used in laboratory conditions. The Cylindrical Cavity Expansion Theory (CCET) has been utilized to model the bulging behaviour of granular columns, leading to the prediction of settlement and load-carrying capacity performance. Figures 2.10 and 2.11 show the failure mechanism of a single stone column in homogeneous and non-homogeneous soft layers, respectively.

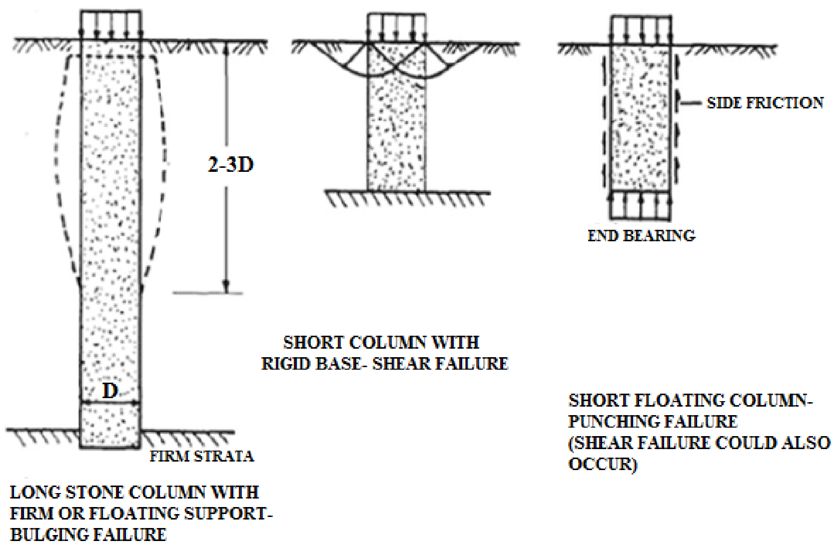

Figure 2.10: Failure mechanisms of a single stone column in a homogenous soft layer (after Barksdale and Bachus, 1983)

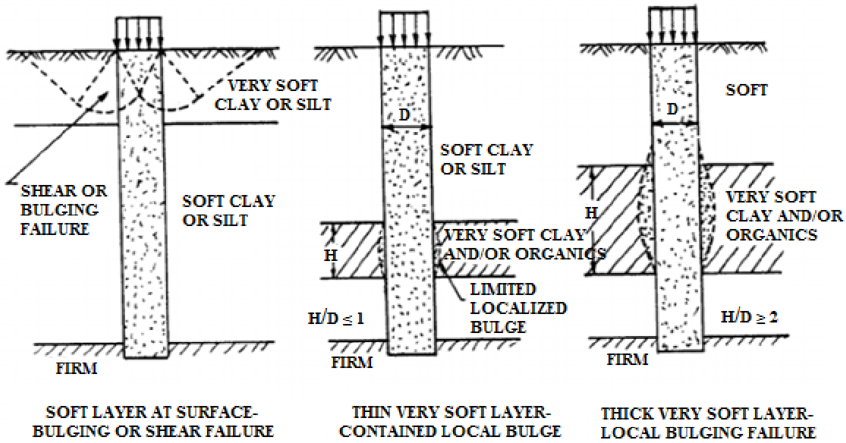

Figure 2.11: Failure mechanisms of a single stone column in a non-homogenous soft layer (after Barksdale and Bachus 1983)

2.4.5 Construction Aspects

There are different methods to construct stone columns, each suitable for various applications. Factors such as ground conditions, properties of the subsoil, cost-effectiveness, availability of equipment, and practicality are important considerations that can help engineers decide which type of stone column is most suitable for a particular project. Common methods for constructing stone columns include vibro techniques and compacted stone columns. Figure 2.12 summarizes the types of stone columns.

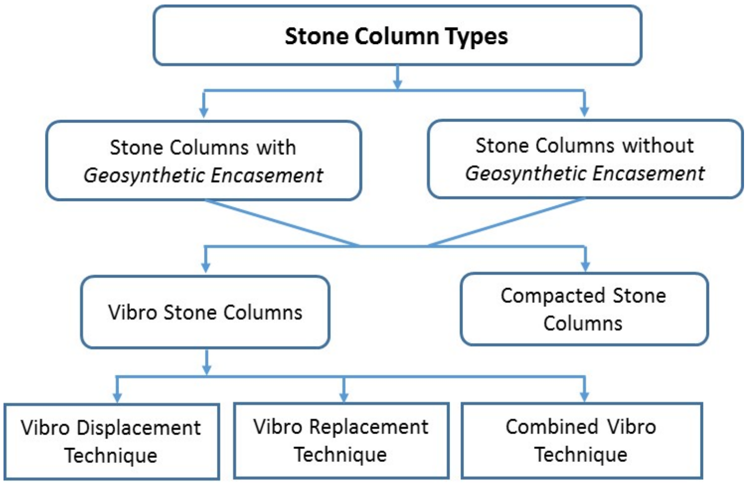

Figure 2.12: Stone column types

2.4.5.1 Construction of Vibro Stone Columns

In vibro stone columns, a depth vibrator is used for two distinct techniques, which differ in both their soil improvement and their load transfer mechanisms. The construction of the columns is generally carried out using either a replacement or a displacement method. In the displacement method, native soil is laterally displaced by a vibratory probe using compressed air. This installation method is appropriate where the groundwater level is low and the in-situ soil is firm. According to Keller Holding guidelines, the vibro displacement technique is usually employed for purely sandy soil with loose constituents. A cylindrical depth vibrator is inserted into the soil, and the soil is displaced laterally as the stone column is being made and compacted. Figure 2.13 shows a typical construction process of the vibro displacement technique and a depth vibrator.

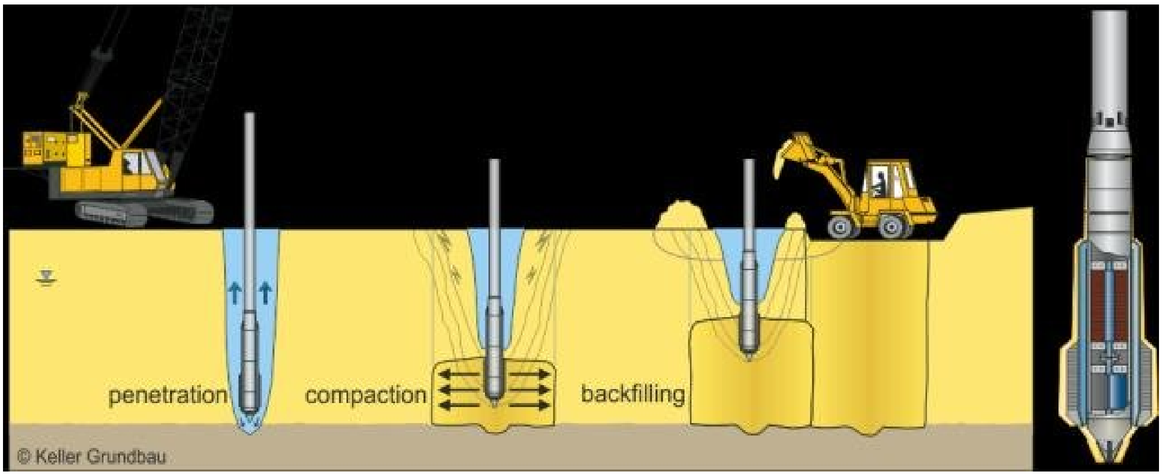

Figure 2.13: Typical construction process of vibro displacement technique and a depth vibrator (Source: Keller Group 2016)

In the replacement method, stone columns are installed using either top-feed or bottom-feed systems, with or without jetted water. The different types of installation methods available under this category are classified as: a) Wet Top Feed; b) Dry Top Feed; c) Dry Bottom Feed. The top-feed methods are used when a stable hole can be formed by the vibratory probe. The wet top-feed method is employed for medium to deep treatment below the water table and for the treatment of softer cohesive soil (with undrained shear strength ranging from 15-50 kPa, according to Keller Holding). In this method, water is forced through the head of a vibrator mounted on the end of a drilling rig. The desired depth is achieved through the combined effect of vibration and high-pressure water jets. Upon reaching the desired treatment depth, stone backfill of 12-75 mm size is added and densified by the vibrator located near the bottom of the probe. The dry top-feed method is similar to the wet top-feed method and uses controlled air flush to aid construction.

Although wet top-feed and dry top-feed methods are used in some projects, the bottom-feed process is frequently employed for the construction of vibro replacement columns. This method feeds coarse granular material to the tip of the vibrator with the aid of pressurized air. According to Menard Company, the vibro replacement technique is well-suited for improving soft soils such as silty sands, silts, clays, and non-homogeneous fills. It enhances the load-bearing capacity of in-situ soils and reduces the differential settlements of compressible soils, allowing for the use of shallow footings and thinner base slabs. Figure 2.14 illustrates a typical construction process of the dry bottom-feed vibro replacement technique.

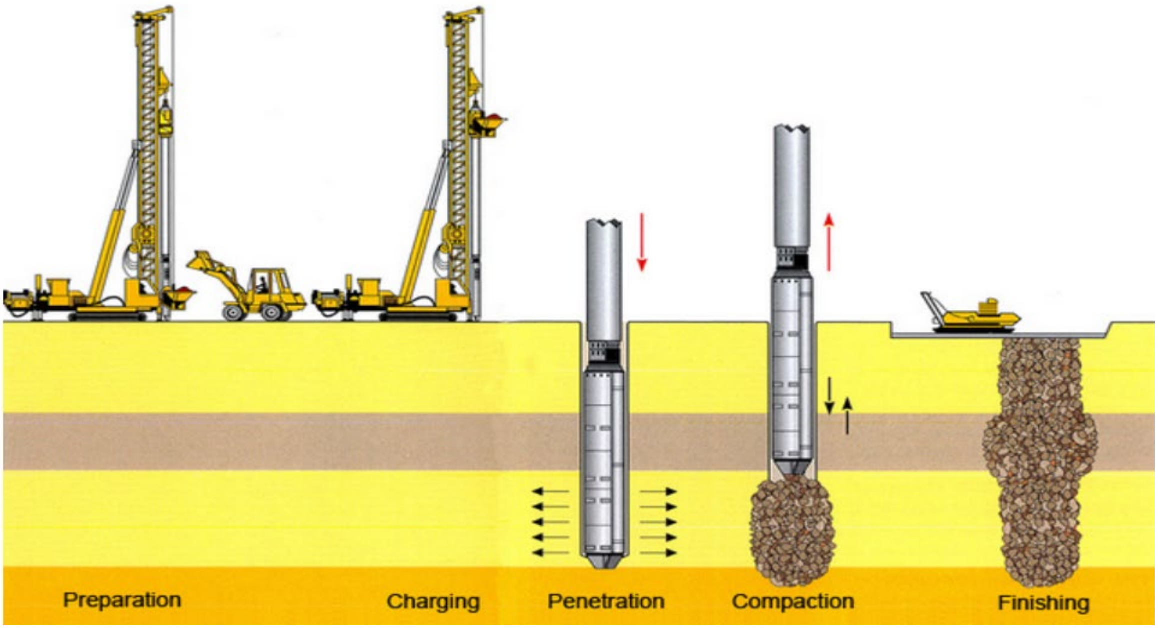

Figure 2.14: Typical construction process of dry bottom-feed vibro replacement technique (Source: Keller Group 2016)

Another significant factor in the design and construction of stone columns is the choice of aggregates, considering their size, shape, and availability. According to Mazumder et al. (2018), stone columns typically consist of crushed coarse aggregates ranging from 15 to 75 mm in size. The ratio of stone sizes mixed is determined according to design standards. For instance, the stone column standards of France, published in 2011, require the backfill to be of high quality, with particle sizes as homogeneous as possible. Bottom-feed vibrators are particularly sensitive to particle size, as unsuitable sizes can lead to pipe plugging. In general, the standard for particle homogeneity is less than 5% particles smaller than 80 µm.
The correct selection of vibro stone column construction technique and proper quality control are key factors in effectively improving soft soils.

2.4.5.2 Construction of Compacted Stone Columns (Geo-Piers)

Compacted stone column, Geopier, or rammed aggregate pier are different names for a specific type of stone column used in the ground improvement industry to enhance shallow to intermediate soft clay, loose sand, and soft loose silt soil to support shallow foundations. This method is typically employed in developing countries where advanced technology and vibro techniques may not be readily accessible. According to Farrell Design-Build recommendations (http://www.farrellinc.com), this particular stone column utilizes a replacement technique, improving soft soils and fills through compaction and ramming of thin lifts of selected granular materials and crushed rock into a drilled cavity. Soft soil is drilled out and removed from the area, after which high-quality material is compacted to greatly densify lifts in the drilled cavity, expanding the formed column into the adjacent soil. The improved soil can support heavier loads on strip footings and conventional shallow spread with reduced settlement. Figure 2.15 illustrates the steps of the construction process for this type of stone column.

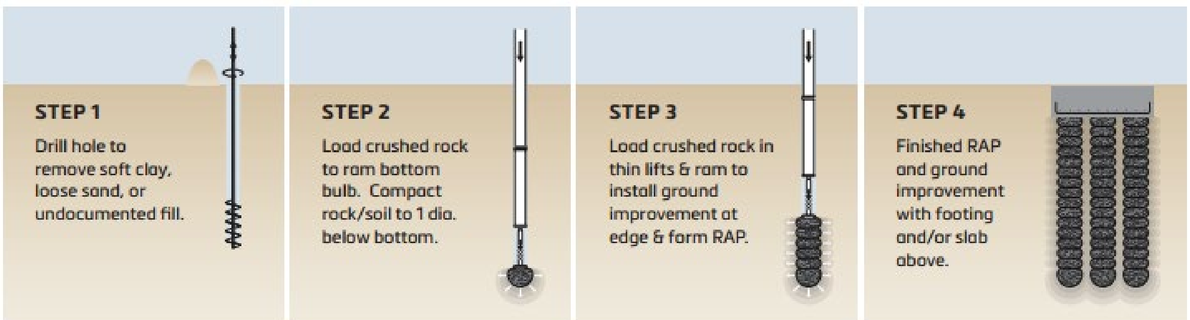

Figure 2.15: Step by step construction process of compacted stone column (Source: Farrell Design 2018)

In general, compacted stone columns are constructed with diameters ranging from 600 mm to 900 mm, and the depth for which these columns are designed typically varies from 1.8 m to 9 m. The columns are constructed by drilling and ramming crushed rock in 300 mm lifts. The ramming equipment consists of excavators equipped with 1000 kg to 2000 kg hydraulic hammers with bevelled tampers.

2.4.6 Clogging in Stone Column

The clogging phenomenon in stone column was confirmed by Weber et al. (2010), through centrifuge tests. While some attempts have been made to account for the impact of clogging on consolidation (Indraratna et al., 2013; Deb and Shiyamalaa, 2015), there is still a lack of quantification regarding clogging. Tai (2017) conducted a model test to quantify the degree of clogging, compressing a unit cell containing a single stone column and its surrounding soil in one dimension. CT scanning revealed that the clogged zone varied in depth, occupying up to 20% of the outer area of the model column at the top and decreasing rapidly along the length of the column. The porosity of the model column was computed, and parameters related to clogging were determined. Figure 2.16 shows the CT scan images conducted by Tai (2017).

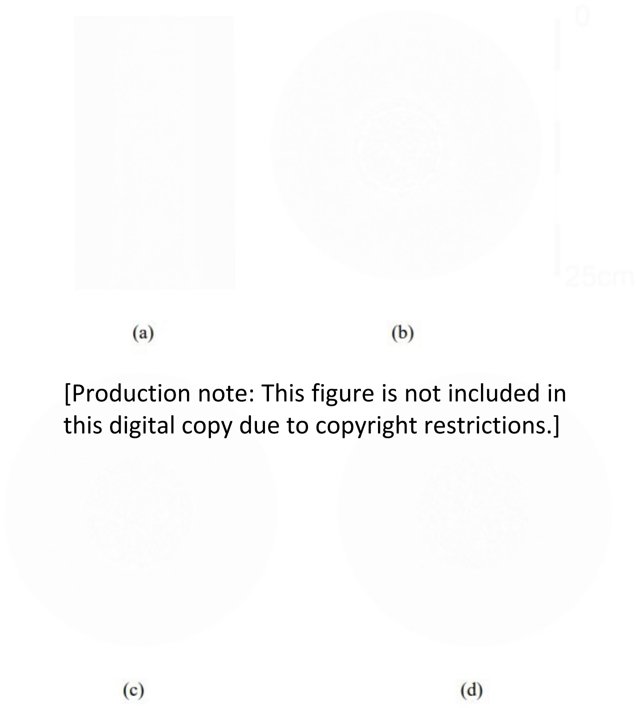

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Figure 2.16 CT scan images: (a) longitudinal section; (b) cross-section (depth 15 mm); (c) cross section (depth 130 mm); (d) cross section (depth 395 mm) (after Tai 2017)

The CT scan results were utilized to formulate a consolidation model aimed at capturing the impact of initial clogging as well as time-dependent clogging. The model underwent verification through comparison with existing models; however, some noticeable disparities emerged between the results with and without clogging. It seems that if the model were applied to forecast the response based on the unit cell concept, "no clogging" and "initial clogging" would represent the upper and lower limits of predictions. An additional intriguing discovery was that, apart from diminishing the permeability of soil within the clogged zone, clogging could also result in increased compressibility due to the infiltration of clay particles into the clean stone column. Consequently, the overall settlement might escalate compared to scenarios without clogging. This observation might contradict the more commonly held belief or perception that clogging typically obstructs the dissipation of excess pore water pressure, leading to a diminished rate of soil consolidation.

2.4.7 The Influence of Granular Materials on Behaviour of Stone Columns

In the design of stone columns, one of the key governing factors is the choice of material, which significantly affects the stiffness of the stone columns and consequently the settlement of the treated soil. Mohammed (2015), conducted a comprehensive investigation on this aspect, using several materials with different friction angles to simulate the stone columns. Settlement calculations for soft clayey ground reinforced with stone columns were performed using finite element analysis with 15-noded triangular elements in PLAXIS 2D. The project examined in this study spanned approximately 150 km and was part of the Trans-Asia Railway line, connecting Kunming in China to Singapore. The ground improvement technique employed in that project was vibro replacement stone column. Crushed stones with varying friction angles, ranging from 28.5º to 40º, were used to explore the effects of granular material on the behaviour of stone columns. Figure 2.17 illustrates a typical relationship between settlement and time for reinforced soft clay with different friction angles of crushed stone columns. For each friction angle, a similar pattern of settlement development with consolidation time was observed. It is evident that increasing the friction angle accelerates the consolidation time for reinforced clay, while the settlement decreases with an increasing friction angle. Additionally, the researcher investigated the lateral bulging behaviour of stone columns made of crushed stones with different friction angles, estimating the lateral movement along the interface of stone columns and soft soil. It was observed that as the weight class increased, the side displacement gradually increased until it reached its maximum value of lateral bulging. At this juncture, when the stone column transitions from a flex to a plastic state, it becomes unable to return to its original form.

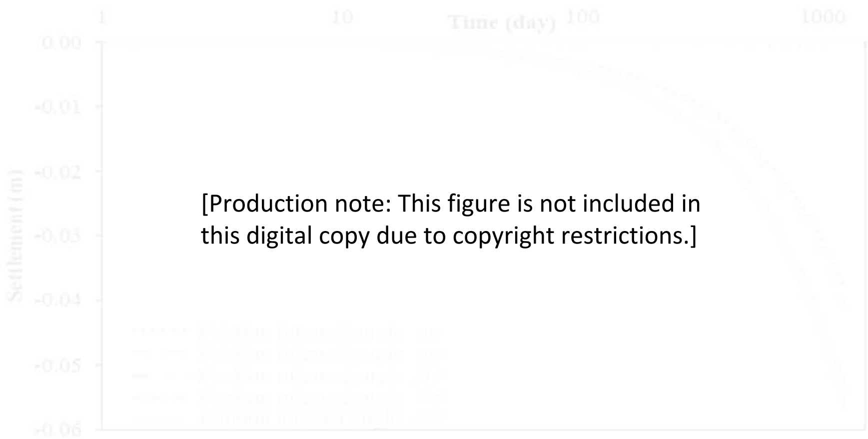

Figure 2.17: A typical relationship between settlement and time for reinforced soft clay with different friction angles of crushed stone columns (after Mohammed 2015)

As demonstrated in Figure 2.17, the crushed stones with a friction angle of 40º resulted in smaller settlement compared to stones with other friction angles.

Reihani and Dehghani (2014), examined the impact of friction angle on the load-bearing capacity of stone columns. In their study, they initially investigated the effect of varying the friction angle of the stone column materials, followed by consideration of the friction angle of the clay. Figure 2.18 illustrates the stress-settlement behaviour under loading for different friction angles of clayey soil.

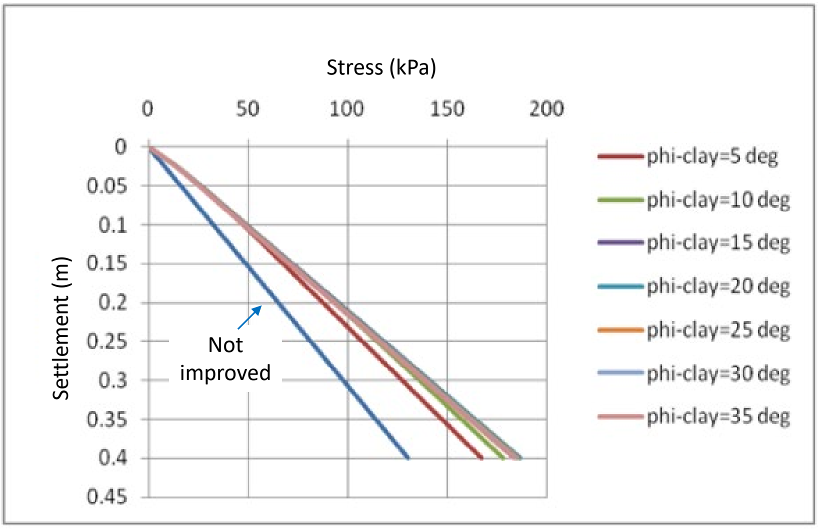

Figure 2.18: Stress-settlement behaviour under loading for different friction angle of clayey soil (after Reihani and Dehghani 2014)

According to the conducted modelling, in cases where the soil is improved, an increase in the friction angle of clayey soil also increases the bearing capacity of stone columns, resulting in lower settlement values.

Previous investigations suggest that an increase in friction angle results in less settlement and a higher bearing capacity of the treated soil. However, limited research has been conducted on the effects of the shape and size of granular materials on the overall behaviour of stone columns. Similarly, there have been few studies on the effects of friction angles between the stone and soil particles in the soil-stone column composite. This indicates a gap in the research that should be explored in future investigations.

2.4.8 Recent Developments

Based on an experimental investigation, Dash and Bora (2012), reported that soft clay beds improved by stone column-geo-cell sand mattress increased the bearing capacity by 9.5 times. Results indicated that this provision led to an increase in the stiffness of the foundation bed and subsequently a significant reduction in the settlement of the footing.

2.4.8.1 Geosynthetic Encasement

Geosynthetic encasement refers to the use of synthetic materials, such as geotextiles or geomembranes, to surround or encapsulate certain elements, such as stone columns, within the very shallow ground where soil lacks sufficient lateral confinement. In addition, these materials are engineered to provide specific functions such as reinforcement, filtration, separation, or containment in geotechnical and ground improvement applications. Eega and Tuppala (2021), conducted an experimental investigation in which they analysed the bearing capacity and settlement of soil, soil with stone columns, and soil with encased stone columns using a scaled model of a rectangular box filled with soil. Pipes filled with coarse aggregates ranging from 6.3mm to 10mm were used as stone columns, while gunny bags were utilized as geosynthetic material for the encased columns. From their experimental results, it was concluded that the use of stone columns decreased settlement by 33.3%. Remarkably, a 61.11% decrease in settlement was observed when encased stone columns were used. Figure 2.19 illustrates the settlement analysis for the three different scenarios. It is evident that for the same loading, the settlement in the soil is significantly reduced when encased stone columns are employed.

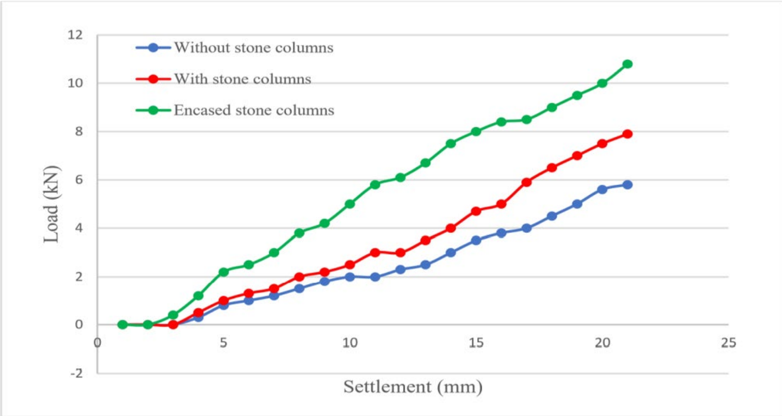

Figure 2.19: Graph of settlement analysis (after Eega and Tuppala 2021)

Sarvaiya and Solanki (2017) conducted an experimental investigation to understand the effects of geosynthetic encasement on a floating single stone column, with the bottom of the column resting on soft soil. The researchers utilized four types of geosynthetic materials as encasements to examine how different materials can influence the outcomes. A series of laboratory model tests were conducted on single columns in a unit cell tank, where the diameter of the stone columns was 55 mm and the length of the stone columns, both with and without geosynthetic reinforcement, was 300 mm. The load settlement results were compared with the results obtained from load tests on untreated clay beds. The findings from the experiments concluded that geosynthetic encasement plays a significant role in reducing settlement compared to ordinary stone columns. However, the type of material used as encasement also plays a crucial role in determining its efficiency. Figure 2.20 illustrates the stress-settlement curves from the experiment, showing that different materials have varying degrees of effectiveness in reducing settlement.

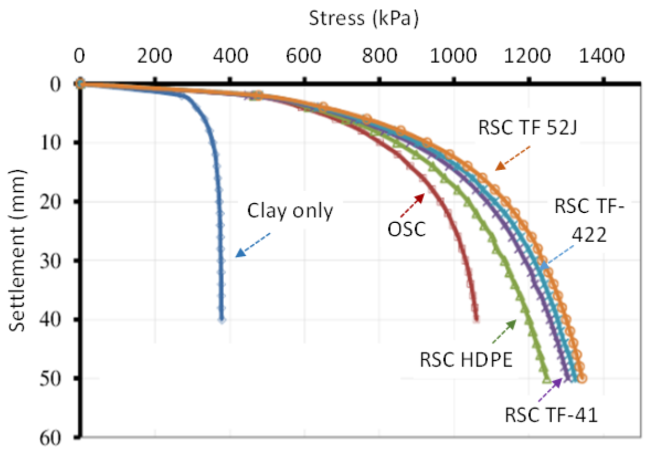

Figure 2.20: Settlement-stress response of the ground using different types of geosynthetic materials (after Sarvaiya and Solanki 2017)

Previous studies have demonstrated the significant benefits of geosynthetic encasements in reducing settlement and improving bearing capacity of treated soil. Numerous investigations have focused on proving its effectiveness for single stone columns in homogeneous soils. However, further research is recommended to explore the potential advantages of geosynthetic encasements for stone column groups and in layered soils.

2.4.8.2 Internally Reinforced Stone Columns

Reinforcing stone columns internally, through methods such as chemical grouting, concrete plugs, or the addition of inclusions like fibres and plastic, results in increased column stiffness and lateral confinement in the adjacent soil, thereby enhancing its load-carrying capacity. In a study by Ayadat and Hanna (2008), laboratory tests were conducted on internally reinforced sand columns using steel, aluminium, and plastic horizontal wire meshes. The researchers found that the effectiveness of the columns increased with higher mesh numbers. Additionally, they observed that ductile materials such as aluminium plates provided the best reinforcement. In another investigation, Shivashankar et al. (2010), studied the performance of stone columns installed in weak ground and reinforced with vertical nails. They reported that an increase in the number of nails led to a corresponding improvement in performance.

2.4.8.3 Cost Effectiveness through Substitution of Stone with Alternative Materials

With regard to the cost of stone columns, a significant portion of the expense is attributed to the cost of the stone material. Therefore, substituting some of the stone with a less expensive alternative material, without compromising performance, can potentially decrease the overall project cost. This approach may lead to a more economically viable method for ground improvement. Several alternative materials can be used instead of traditional stone aggregate for stone column ground improvement. For instance, recycled materials such as crushed concrete, recycled glass, and recycled plastic materials can be used as substitutes for stone aggregate. Using recycled materials not only reduces costs but also promotes sustainability by reusing waste materials. Other materials such as recycled tires, foam concrete (also known as cellular concrete), or geofoam can also benefit this approach. Beena (2010), conducted an experimental investigation in which the stone chips in the stone column were replaced with quarry dust in varying proportions to reduce the cost of the stone column. In this experiment, the quarry dust percentage varied from 30%, 50%, 70%, to 100%. The pressure-settlement behaviour for columns with different proportions of quarry dust is depicted in Figure 2.21.

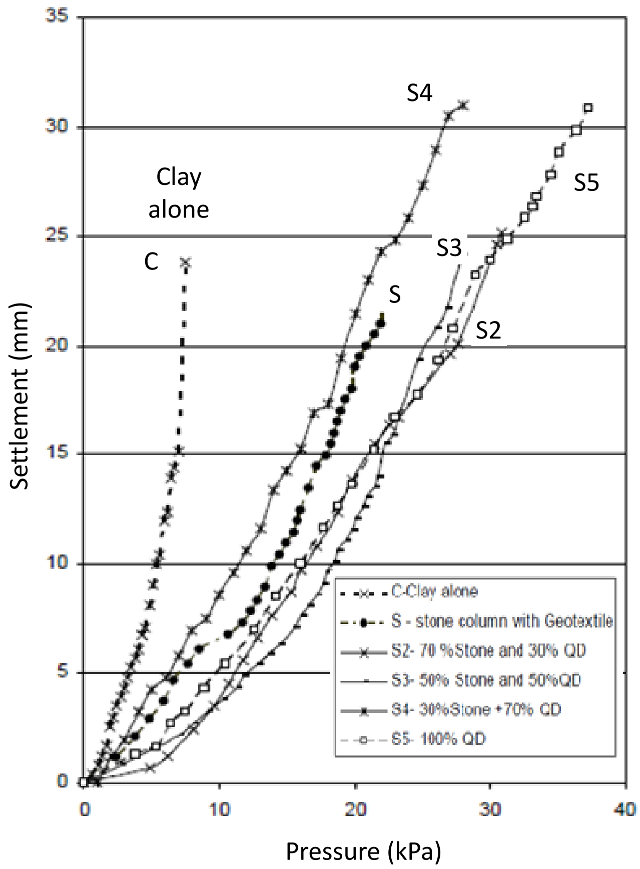

Figure 2.21: The effect of various proportion of quarry dust (after Beena 2010)

From that study, it was revealed that it is possible to replace 30% of the stones with quarry dust without compromising the strength and performance of the system.

Alnunu and Nalbantoglu (2021) conducted an investigation to assess the effectiveness of stone columns constructed from various waste materials, including shredded bricks, crushed waste stone, and crushed old concrete, in treating loose sand in North Cyprus. They analysed the load-settlement responses of both unreinforced and reinforced soils, comparing single stone columns and groups of stone columns constructed with these materials. Their findings indicated a significant improvement in the settlement behaviour of the loose sand. According to the results, selected waste materials from various local construction sites can serve as substitutes for aggregates without any significant difference in load-settlement response.

2.4.9 Applications of Stone Columns in Transportation Infrastructures (Railway Tracks and Highway Embankments)

Transportation infrastructure requires a high level of performance in terms of both structure stability and ground settlement. However, constructing transportation structures like roads and railways in problematic areas, where loose or soft cohesive deposits are prevalent, often presents challenges such as deformations, excessive settlement, and stability issues. Geotechnical engineering offers various remedies to mitigate or alleviate these problems. For example, methods such as pile construction, replacing soft soil with stiffer soil deposits, or employing techniques like stone columns are beneficial ground improvement methods commonly applied in transportation projects.

Among all ground improvement techniques, stone columns are the most renowned column type technique for improving soft soil, enabling the ground to withstand low to moderate loading applications. Stone columns are widely recognized for their versatility and effectiveness in enhancing soil stability and reducing settlement, making them a viable choice for transportation projects where soil conditions pose significant challenges. Additionally, advancements in construction technology and materials have expanded the range of applications for stone columns, allowing engineers to tailor solutions to specific project requirements and site conditions. According to Salehi et al. (2022), the improvement of the treated ground relies on several factors, such as the strength of backfill materials and the durability of the natural deposits, along with the diameter, length, and spacing of the columns. These factors play crucial roles in determining the effectiveness and long-term performance of ground improvement techniques. For instance, the selection of appropriate backfill materials influences the load-bearing capacity and settlement characteristics of stone columns, while the diameter, length, and spacing of the columns determine the extent of soil improvement and the distribution of applied loads. Moreover, the success of ground improvement methods in transportation projects also depends on site-specific conditions and project objectives. In some cases, combining different ground improvement techniques, such as stone columns with soil stabilization additives or geosynthetic encasement, may be necessary to achieve the desired level of performance. Additionally, factors such as environmental impact, construction cost, and project schedule need to be considered when selecting and implementing ground improvement solutions. Table 2.5 summarizes the typical geotechnical parameters of backfill materials used in the construction of stone columns. The utilization of the stone column ground improvement technique in various transportation projects worldwide, along with previous academic investigations, demonstrates the efficiency of this viable technique. Some past numerical and experimental investigations and case studies are presented here.

Table 2.5: Typical geotechnical parameters of backfill materials used in construction of stone columns

Reference	Unit weight, γ (kN/m^3)	Young's modulus, E (MPa)	Friction angle (φ°)	Dilatancy angle (ψ°)	Poisson's ratio (v)
Zahmatkesh (2010)	19	55	43	10	0.3
Pivarc (2011)	17.4	45	45	______	0.2
Fattah and Majeed (2012)	17	100	40	______	0.3
Piccinini (2015)	20	40	40	0	0.3
Soriano et al. (2017)	20	80	40	5	0.25
Sakr et al. (2017)	18.9	45	38	8	0.3
Alkhorshid et al. (2018)	19	45	39	5	0.3
Hadri et al. (2021)	20	45	38	______	0.33
Singh and Kumar (2021)	22.8	55	42	14	0.3
Grizi et al. (2022)	19	70	45	15	0.3

Undoubtedly, one of the most common structures traversed by high-speed trains is ballasted railway tracks. The heightened vibrations in both the nearby structures and the track itself, caused by the high speed of such trains, might impact the long-term serviceability and maintenance costs of the tracks. It is evident that the subgrade plays a significant role in providing stable support for the track. However, to prevent irreversible deformations, the stresses on the subgrade should be minimized, as increased levels of deformations and stresses will decrease the safety and ride quality of the train due to progressive degradation of the track geometry. In areas with poor ground conditions where the natural subsoils are insufficient to support the embankment and rail system, ground improvement techniques such as stone columns are required to address the problematic soil.

Shahraki and Witt (2015), conducted a 3D finite element analysis to investigate the effect of constructing stone columns for a rail track under the passage of high-speed trains, overlaying soft soil layers. In that study, they compared three different models: one without any improvement and the other two improved by stone columns. The improved models differed in terms of arrangement (triangular vs. square), diameter, and spacing, but all material properties remained constant. Figure 2.22 illustrates the effect of installing stone columns in that study when a single train traveling at a speed of 300 km/h passes over the improved track. In Figure 2.22, the vertical deformation perpendicular to the direction of the train passage, precisely in the middle of the model, is presented.

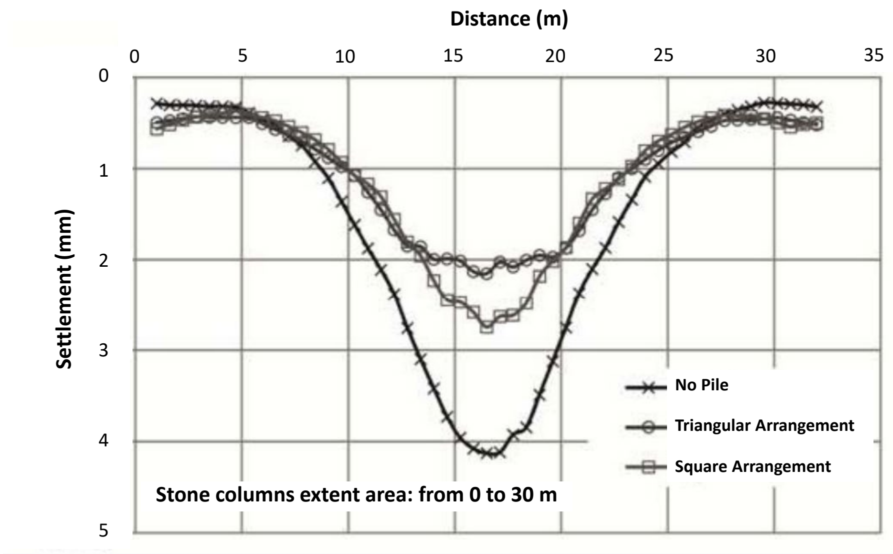

Figure 2.22: The settlement comparison due to passage of a train with speed of 300 km/h on ground without improvement and ground improved with square and triangular arrangements of stone columns (modified after Shahraki and Witt 2015)

According to the graph, the left side appears to have the maximum deformations (the track that has been loaded by the passing train). In that study, stone columns in the square and triangular arrangements caused a 35% and 51% reduction in vertical deformation, respectively, which proves to be a significant enhancement compared to the scenario without improvement.

Shahraki and Witt's (2015), study delved further into the intricacies of ground response by also examining the passage of two trains traveling at different speeds: 180 km/h and 300 km/h, in opposite directions. Their findings provided valuable insights into the dynamic behaviour of the ground under varying train speeds, revealing a nuanced relationship between train velocity and ground deformation. Interestingly, their results indicated that the train traveling at the lower speed of 180 km/h generated more deformation compared to its faster counterpart. This seemingly counterintuitive observation underscores the complex interplay between train speed, ground properties, and the resulting soil response. Factors such as train weight distribution, track conditions, and soil stiffness variations along the route contribute to the differential impact of train velocities on ground deformation. Their discoveries regarding this matter are substantiated and validated in Chapter three of this thesis, where a comparable scenario is explored, involving two vehicles moving in opposite directions at different speeds along a road embankment. Furthermore, in their investigation the triangular arrangement proved to be a better option, as it resulted in less deformation compared to the square arrangement.

Deshpande et al. (2021), investigated the effects of geosynthetic-encased stone columns used to improve an already failed railway track built on soft clays in India. They conducted a detailed numerical analysis using soil properties gathered from the failed railway site. Table 2.6 summarizes the geotechnical properties of the materials used in that finite element analysis.

Table 2.6: Geotechnical properties of the used materials in FEM analysis conducted by Deshpande et al. (2021)

Material	**E (MPa)**	**μ**	**γ (kN/m^3)**	**c′ (kPa)**	**Φ′ (°)**	**e**	**K_x (m/d)**	**K_y/K_x**
Soft Clay (Topsoil)	2	0.4	15	20	10	1.2	3.51×10^{-5}	0.5
Silty Clay (Bottom Soil)	20	0.3	19.5	45*	15	0.76	3.51×10^{-5}	0.5
Embankment Soil	10	0.3	19	20	25	0.38	12.96	0.667
Stone Column	40	0.3	22	0	34	0.3	0.001	1
Sandy Clay	20	0.3	22	43*	26	0.38	____	____

**A very large value reported by Deshpande et al. (2021)*

According to their comprehensive analytical simulations and prevailing site conditions, they concluded that to achieve minimum settlement, an ideal spacing of 2.5 m is needed. Figure 2.23 displays the degree of consolidation and the maximum bulging estimated in that investigation for a centrally placed, encased stone column with respect to spacing and time.

Based on the graph, the maximum bulging occurs at 90% consolidation for all various column spacing scenarios; however, the consolidation process is much quicker for smaller spaced columns. The phenomenon of bulging started to take place from the early stage and increased with the progression of surcharge load.

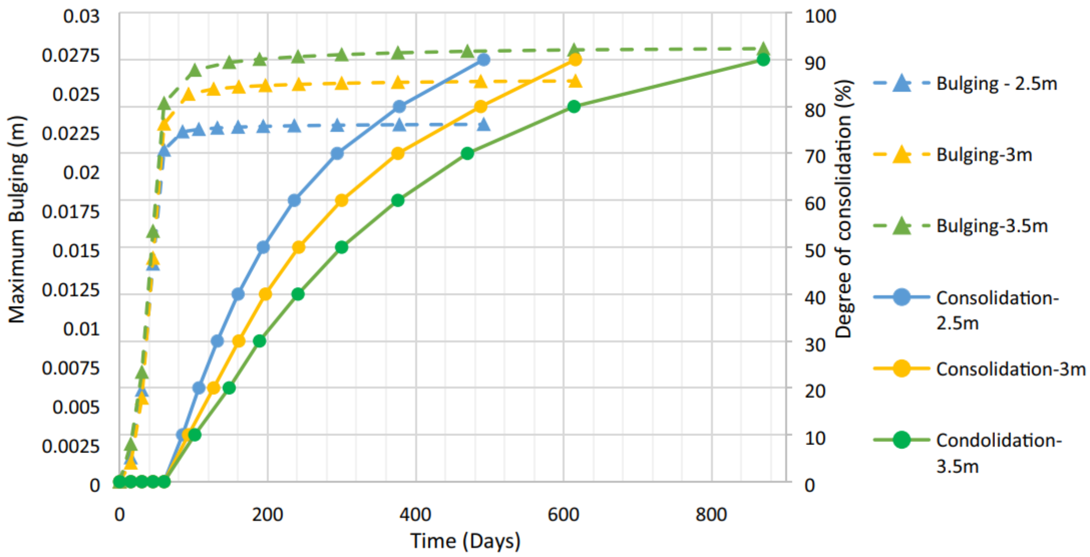

Figure 2.23: Estimated degree of consolidation and maximum bulging with respect to spacing and time for encased stone column (after Deshpande et al. 2021)

These results clearly demonstrate the effectiveness of spacing in the speed of the consolidation process and the mitigation of maximum bulging for stone columns. It can therefore, be said that column spacing is a critical parameter for improving the stability and bearing capacity of the embankment. Soft soils are prevalent in numerous expressway and motorway projects worldwide. Because of their low shear strength and propensity to consolidate and deform over time, significant considerations such as the application of stone column ground improvement techniques are necessary in the design of embankments and structural foundations in these challenging conditions. Debbabi et al. (2020), conducted a numerical analysis to understand the effects of constructing an embankment overlaying a specific soft soil called Sabkha in Algeria. Using the FEM code PLAXIS 2D, the researchers investigated the influence of variations in the friction angle of stone column materials on vertical settlement and lateral deformations of the stone column supporting a highway embankment. Figure 2.24 shows the predicted lateral deformation of the column for different friction angles of the stone column material (30º, 39º, and 45º) as a function of column depth. According to Figure 2.24, it is evident that with an increase in friction angle values (from 30º to 45º), lesser lateral deformations can be expected. This highlights the significant role of the friction angle of the stone column materials in reducing lateral deformation.

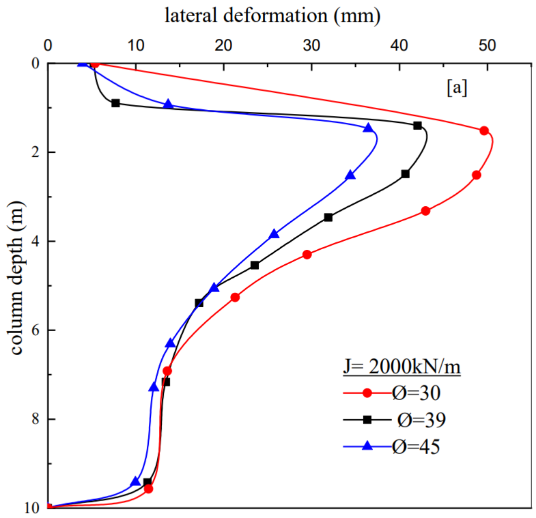

Figure 2.24: Predicted lateral deformation of the column for different friction angles of the stone column material (30º, 39º and 45º) as a function of column depth (after Debbabi et al. 2020)

Dawson et al. (2015), investigated a case history involving the use of stone column ground improvement to support stabilizing wall approaches and bridge abutments for a newly constructed bridge over the Puyallup River in Tacoma, Washington. In this project, ground improvement of approximately 57,000 cubic meters of liquefiable alluvial soils was carried out through the construction of stone columns in late 2010 and early 2011, immediately followed by the construction of embankments and wall approaches. Figure 2.25 illustrates the location and layout of the stone columns selected for this project.

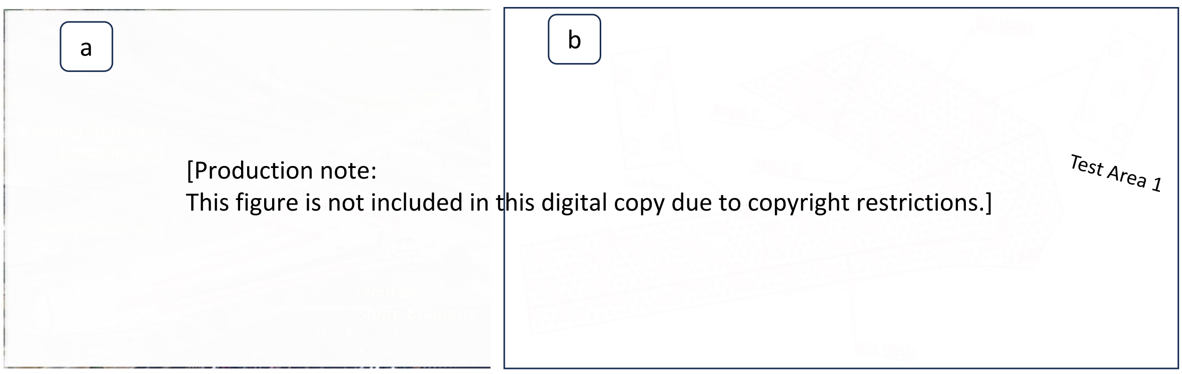

Figure 2.25: Stone column ground improvement project in Washington, USA; (a) vicinity map, (b) stone column layout selected for that project (after Dawson et al. 2015)

As depicted, two groups of five stone columns were installed as test sections. Settlement monitoring commenced with the initiation of embankment construction and persisted until

2012. Vibrating wire settlement monitoring devices were positioned in the test sections at the embankment base, near the end of the geosynthetic reinforcement, along the wall face, and midway between stone columns in the native soil. Additionally, steel settlement plates with extendable risers were installed just in front of the wall faces. Figure 2.26 displays example plots of settlement versus time related to the study.

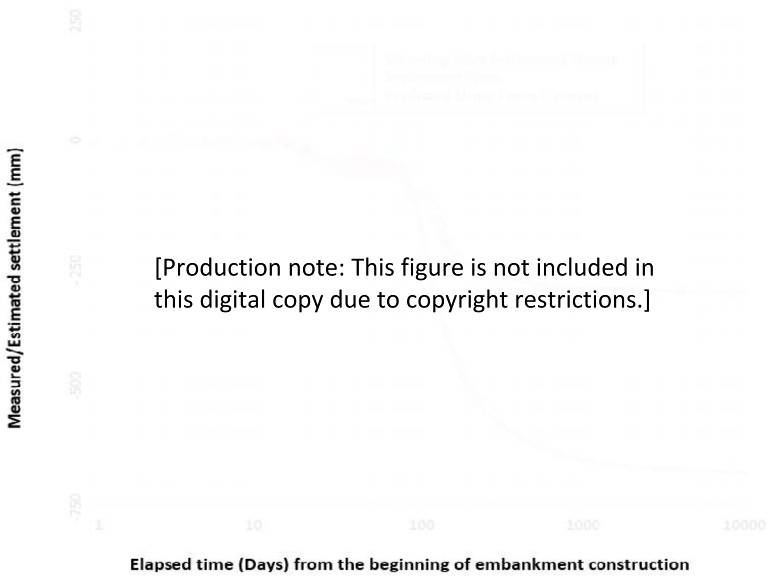

Figure 2.26: Measurement and prediction of settlements using stone columns at various time intervals (after Dawson et al. 2015)

Tai (2017), investigated the impact of stone column ground improvement on an embankment erected in 2012 in NSW, Australia. Around 50 stone columns were built at the southwestern corner of the site, indicated by a white square in Figure 2.27(a). The construction sequence of the embankment is depicted in Figure 2.27(b).

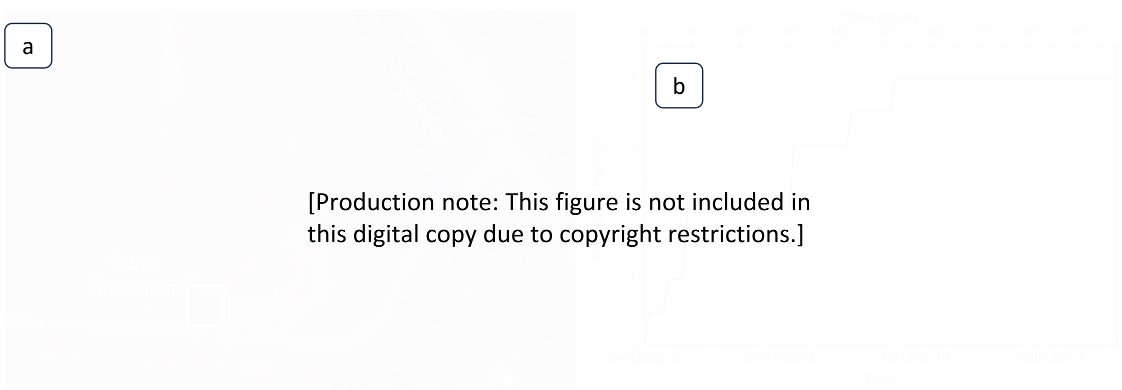

Figure 2.27: Stone column ground improvement project in NSW, Australia; (a) satellite image of the location of embankment, (b) construction sequence of the embankment (after Tai 2017)

The embankment was constructed in four stages over a period of 50 days, followed by the application of embankment loading for more than six months. The embankment fill, with a unit weight ranging from 17.5 to 20 kN/m^3, comprised 1 m of rock-fill at the bottom. To ensure a more uniform distribution of stress, it was then overlain with a layer of geogrid. Subsequently, local soils that could be conveniently obtained were used to build the embankment to its final height. In that study, the efficiency of stone columns in terms of settlement reduction was demonstrated, and their lateral deformations were measured using inclinometers placed in various locations. Additionally, piezometers placed at different depths recorded the excess pore water pressure. The rapid dissipation of excess pore water pressure due to the embankment load confirmed the effectiveness of stone columns in terms of radial drainage as well.

Figure 2.28 depicts the evolution of embankment load over time, the measured excess water pressure at various depths and times, and the site rainfall at different times. According to the data presented in Figure 2.28, the maximum excess pore water pressure was recorded at a depth of 6 m during the period of heaviest rainfall.

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Figure 2.28: Recorded data during the construction of embankment; (a) evolution of embankment load based on time, (b) measured excess water pressure at different depths and time, (c) site rainfall at different times (after Tai 2017)

Kahyaoglu (2017), conducted a numerical analysis to understand the settlement behaviour of reinforced embankments supported by stone columns, using PLAXIS 2012. Figure 2.29 illustrates a 3-meter thick geosynthetic-reinforced embankment constructed on soft deposits. In this study, the water level was situated at the ground surface.

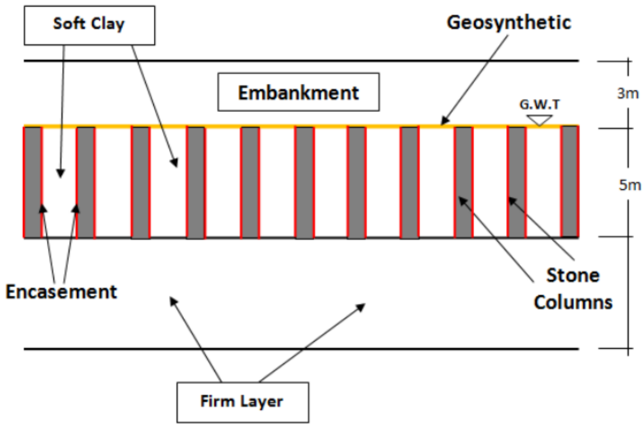

Figure 2.29: Cross section of geosynthetic reinforced embankment constructed on soft deposit and location of encased stone columns (after Kahyaoglu 2017)

The square arrangement of stone columns was selected, with columns having a diameter of 0.8 meters spaced 2.4 meters apart from each other, centre to centre, resulting in an area replacement ratio of 9%. All stone columns were encased with geosynthetics. For basal reinforcement, one layer of geosynthetic was placed at the base of the embankment. Through parametric analysis, the researcher predicted that the settlement variation of the soft deposit beneath the embankment was 140 mm. This value decreased to 40 mm after the inclusion of basal reinforcement with a stiffness of 1000 kN/m. However, increasing the stiffness of the basal reinforcement did not have a noticeable influence on the settlement behaviour of the encased stone columns.

Zhang et al. (2020), conducted an experimental investigation to determine the effects of vertical cyclic loading on a geosynthetic-encased stone column installed in soft clay. As illustrated in Figure 2.30, a 600 mm tall encased stone column was installed at the centre of the tank, atop a hard soil layer with a thickness of 180 mm. Then, soft clay was filled around the column from bottom to top.

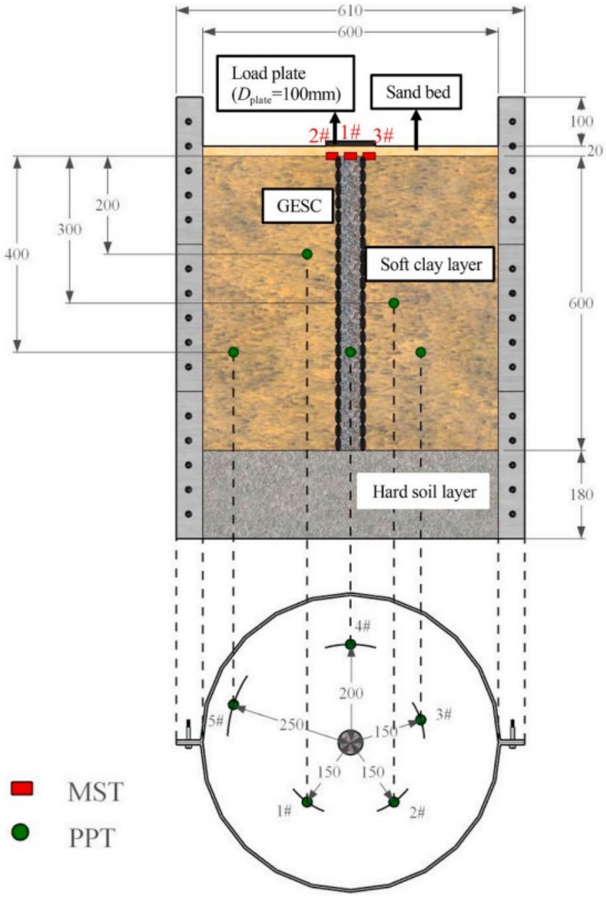

Figure 2.30: Arrangement of the geosynthetic-encased stone columns and soil layers and implemented gauges (after Zhang et al. 2020)

Subsequently, the accumulated settlements were measured for various loading frequencies, as seen in Figure 2.31. Results showed that greater settlement occurs with increasing frequency.

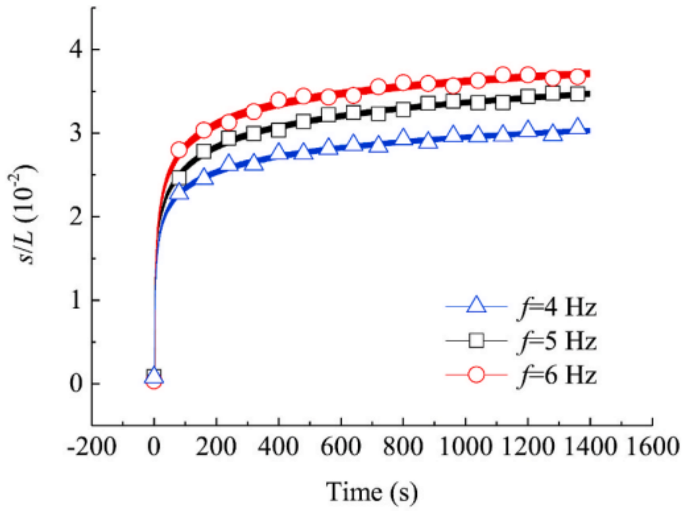

Figure 2.31: Measured accumulated settlements for various loading frequencies with time (after Zhang et al. 2020)

According to Equation 2.4, the loading frequency is proportional to the vehicle speed. Therefore, vehicle speed is the determining factor for mitigating settlement in expressways and high-speed railways, and a maximum vehicle speed limit should be considered for design requirements.

$$f = \frac{v}{L_v} \tag{2.4}$$

where, v is the vehicle speed and L_v is the vehicle length, respectively.

The numerical analyses, experimental investigations, and case histories mentioned above, conducted by previous researchers, clearly demonstrate the effectiveness of stone column ground improvement as a viable technique for enhancing soft soil deposits in transportation projects.

2.5 Introduction of Controlled Modulus Columns and Their Applications

The Controlled Modulus Column (CMC) was initially developed by Menard in the 1990s as a cost-effective substitute for piles. It enhances the stiffness of the treated soil mass by facilitating efficient load distribution between the soil and the columns. Furthermore, due to the limitations of stone columns and their shortcomings in certain areas, such as inadequate lateral confinement of soils with very soft clays, controlled modulus columns have been utilized worldwide to enhance the ground's bearing capacity and mitigate settlement. According to Salehi and Khabbaz (2024), Controlled Modulus Columns (CMC) can be applied to various soil conditions. The technology is effective in loose sands, soft loams, organic soils, and anthropogenic soils such as uncompacted fills and heaps. Controlled Modulus Column (CMC) technology is well-suited for all types of enclosed buildings, infrastructure, and special structures and enables the construction of projects that non-rigid deep foundation solutions are unable to handle, particularly in applications with very high loads, environmentally sensitive projects, and applications with stringent settlement criteria.

2.5.1 Design Aspects

According to Menard Oceania, the performance of this technology falls between deformable and rigid deep foundation systems, leaning towards the rigid foundation systems. In the Controlled Modulus Column (CMC) solution, the installation of semi-rigid to rigid soil reinforcement columns in weak soil reduces the overall deformability of a soil deposit.

Typically, the diameter of these columns ranges from 250 mm to 600 mm. They are usually installed at spacing ranging from 1.2 m to 2.5 m and have lengths generally ranging from 10 m to 20 m, with larger diameter columns installed to depths of up to 30 m. Once installed according to design requirements and construction sequences, a network of components efficiently and uniformly distributes loads throughout the soil mass. The success of installation is dependent on various factors including installation parameters, type of rig used, and, most importantly, the site's geological conditions.

In the design of a CMC network, an intermediate load transfer platform (LTP) is typically utilized to support uniformly distributed loads. Wong and Muttuvel (2012) argued that the necessity of an LTP may vary depending on the embankment height and spacing of the CMC, and its requirement should be determined solely by the differential settlement tolerance at the top of the embankment. Nonetheless, CMC are designed to enhance the soil as a composite material, and the structural load above is not intended to be solely supported by them. Improvement occurs when an equivalent vertical modulus reinforces the shallow ground, with key elements of the design including the features of the vertical inclusion network such as column diameter, spacing, thickness, soil and column modulus, and the Load Transfer Platform, in addition to soil properties.

According to Plomteux and Lazacedieu (2007), once the four main components of acting forces on an individual CMC inclusion over its full length reach equilibrium, stress distribution occurs. Equation 2.5 predicts the behaviour of an individual CMC upon reaching equilibrium under loads (Combarieu, 1988).

$$Q + F_n = F_p + Q_p \qquad (2.5)$$

where, Q is the vertical load on the head of the CMC, F_n is the resultant negative skin friction acting on the upper portion of the CMC, F_p is the resultant positive skin friction mobilized on the lower part of the CMC, and Q_p is the tip resistance in the anchorage layer.

Figure 2.32 displays a typical load distribution diagram between an inclusion network and the surrounding soil. The four acting forces of Q, F_n , F_p and Q_p can be found in the image.

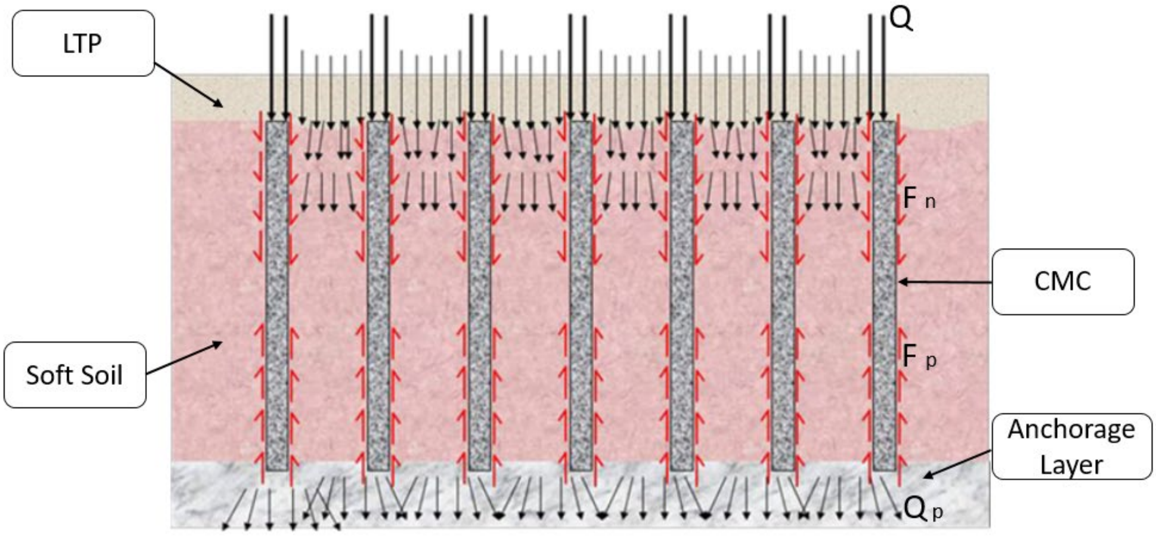

Figure 2.32: Typical load distribution between soil and CMC (after Combarieu, 1988)

In the design of rigid inclusions, the mitigation of both differential and total settlements, with or without the use of basal geosynthetic reinforcement, along with the prevention of lateral spreading and increasing stability, are the sought-after objectives in any project.

2.5.2 Construction Aspect

As per Menard Oceania, the installation of Controlled Modulus Columns (CMC) involves employing a specially designed displacement auger. This auger, operated by equipment with substantial torque capacity and high static down thrust, displaces the soil laterally with minimal spoil and vibration during penetration. The auger is driven into the ground to the required depth, simultaneously increasing the density of the surrounding soils. Subsequently, a cement mixture (grout) is pumped with moderate pressure through the hollow stem augur to form the column from bottom to the top to create the Controlled Modulus Column (CMC), also referred to as a rigid or semi-rigid inclusion. The grout is usually a lean pea-gravel concrete or sand-mix mortar with slump in the range of 8 to 12 (based on the required resistance). The result is a composite of soil-Controlled Modulus Column (CMC) acting as a homogeneous structure with enhanced bearing capacity. Figure 2.33 illustrates the construction process of Controlled Modulus Columns. As depicted, the CMC inclusions are grouted columns formed using specially-designed tooling that displaces soil laterally, resulting in minimal spoil. After the auger is removed, a column of cement-based grout is left in place.

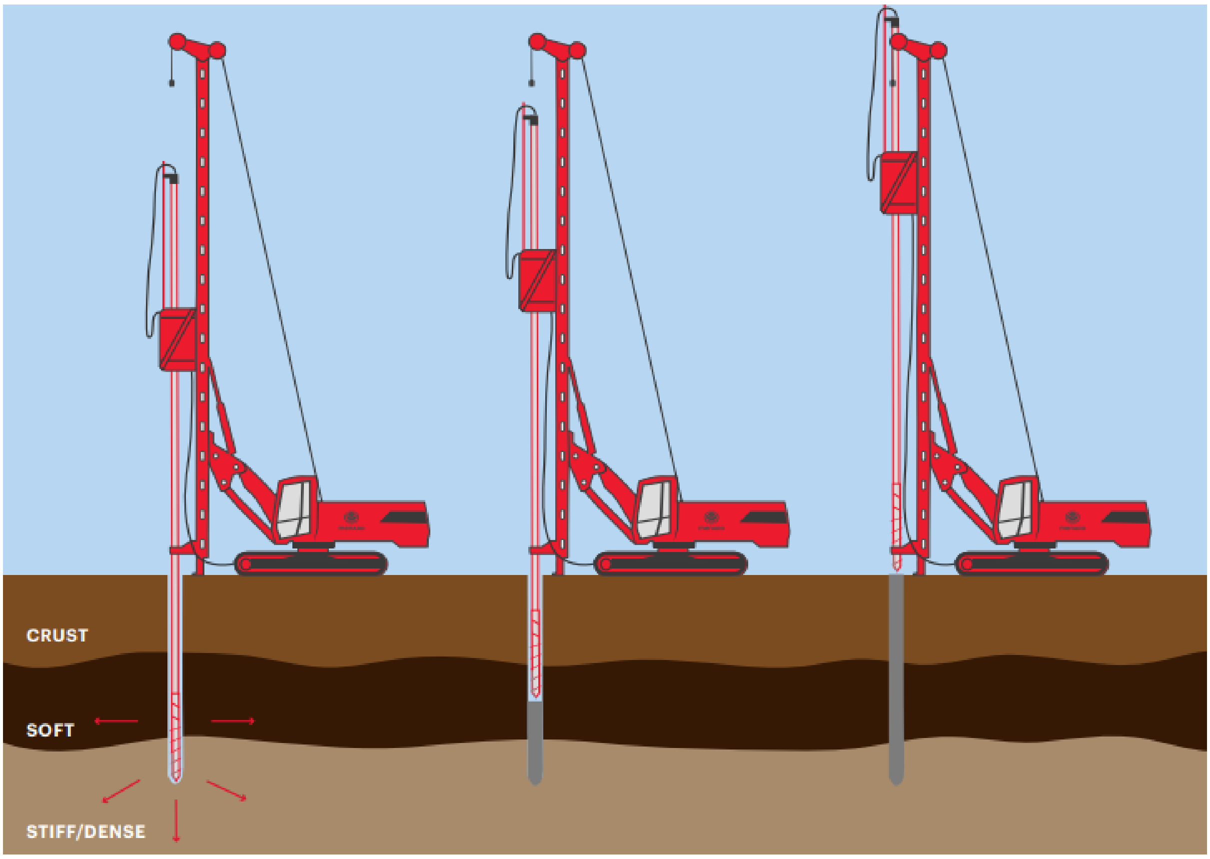

Figure 2.33: Construction process of controlled modulus columns (CMC) (Source: Menard Oceania)

According to Masse et al. (2004), the sequences of column construction were generally executed in a "hit and miss" pattern. In this pattern, every alternate column along a single row was constructed at a time in one direction only, so that double the centre-to-centre design column spacing would be the distance between each successive constructed column. Once the constructed "hit" columns gained adequate strength, the in-between "miss" columns were constructed until the row of CMC columns was completed. However, based on Chapter Four of this thesis and insights from industry experts, nowadays, this construction pattern for CMC is no longer favoured due to its complications and the potential risk of cracking the already installed columns. Based on experimental investigations conducted by Masse et al. (2015), it must be noted that this technique is entirely vibration-free, making the use of CMC very attractive for sites with challenging environments and those sensitive to vibration.

2.5.3 Load Transfer Platform (LTP)

As previously mentioned, it is necessary to place a Load Transfer Platform (LTP) over the CMC in order to uniformly distribute the load among the inclusions. This ensures that the CMC/soil combination acts as a composite layer. The LTP can consist of various different materials. Based on Coghlan et al. (2024), the most common type of LTP is a layer of granular material compacted layer by layer. Generally, this comprises well-graded sand or gravel with less than 10% fines, with a thickness typically ranging between 0.4 and 0.8 meters. However, this may vary depending on site conditions and the geometry of the foundation. If achieving the required thickness of LTP is not feasible, single or multiple geotextile membranes can also be integrated into the platform.

When calculations indicate that horizontal or lateral loads exceed the capacity of a CMC section, a steel reinforcement mesh can be integrated into the transfer platform. A typical example of this is beneath high embankments (>8m on very soft soils) where lateral loads can become significant. This approach was successfully implemented in the LGV High-Speed Train project from Paris to Bordeaux, as illustrated in Figure 2.34.

Figure 2.34: Steel reinforcement cage under embankment, LGV Project Paris – Bordeaux (after Coghlan et al. 2024)

In cases where CMC are installed in very soft soils to support an embankment height of 2.5m or less, there may be susceptibility to an undulating effect on the platform. The load for such a small embankment is generally quite low, resulting in a wide grid of CMC. This type of arrangement can be prone to settlement between columns. To mitigate this effect, a system of caps can be constructed on the heads of the CMC. The dimensioning of the CMC and the caps should satisfy the condition in equation 2.6 referenced from ASIRI (2013).

$$H_M > 1.5(s - a) \tag{2.6}$$

Where, H_M is the thickness of LTP, s is the centre-to-centre distance between CMC columns, and a is the diameter of the CMC Cap. Figure 2.35 schematically illustrates the CMC cap within the minimum LTP thickness.

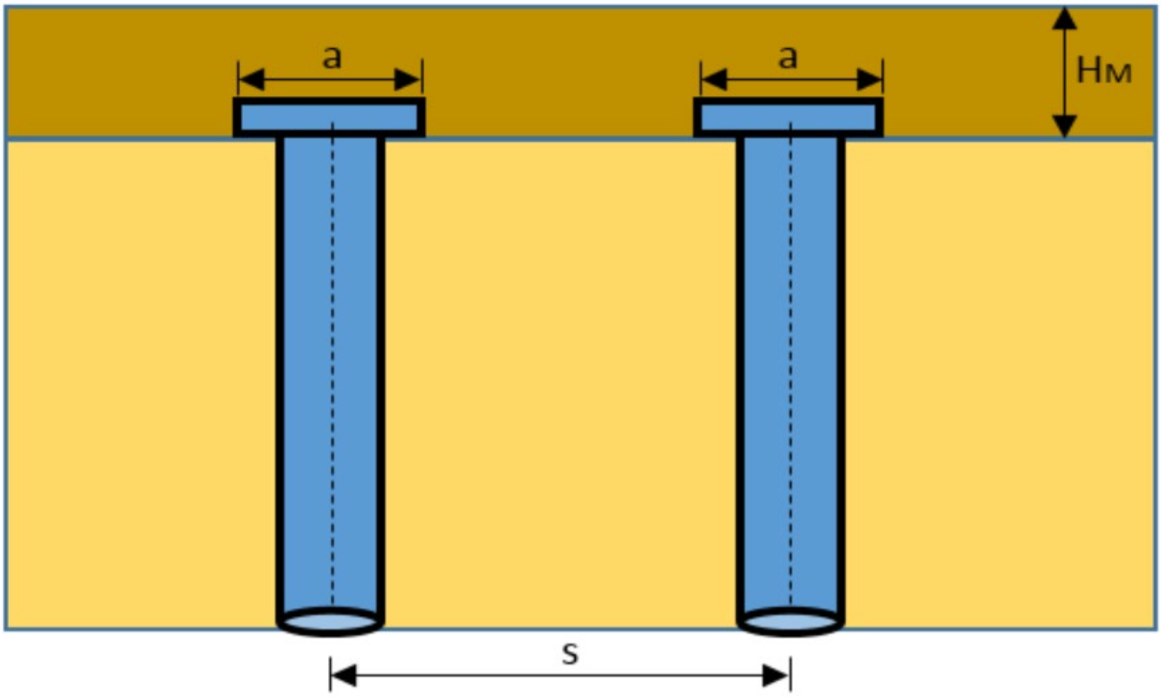

Figure 2.35: CMC Cap with Minimum LTP (Source: ASIRI 2013)

2.5.4 Applications of Controlled Modulus Columns in Transportation Infrastructures (Railway Tracks and Highway Embankments)

Soft soil deposits are primarily characterized by their high compressibility and low bearing capacity, which pose significant challenges to the construction and stability of infrastructure, particularly transportation systems. The inherent properties of soft soils, such as high water content, organic content, and fine-grained particles, contribute to their low shear strength and poor load-bearing capacity. Consequently, these deposits require improvement before the construction of any structure, particularly transportation infrastructure, where dynamic loads can exacerbate horizontal and vertical displacements. Among the array of ground improvement techniques available, controlled modulus columns (CMC) have emerged as a successful solution employed in numerous transportation projects. These columns effectively bolster the bearing capacity of foundations and mitigate the settlement of structures built in weak soil conditions. Figure 2.36 provides a schematic representation of the principal mechanisms linked to the behaviour of rigid inclusions utilized in the foundation of transportation structures. This visual aid elucidates the intricate interplay between various factors influencing the performance of rigid inclusions and underscores their significance in ensuring the stability and longevity of transportation infrastructure.

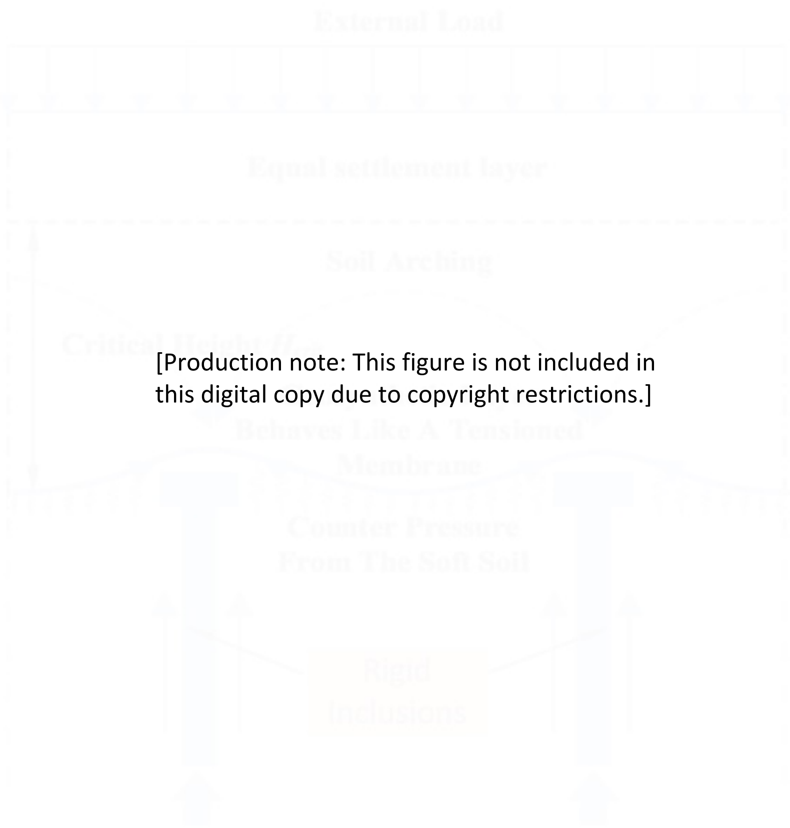

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Figure 2.36: The mechanism of loading transfer for rigid inclusions (modified after Wang et al. 2019)

As seen in Figure 2.36, the embankment fill forms an arch that supports the applied loading from traffic and the self-weight of the soil. The majority of the loading is transferred to the rigid inclusions through the soil arch, and if present, the geosynthetic layer as well, with only a small portion borne by the soil itself. Due to the complicated nature of this phenomenon and the multitude of factors involved, numerical methods emerge as the most suitable approach for assessing displacement fields and the resultant stress in the surrounding soils. These numerical techniques, such as finite element analysis (FEA) and finite difference method (FDM), enable engineers to simulate and analyse the behaviour of soil-structure interaction with a high degree of precision and detail. The proper choice of modelling technique for soil layers and inclusions is of paramount significance to accurately account for extreme displacement. Table 2.7 outlines typical CMC geotechnical parameters, material models, and software used in previous numerical studies.

Table 2.7: Typical CMC geotechnical parameters plus material model and software used in some previous studies

Reference	Program	Model	E (GPa)	*v*	γ (kN/m³)
Lauzon et al. (2009)	PLAXIS2D	Elastic	17.55	0.25	25
Alkaissi (2009)	P6.2	Elastoplastic	11	0.2	24
Wong and Muttuvel (2012)	PLAXIS2D	Elastic	10	0.25	25
Rivera et al. (2014)	PLAXIS3D	Elastic	10	0.2	24
Nguyen et al. (2019)	FLAC3D	Elastic	5.1 to 10.04	0.2	24
Mahdavi et al. (2019)	FLAC3D	Hoek-Brown	10	0.2	24
Wang et al. (2019)	LS-DYNA	Elastic	30	0.2	23
Pham (2019)	FLAC3D	Elastic	5	0.2	25
Pham and Dias (2021)	FLAC3D	Elastic	20	0.25	25
Ghosh et al. (2021)	PLAXIS3D	Elastic	12.5	0.2	24

Due to the importance and broad usage of this ground improvement technique, some past numerical and experimental investigations, as well as case studies, are briefly presented in this section.

Rapid development in high-speed trains necessitates the construction of new ballasted railway tracks on soft soils. Controlled modulus columns are utilized to control and mitigate the amplified vibrations in the tracks caused by the high speed of these trains. Burtin and Racinais (2016), conducted a numerical analysis for a case history where 4000 concrete rigid inclusions (CMC) and 700 vertical drains were installed to improve soft clayey ground during the construction of a 300-kilometer high-speed railway between Tours and Bordeaux in France.

The anticipated commercial speed of the train was intended to exceed 320 km/h. Figure 2.37 presents the cross-section of that project, with the location of soil improved by rigid inclusions shown in the image.

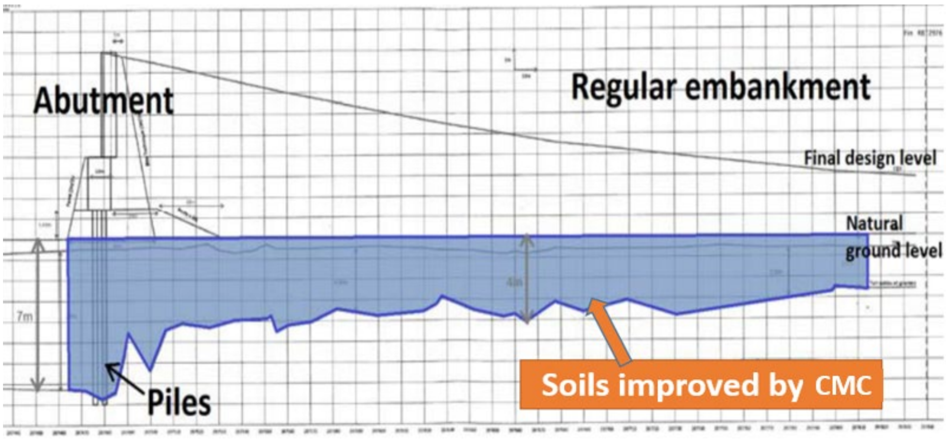

Figure 2.37: The cross section of soil improved by rigid inclusions (modified after Burtin and Racinais 2016)

To examine the effectiveness of the proposed ground improvement, PLAXIS 2D software was utilized. To validate the numerical model, vertical displacement sensors and profiles with inclinometers were installed at the embankment toe. The curves in Figure 2.38 show the estimated values from the finite element analysis and the measured values at the abutment location.

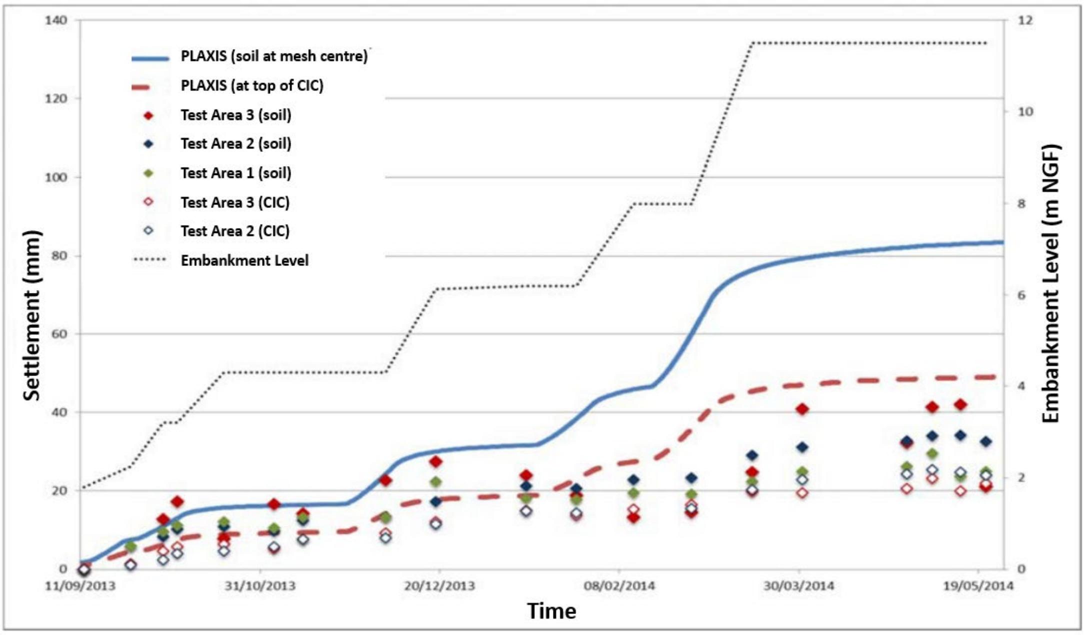

Figure 2.38: Evolution of forecasted and measured settlements during filling advancement (modified after Burtin and Racinais 2016)

According to Figure 2.38, two settings of vertical displacement sensors were at the CMC top (hollow diamonds) and at the mesh centre (filled diamonds). The blue curve and the dotted line curve show the maximum estimated settlements calculated using PLAXIS at the mesh centre and the CMC top, respectively. After comparing the results, it was revealed that the ratio between forecasted and measured values was approximately 2.1, proving the conservatism of the PLAXIS analysis.

Oteo et al. (2016), conducted a numerical analysis to investigate the functionality of the new high-speed railway line between three cities in Spain and its effects on the existing railway lines. The weak soil in the area consisted of soft to very soft silty clays at the top and black clays with altered gypsum (N_{SPT}IU-50) at the bottom. Therefore, the actual deformability of the ground and the proximity of the existing railway to the new branch line were two significant factors necessitating ground improvement along this stretch of the embankment.

Using Equation 2.7 and the design requirements of A/A_p = (10 to 11) and $= E_S^*/E_S =$ (4 to 5), the CMC diameters selected for this project were between 360 mm and 450 mm.

$$E_S^* = E_S + A_p/A \,.\, (E_p - E_S) \qquad (2.7)$$

where, E_S^* is the apparent deformation, E_p and E_S are the moduli of deformation for the CMC and the soil, respectively, and A_p/A is the area of the column per square meter.

With such a straightforward initial design, the PLAXIS 3D code was utilized to predict the effect of reinforcement on the existing adjacent railway lines. Figure 2.39 shows the 3D model created by the researchers for this project.

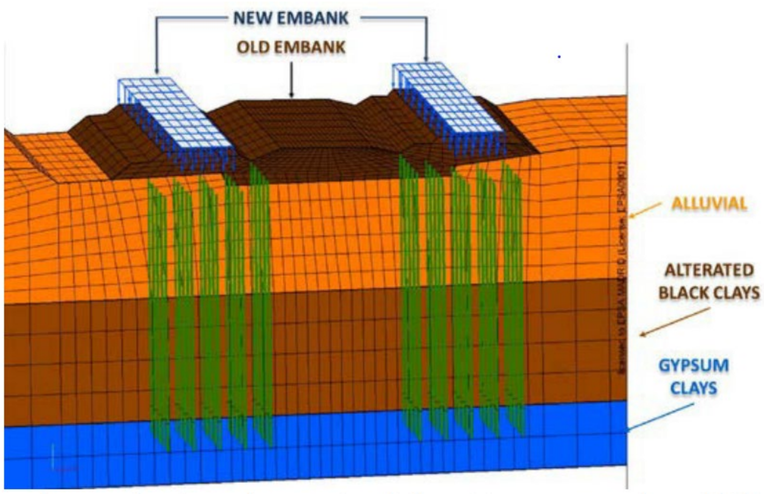

Figure 2.39: PLAXIS 3D model created for the existing and new railway project in Spain (after Oteo et al. 2016)

The results of the numerical model revealed vertical displacements of approximately 3 mm to 6 mm in the previous railway tracks and close to none for the reinforced ground beneath the new track. The designers considered two rows of 360 mm diameter CMC in grids of 1.5 × 2 m near the existing tracks and grids of 2 × 2 m for the rest of the ground treatment. The average length of these CMC was about 15 m. In some special cases, CMC with a diameter of 450 mm were used for areas where the embankment height was greater.

Wang et al. (2019), conducted a numerical analysis to understand the influence of rigid inclusions on existing railroads. Initially, they compared various analytical methodologies in terms of the stress reduction ratio *(SRR)* value to determine the most favourable rigid inclusion layout. The term *SRR* describes the correlation between the mean stress endured at the base of the embankment (σ_s) due to the subgrade and the stress induced by the external load in addition to the overlying own overburden of the embankment, which can be expressed as:

$$SRR = \frac{\sigma_s}{\gamma H + q} \tag{2.8}$$

where γ is the unit weight of the embankment fill, *H* is the embankment height, and *q* is the uniform surcharge on the embankment. When soil arching is fully developed, the value of *SRR* is expected to be approximately 0. In contrast, in the absence of soil arching, an anticipated value of *SRR* is approximately 1. Figure 2.40 depicts four rigid inclusion distribution designs suggested by Wang et al. (2019): (A) triangular pattern with larger gaps, (B) triangular pattern with smaller gaps, (C) square pattern with larger gaps, and (D) square pattern with smaller gaps.

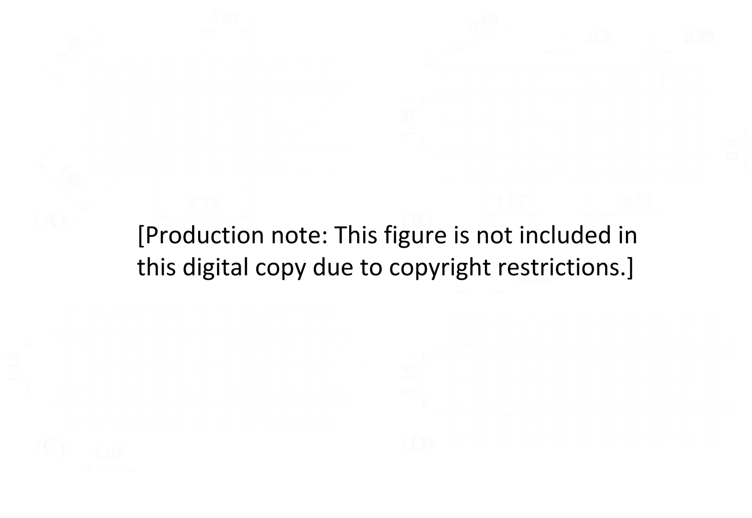

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Figure 2.40: Possible rigid inclusion arrangements; (A) triangular pattern with larger gaps, (B) triangular pattern with smaller gaps, (C) square pattern with larger gaps and (D) square pattern with smaller gaps [all units are in metres.] (after Wang et al. 2019)

Using various analytical methods, different values for *SRR* were calculated for each layout. Figure 2.41 shows the comparison of these methods for the suggested layouts.

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Figure 2.41: Comparison of stress reduction ratio (SRR) using various design techniques for suggested layouts; (A) triangular pattern with larger gaps, (B) triangular pattern with smaller gaps, (C) square pattern with larger gaps and (D) square pattern with smaller gaps (after Wang et al. 2019)

According to Figure 2.41, the square layout with smaller gaps has the smallest value of *SRR*, proving to be the optimal approach in decreasing the vertical stresses applied to the subgrade. However, this configuration presents a challenge as it requires twice as many CMC as the triangular layout with smaller gaps and the square layout with larger gaps arrangements, and three times as many as the triangular layout with larger gaps.

The larger number of CMC needed for certain arrangements, such as the square layout with smaller gaps, has two main drawbacks: (i) cost, and (ii) the potential occurrence of soil heaving due to the installation of a large number of CMC. The most economical design with the least required CMC is the triangular layout with larger gaps, but, according to the diagram, it has larger values of *SRR* and therefore, is less effective in terms of settlement reduction and stress transfer. After considering all factors and comparing calculated *SRR*s, the square layout with larger gaps was eventually chosen as the most appropriate design. This choice was made due to its lower *SRR* values (in most cases) compared to other layouts while requiring the same number of CMC.

Subsequently, the adopted 3D finite element program (LS-DYNA) was used to predict the vertical settlement caused by cyclic effects, incorporating the presence of rigid inclusions in the square layout with larger gaps arrangement.

Figure 2.42 illustrates the vertical stress associated with the elastic subgrade under cyclic loading, both with and without inclusions, at a depth of 2 m below the ground surface. The figure clearly demonstrates the favourable impact of rigid inclusions in terms of reducing vertical stress.

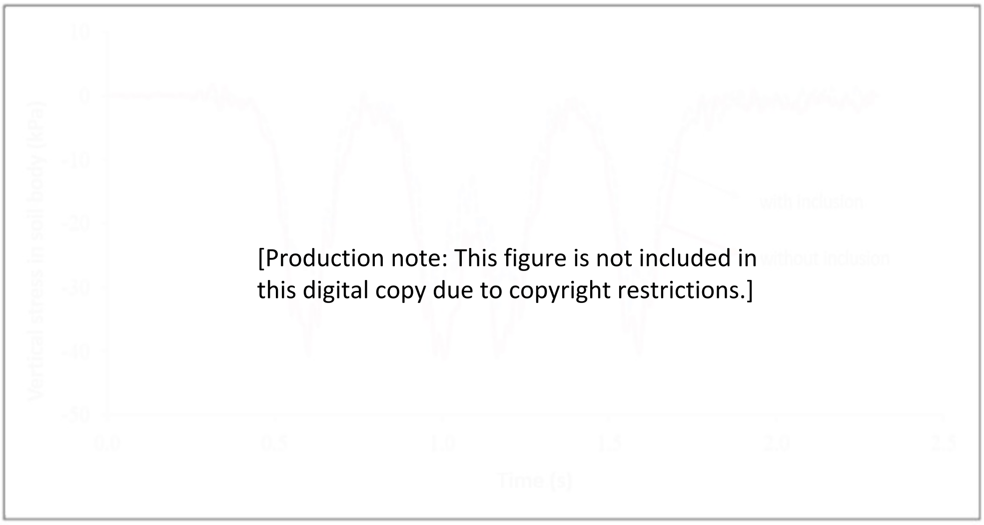

Figure 2.42: The vertical stress related to elastic subgrade for cases with inclusion and without inclusion due to cyclic loading at point 2 m below the ground surface (after Wang et al. 2019)

In Figure 2.43, the comparison of settlement profiles and vertical settlements vividly illustrates the impact of rigid inclusions on surrounding soil, compared with untreated soil conditions. The discernible effect of cyclic loading on ground settlement emerges prominently from the data presented. This visual representation serves as a compelling testament to the efficacy of rigid inclusions in mitigating settlement issues, offering a clear contrast between treated and untreated soil responses under similar loading conditions. By delineating the distinct settlement behaviours, this figure underscores the practical significance of incorporating rigid inclusion techniques in soil stabilization practices, particularly in contexts where cyclic loading is prevalent.

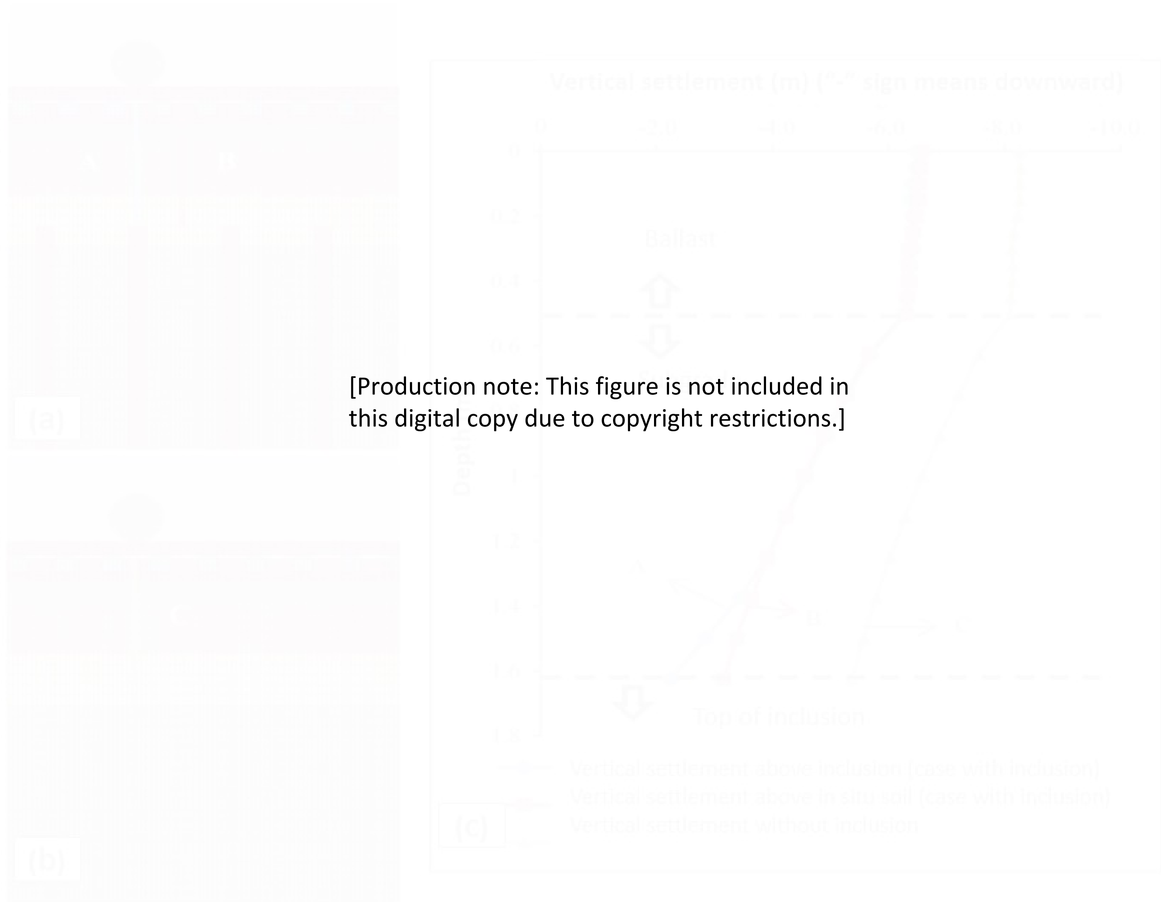

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Figure 2.43: Comparison of settlement profiles and vertical settlements; (a) settlement profile above rigid inclusion and its surrounding soil, (b) settlement profile above untreated soil, (c) vertical settlement for: A above rigid inclusion, B above treated soil, and C above untreated soil (after Wang et al. 2019)

Recently, the use of controlled modulus columns in soft soil conditions for supporting bridge approaches and road embankments is gaining increased popularity. These drilled columns, inserted into the firm layers of soil, enable designers to rely on the rigid inclusions to permanently bear the majority of the vertical loads, thereby minimizing ground settlement caused by static and cyclic loading to a great extent.

Rizal and Yee (2018), conducted numerical modelling to study the effects of a CMC ground improvement solution proposed for a 39 km new highway project constructed in Central Java, Indonesia. For various reasons, the CMC technique was adopted to support the bridge approach embankments, aiming to improve slope stability, bearing capacity, and minimize post-construction settlements. In that project, since the bridge abutments had already been constructed before the commencement of any ground improvement work, the choice of ground improvement technique was limited to methods that exhibit minimal lateral soil movement and vibration during works, to avoid potential damage to the foundations and completed bridge abutments. Any casing-driven granular columns, such as vibro stone columns, could cause excessive ground vibration during installation works. Additionally, the usage of stone columns was deemed inappropriate due to the very low shear strength of the underlying soft soils, which could lead to extreme column bulging and potential column failure during loading. Therefore, the CMC solution was utilized with the following design requirements: (i) maximum permissible residual settlement after 10 years to be less than 100 mm, (ii) minimum factor of safety of 1.5 against slope failure, and (iii) traffic loading not to exceed 15 kPa. Figure 2.44 shows the location of CMC in that project. The CMC treatment area was 60 m (the base width of the embankment) by 30 m. The height of the embankment varied from 6 m to 11 m.

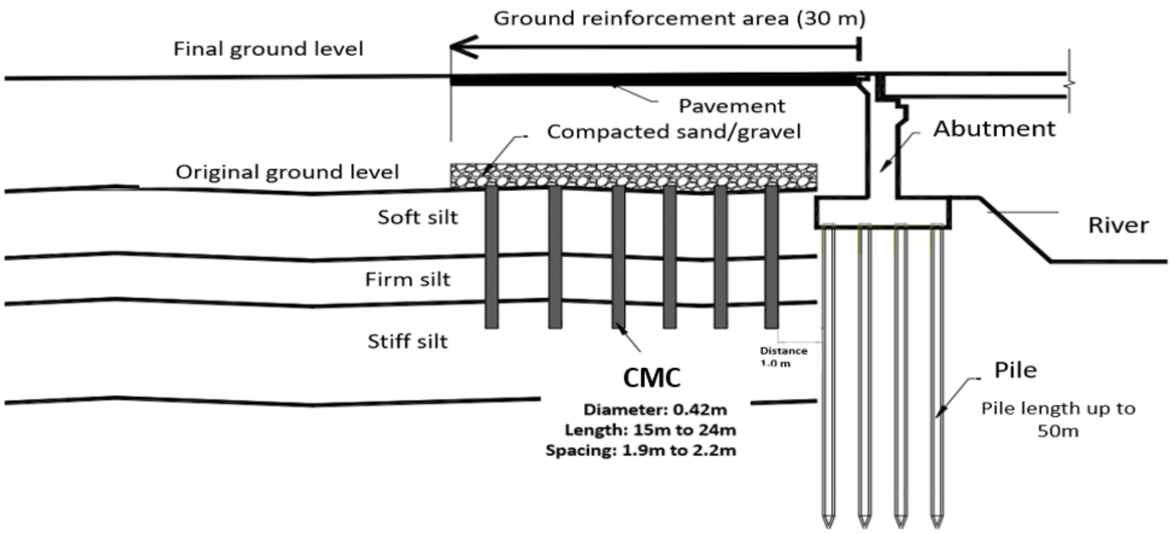

Figure 2.44: The cross-sectional view of the CMC treatment zone within the bridge approach
(modified after Rizal and Yee 2018)

To estimate the deformation of the embankment, numerical analysis using PLAXIS 2D was carried out, considering a CMC-soil interface factor of 0.8 and a soil stiffness modulus (E_y) of 750 N_{spt}. Figure 2.45 displays the results of vertical deformation caused by traffic loading of 15 kPa.

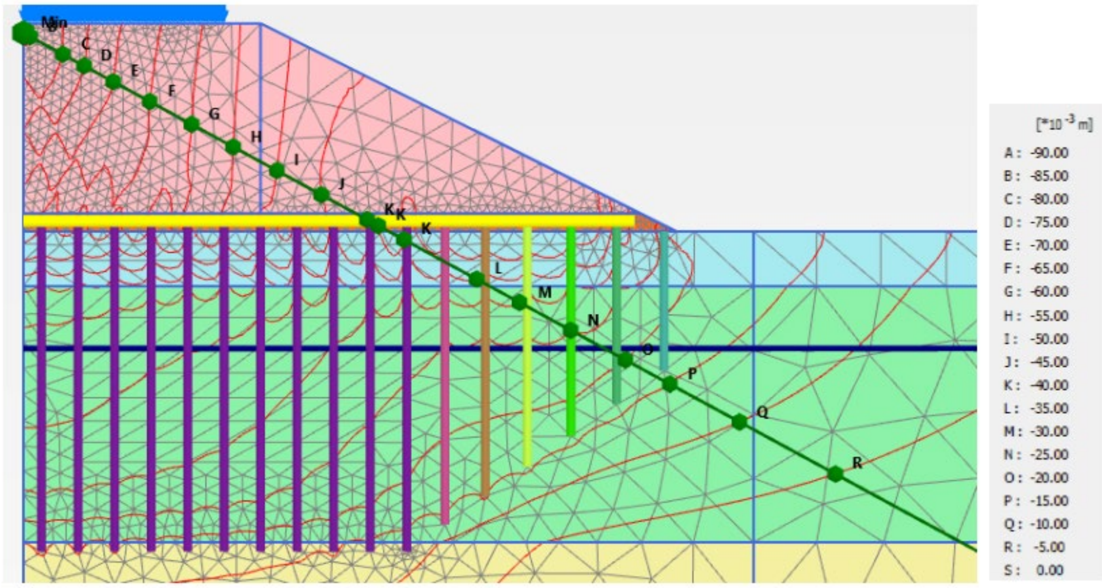

Figure 2.45: Results of vertical deformation (after Rizal and Yee 2018)

According to Figure 2.45, the maximum settlement occurs at the top of the embankment. CMC were constructed through soil displacement using displacement augers. After 28 days of CMC construction, plate load tests (PLT) were performed to validate the results obtained from PLAXIS analysis. Figure 2.46 compares the PLT measurements with the PLAXIS results.

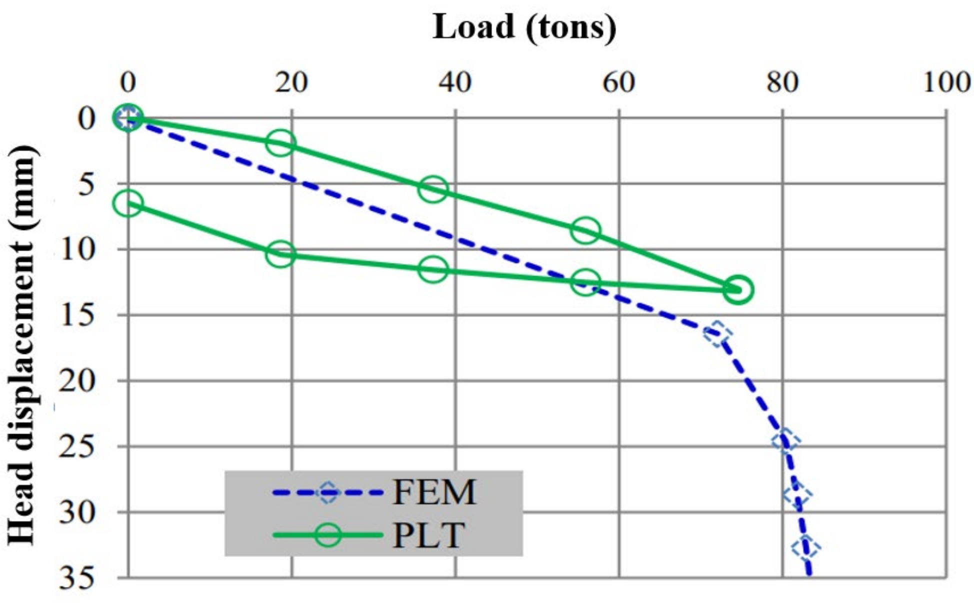

Figure 2.46: Comparison of plate load test (PLT) results with those of the finite element method using PLAXIS (after Rizal and Yee, 2018)

The length and diameter of the constructed CMC were 20 m and 420 mm, respectively. The columns were installed through a layer of soft to firm silt and terminated in hard clay with N_{spt} = 20. The green solid line represents the results obtained from the PLT test with a maximum load of 75 tons, while the blue dotted line represents the estimated results from finite element analysis. According to Figure 2.46, the difference between the results obtained from the two methods is negligible.

Mahdavi et al. (2016), conducted a numerical investigation to compare drained and coupled-flow deformation analyses for a road embankment constructed on CMC-improved ground. To simulate an embankment built on the improved ground with end-bearing CMC and a geosynthetic reinforcement layer, the FLAC3D finite element program was employed. The geotechnical properties for the soft clay, embankment, columns, and the geosynthetic layer are presented in Table 2.8.

Table 2.8: Geotechnical properties of materials used in numerical analysis conducted by Mahdavi et al. (2016)

Materials	E (MPa)	ν	γ (kN/m^3)	*c*´ (kPa)	Φ´ (°)	K (m/s)
Embankment Soil	30	0.3	20	5	32	____
Soft Clay	20	0.3	17	0	26	1×10^{-9}
CMC	10,000	0.15	24	____	____	____
Geosynthetic Layer	J = 1100 kN/m			K_S = 85 MN/m/m		

Figure 2.47 displays the variation of settlement at the base of the embankment according to the distance from the toe for end-bearing CMC. As can be clearly seen from the detailed analysis of Figure 2.47, for both cases of drained and coupled analysis, the centre of the embankment top undergoes the maximum settlement. This observation aligns with the expected behaviour of embankment structures under load, where the highest settlement tends to occur at or near the centreline due to the distribution of stresses and deformation patterns. However, upon closer examination and comparison of the results, it becomes evident that the coupled analysis exhibits approximately 32% more settlement compared to the drained analysis. This discrepancy in settlement behaviour between the two analysis methods highlights the significance of considering coupled-flow effects, such as pore pressure generation and dissipation, in the numerical modelling of embankment systems. The coupled analysis accounts for the interaction between soil deformation and pore water pressure

changes, leading to a more realistic representation of the embankment response under loading conditions.

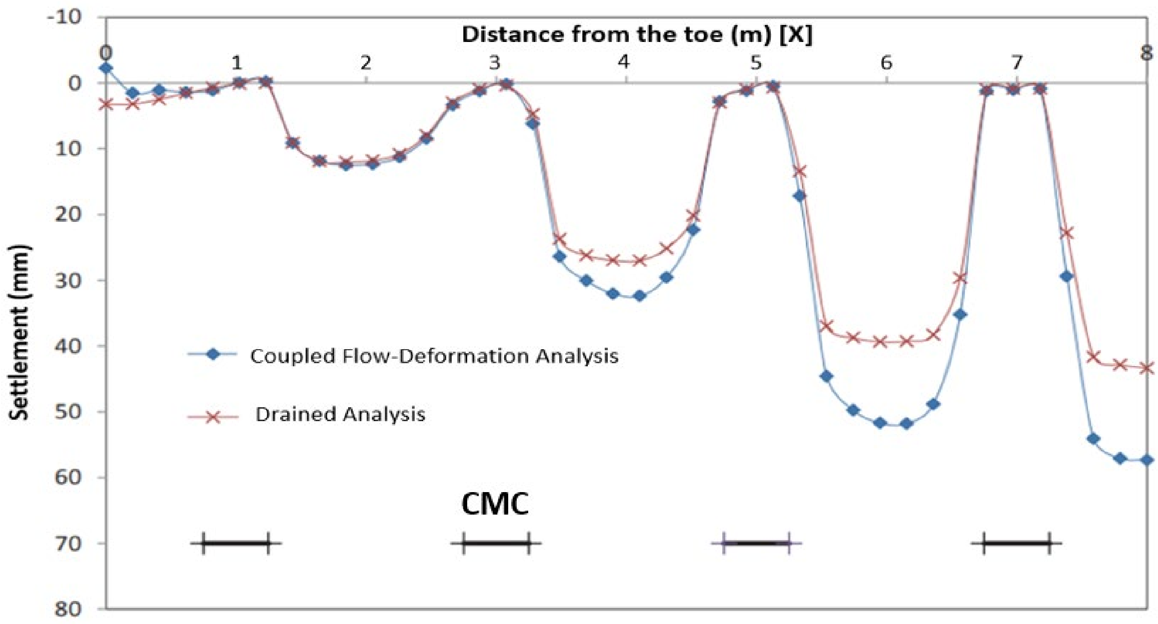

Figure 2.47: Variation of settlement at the base of the embankment (after Mahdavi et al. 2016)

Figure 2.48 indicates the tension in the geosynthetic layer through the column centre and in the direction perpendicular to the traffic.

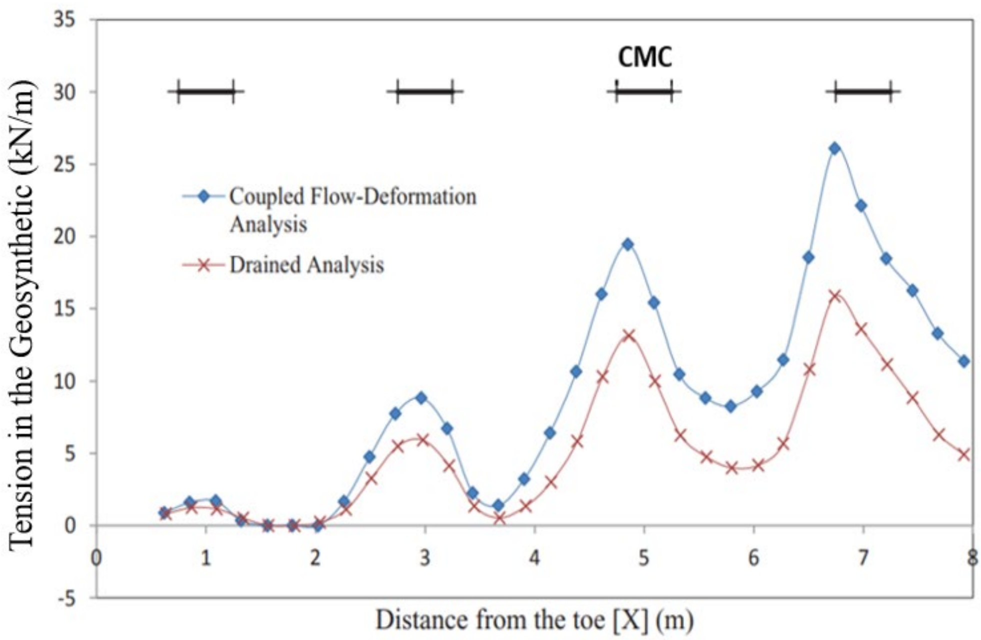

Figure 2.48: Tension in the geosynthetic layer (after Mahdavi et al. 2016)

According to Figure 2.48, the tension in the geosynthetic layer is undervalued in drained analysis, possibly due to the underestimation of lateral displacement and differential settlement. Therefore, the tensile force in the coupled analysis shows a maximum increase of approximately 62%.

Ghosh et al. (2021), conducted numerical modelling as well as a field study for a project involving column-supported and geosynthetic-reinforced embankments in Sydney, Australia. In this case history, various ground improvement techniques were utilized to mitigate slope stability issues and reduce post-construction settlements. However, to reinforce the shallow soil located just behind the bridge abutments, CMC were applied to improve embankment stability and control excessive settlement. The PLAXIS 3D package was chosen as the finite element software for the analysis. Figure 2.49 schematically illustrates the selected section for finite element modelling in that study.

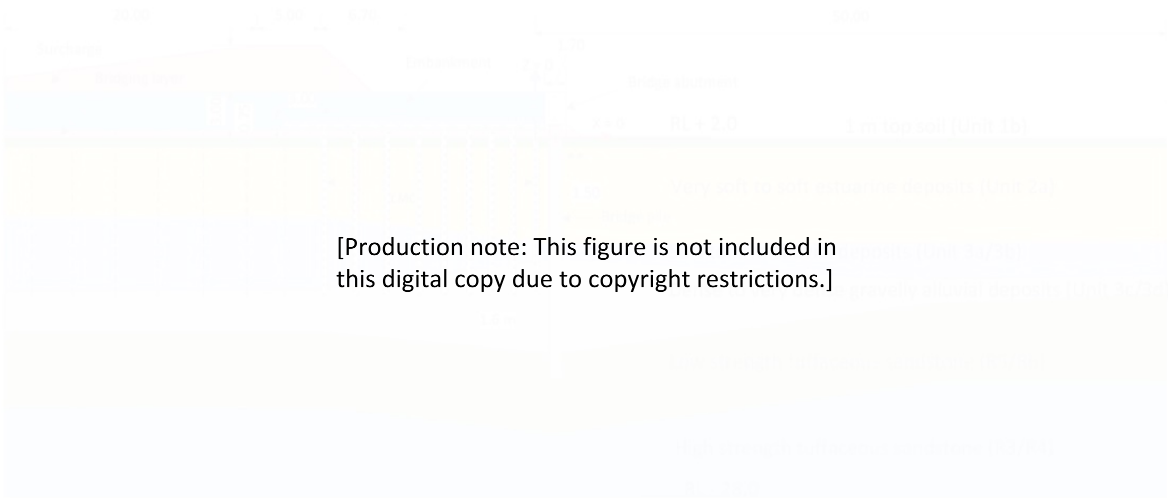

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Figure 2.49: Schematic illustration of the selected section for finite element modelling (after Ghosh et al., 2021)

Figure 2.50 shows the development of settlement over time under the base of the embankment. As can be seen, once the embankment fill was positioned on the existing layer, immediate and excessive downward movements of soil were detected in both numerical predictions and field measurements.

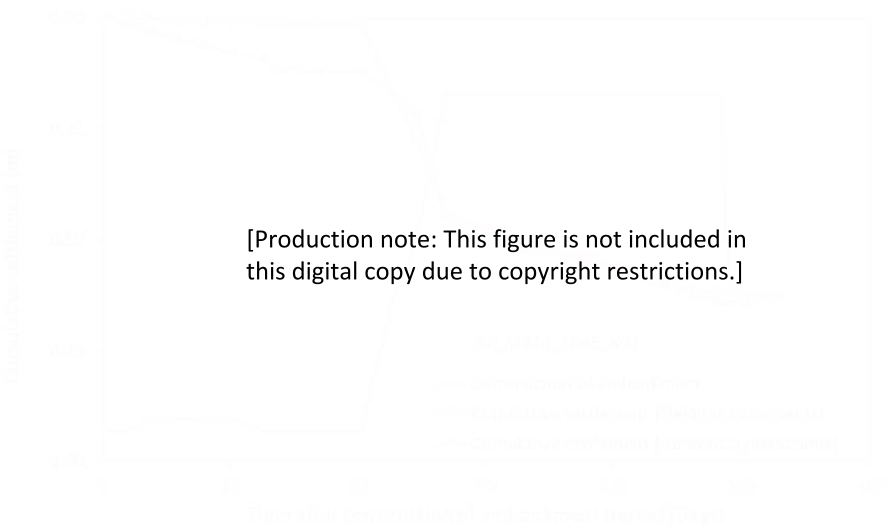

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Figure 2.50: Development of settlement over time under the base of the embankment (after Ghosh et al., 2021)

As depicted in Figure 2.50, an elevation in the embankment height leads to a rise in soil settlement, as observed in both numerical predictions and field measurements. The slight differences between results can be deemed negligible, with numerical analysis being on the conservative side. As discussed by Han and Ye (2001), the speedy process of consolidation in field measurements is explained by the dissipation of excess pore water pressure mechanically through load transfer to columns as well as hydraulically through vertical drains. Figure 2.51 displays the variation of excess pore water pressure measured by piezometers and numerical predictions.

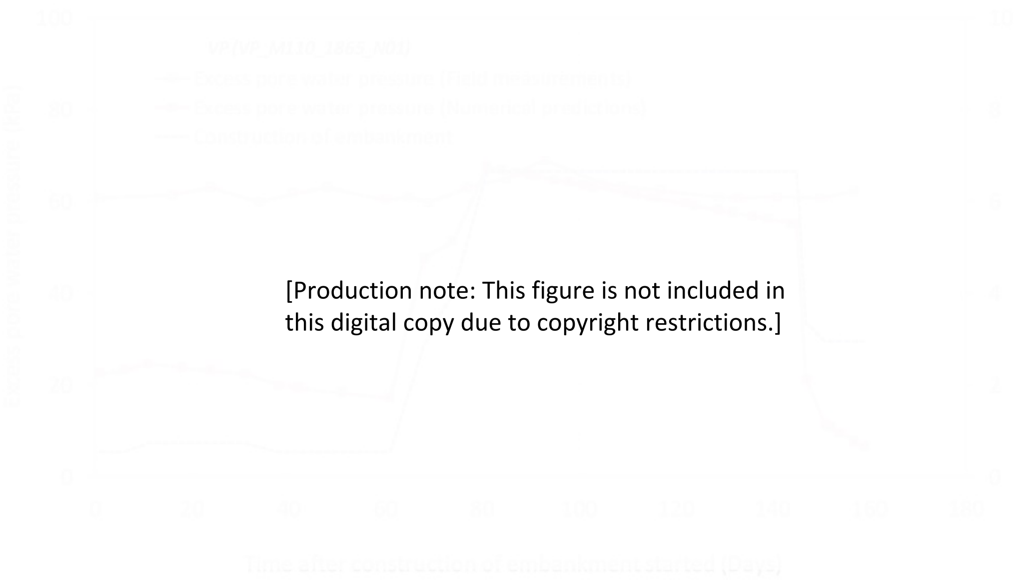

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Figure 2.51: Variation of excess pore water pressure measured by piezometer and its numerical prediction (after Ghosh et al. 2021)

As can be seen in the graph (which agrees with the results reported by previous researchers in the past, e.g., Liu et al., 2007), there are appreciable dissimilarities between the numerical prediction and field measurements of excess pore water pressures at the early stage of the construction of the embankment. However, since the development of excess pore water pressure is proportional to embankment height, therefore, in both cases (measured and computed) during construction of the embankment, a gradual increase of excess pore water pressure can be observed.

Pham and Dias (2021), performed a finite element analysis using FLAC3D (2020) to study the behaviour of a CMC-supported and geosynthetic-reinforced embankment. The analysis aimed to decipher the arching efficacy for non-cohesive and cohesive embankments. Due to the stiffness difference between the soft subsoil and rigid inclusions, the occurrence of differential settlement is inevitable, often leading to the development of arching in the embankment layer. The arching of CMC-supported embankments is a phenomenon defined as the redistribution of stress, facilitating the transfer of more loads to the rigid inclusion component and decreasing the loads acting on the subsoil and geosynthetic layer. The arching efficacy can be calculated using Equation 2.9 (Terzaghi, 1943; Low et al., 1944; Hewlett and Randolph, 1988).

$$E_a = \frac{P_c}{(\gamma H + q).A} \times 100\% \tag{2.9}$$

where, E_a is the arching efficacy, P_c is the load distributed on the CMC cap by arching, γ is the unit weight of embankment soils, H is the embankment height, q is the surcharge and A is the CMC contributory area. The range of arching efficacy varies from 0 to 100%. For the case of no arching, there is 0 efficacy while for a complete arching, 100% efficacy is anticipated.

Figure 2.52 illustrates that the effectiveness of arching also increases with an increase in the height of the embankment. According to this figure, due to inadequate shear resistance in embankments with lower heights, the evolution of arching is not appreciable, and the applied pressure onto the geosynthetics is massive. However, more shear resistance is accumulated due to the increase in embankment height, resulting in enhanced development of soil arching. Therefore, it can be suggested that once the embankment height increases, the arching efficacy reaches a threshold. Another interesting conclusion of this research is the fact that the cohesion of the soil has a direct impact on the arching efficacy, where more cohesive soils result in increased arching of the embankment.

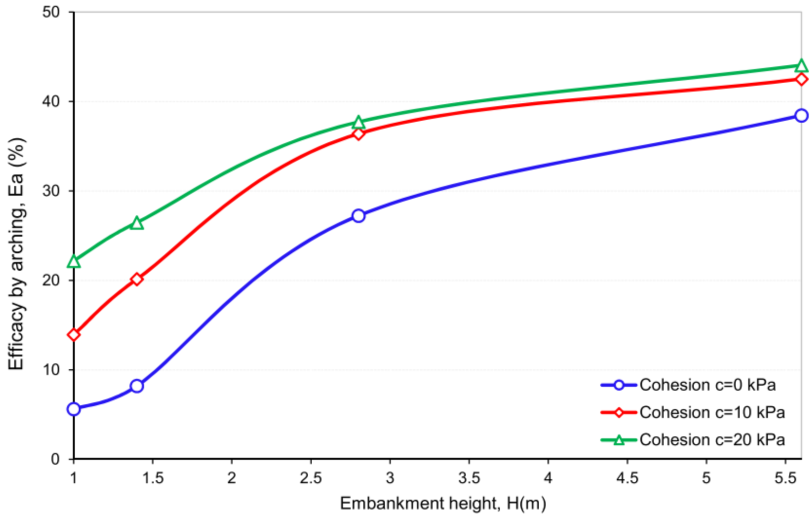


Figure 2.52: Variation of arching efficacy with respect to embankment height for non-cohesive and cohesive embankments (after Pham and Dias, 2021)

The researchers also predicted the vertical deformation and deformed shape of the geosynthetic layer with respect to embankment height. Figure 2.53 displays the variation of vertical displacement for different embankment heights over the distance from the CMC centre.

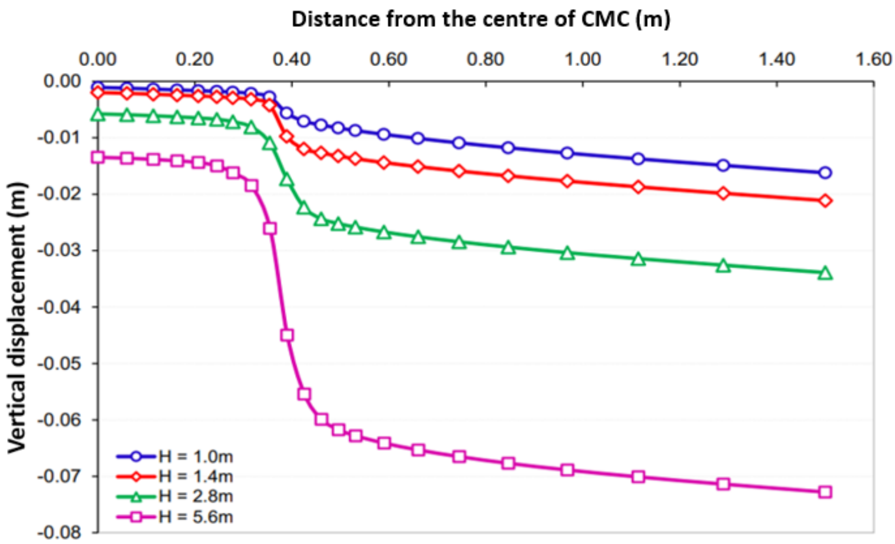


Figure 2.53: Variation of vertical displacement for different embankment heights over the distance from the CMC centre (after Pham and Dias 2021)

It can be clearly seen that the geosynthetic deformation occurs significantly and changes sharply in an area around the edge of the CMC. This finding suggests that an excessive load is concentrated in the vicinity of the CMC edge. It is also evident that the geosynthetic deformation is more profound in embankments with higher heights.

El-Gendy and El-Mossallamy (2020), were interested in the behaviour of embankments constructed on soft soil deposits reinforced with rigid inclusions. They conducted a numerical analysis using PLAXIS 3D 2020 to validate a laboratory model test performed by Van Eekelen et al. (2012). After validating the experimental model, the researchers also conducted a parametric study to understand the effects of the embankment's friction angle on settlement behaviour. Figure 2.54 shows the estimated values of vertical displacement corresponding to various angles of internal friction.

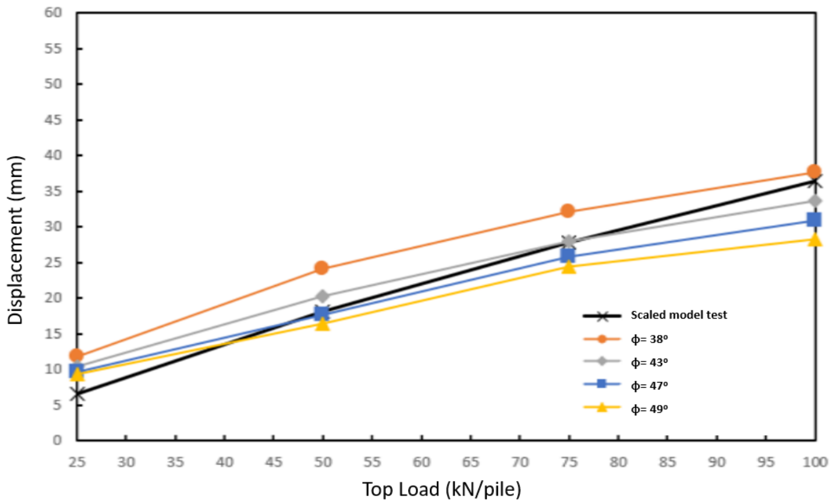


Figure 2.54: Estimated values of vertical displacement for various angles of internal friction (after El-Gendy and El-Mossallamy, 2020)

According to their performed parametric study, an improvement in the arching efficacy of the embankment is obtained as a result of an increase in the internal angle of friction, which consequently leads to a decrease in vertical displacements.

Wong and Muttuvel (2012), recommended a two-phased numerical analysis approach for establishing more economic designs for CMC-supported embankments. Based on their recommendation for a detailed design, the following phases can be considered.

Phase 1: To examine the influence of column spacing on surface deformation and the usefulness of any LTP and the reinforcement within the LTP (if required), an axisymmetric finite element analysis is to be conducted.

Phase 2: To evaluate the lateral movement underneath the batter of the embankment and any transition zones behind the CMC supported zone, a (2D) or (3D) finite element analysis is to be performed. The effect of any preload or surcharge on the lateral deformation of CMC should also be assessed.

An example illustrating the effects of spacing-to-diameter ratio on the variation of total settlement is shown in Figure 2.55. According to the figure, for a CMC with a 0.45 m diameter and a design requirement of 100 mm post-construction total settlement, the optimum spacing of maximum 1.9 m can be detected.

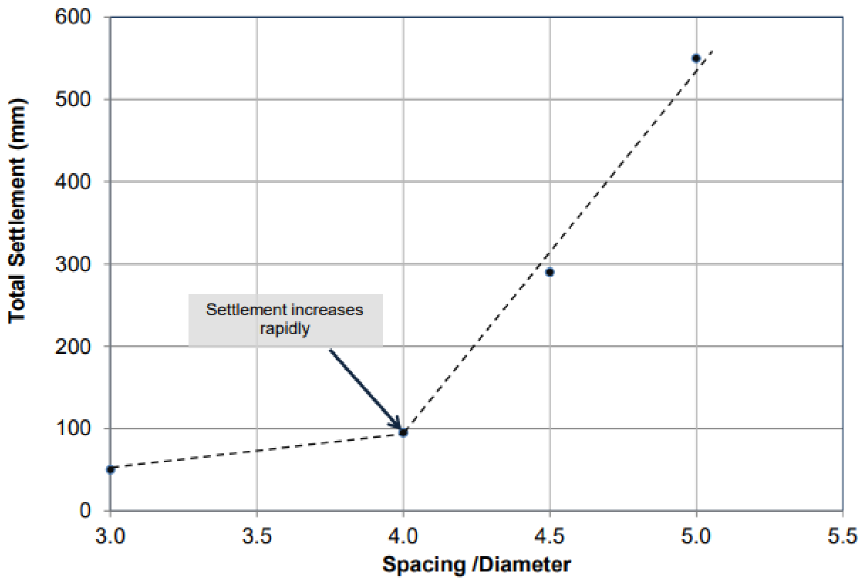


Figure 2.55: Effects of spacing-to-diameter ratio on variation of total settlement (after Wong and Muttuvel, 2012)

Previous research provides a wealth of case histories that serve as compelling evidence, showcasing the efficacy of CMC rigid inclusion as a highly efficient ground improvement method. These case studies, spanning various geographical locations and project contexts, underscore the versatility and applicability of CMC in transportation infrastructure projects around the world.

2.6 Comparison of Stone Columns and Controlled Modulus Columns

Inexperienced engineers who lack familiarity with the various ground improvement methods often struggle to choose between CMC rigid inclusions and Vibro stone columns (VSC) semi-rigid inclusions. Making the correct selection at the design stage is vital to prevent potential complications later on. Therefore, it is crucial to understand the specific construction conditions of the site and consider numerous design factors to determine the most suitable technique for a given project. Higgins (2014) provides an efficiency comparison between CMC and VSC, considering factors such as time, cost, and long-term performance, alongside other ground improvement techniques, as depicted in Figure 2.56.

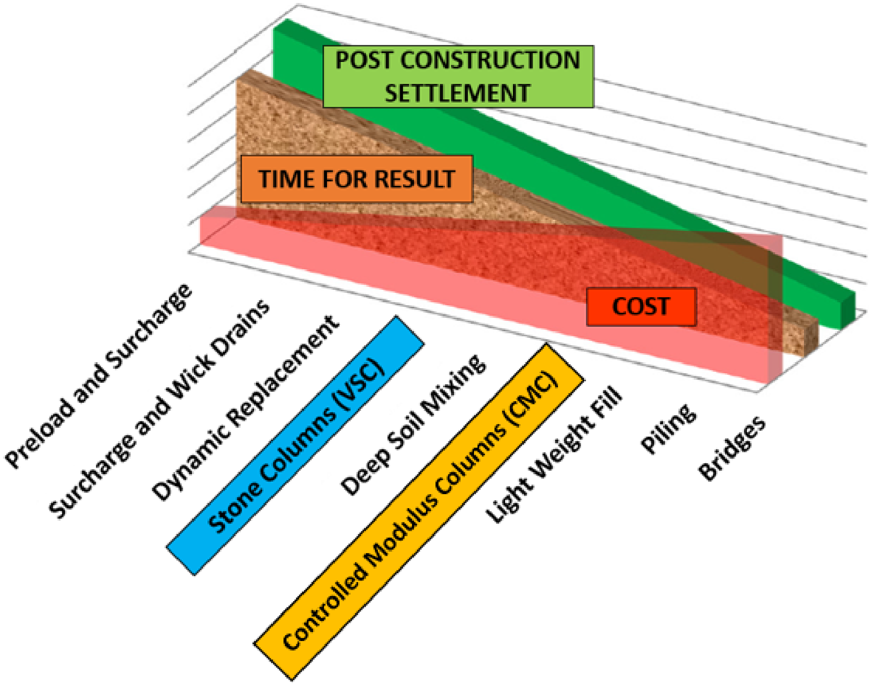


Figure 2.56: Comparison of cost, time for results, and post-construction settlement for various ground improvement techniques (after Higgins, 2014)

When dealing with soils that are categorized as being too compressible but not extremely weak to warrant deep pile foundations, stone columns appear to be an ideal solution for economical shallow foundations. Typically, a stiffness ratio between 5 to 10 (the ratio of the modulus of the column to the modulus of the surrounding soil [Mc/Ms]) is used in practice to determine an equivalent composite modulus for the design of the improved layer. In reality, a settlement improvement factor (i.e., the ratio between the settlement of the improved and unimproved soil) of 3 is generally the greatest value that can be achieved using stone columns. Therefore, the effectiveness of stone columns is limited for extremely compressible soils. Due to this limitation, the expected stiffness of the stone columns reinforced ground may be less than what is required to achieve desirable outcomes related to settlement control of a project. Furthermore, in very soft soil conditions, stone columns themselves may not be internally stable due to lack of lateral confinement, leading to shearing failures or bulging under vertical loading, even after the utilization of geosynthetic encasements. However, despite the limitations associated with the usage of stone columns in very soft soils, their application has grown tremendously worldwide in transportation structures and in areas where intermediate foundation solutions can benefit a project. Stone columns are generally ineffective in very soft or organic soils, which could be a significant driver for the development of Controlled Modulus Columns (CMC). Unlike stone columns, rigid inclusions, such as CMC, are constructed from mortar or concrete and do not risk bulging in layers with low lateral confinement. They are installed in soft ground using a displacement tool to create an internally stable element that reinforces poor soils. Because the modulus of deformation of concrete is significantly greater than that of surrounding soils, CMC rigid inclusions can reduce settlement 10 to 20 times more effectively in certain situations than stone columns. This makes them highly effective in very soft soils. Three fundamental differences between CMC and VSC regarding design approach, ground improvement application, and soil type and construction considerations are briefly discussed here.

2.6.1 Design Approach

For stone columns, since the stiffness of the surrounding soil and column material are in the same relative range, the majority of design methods are based on the following hypotheses:

- Load transfer is a function of the area replacement ratio.
- Equal settlement planes/strain compatibility between columns and soil.
- Lateral expansion of the columns.

In contrast, the load transfer between columns and soil in CMC rigid inclusions is a much more intricate process, caused by differential strain between the columns and the soil alongside them. Since the stiffness of CMC rigid inclusions is significantly higher than that of the surrounding soil, the assumption of strain compatibility cannot be applied to CMC. Regarding equal settlement planes, there is only one neutral plane between the columns and the soil, located along the shaft of the columns at depth; however, elsewhere shear stresses are created at the interface, and the soil and columns do not deform equally. In the design of CMC rigid inclusions, numerical analysis is typically employed to accurately model the complex interaction between the soil and the structure. Design complications of rigid inclusions are particularly problematic for road and railway embankments due to the presence of dynamic loading. Table 2.9 provides a summary of previous investigations involving embankments reinforced with rigid inclusions using numerical modelling.

Table 2.9: Summary of some previous investigations involving embankments reinforced with rigid inclusions using numerical modelling

Reference	**Method**	**Software**	**Cond.**	**Embankment**	**Rigid Inclusion**	**Subsoil**	**Interface**
Han and Gabr (2002)	FDM	FLAC	3D	Hyperbolic elastic model	Isotropic linear elastic	Hyperbolic elastic model	No
Jenck et al. (2007)	FDM	FLAC	2D	Mohr-Coulomb model	Isotropic linear elastic	Mohr-Coulomb model	No
Le Hello and Villard (2009)	DEM/FEM	SDEC	3D	Micro mechanical model	Micro mechanical model	Micro mechanical model	No
Oliveira et al. (2011)	FEM	PLAXIS	2D	Mohr-Coulomb model	Linear elastic	Cam-Clay model	No
Han et al. (2012)	DEM	PFC	2D	Micro mechanical model	Micro mechanical model	Micro mechanical model	No
Al-Ani et al. (2014)	FEM	PLAXIS	3D	Hardening soil	Elasto-plastic	Hardening soil	No
Rowe and Liu (2015)	FEM	Abaqus	3D	Mohr-Coulomb model	Isotropic linear elastic	Drucker-Prager	Yes
Jamsawang et al. (2016)	FEM	PLAXIS	3D	Mohr-Coulomb model	Linear elastic	Soft soil model	No
Yu and Bathurst (2017)	FDM	FLAC	2D	Mohr-Coulomb model	Isotropic linear elastic	Mohr-Coulomb model	Yes
Wu et al. (2018)	FEM	Abaqus	3D	Mohr-Coulomb model	Linear elastic	Cam-Clay model	No
Huang et al. (2019)	FDM	FLAC	3D	Mohr-Coulomb model	Isotropic linear elastic	Cam-Clay model	Yes
Badakhshan et al. (2020)	DEM	PFC	3D	Micro mechanical model	Micro mechanical model	Micro mechanical model	No
Tran et al. (2021)	FDM	FLAC	3D	Cap-yield model	Isotropic linear elastic	Mohr-Coulomb model	No

Furthermore, the way the load from the structure is transmitted to the elements is another fundamental difference between the behaviour of CMC rigid inclusions and stone columns. Because of the assumption of strain compatibility in the case of stone columns, it is believed that the load is transmitted and distributed directly between the soil and the columns. Therefore, only a very thin load transfer platform (LTP), if any, might be necessary to equalize the stresses below a slab. On the other hand, the LTP is a key element of the design for CMC rigid inclusions, as it limits the load that is directly transmitted to the poor soil by creating an arch that will transmit the load from the structure to CMC rigid inclusions. Figure 2.57 illustrates the dissimilarities in design principles of stone columns and CMC rigid inclusions.

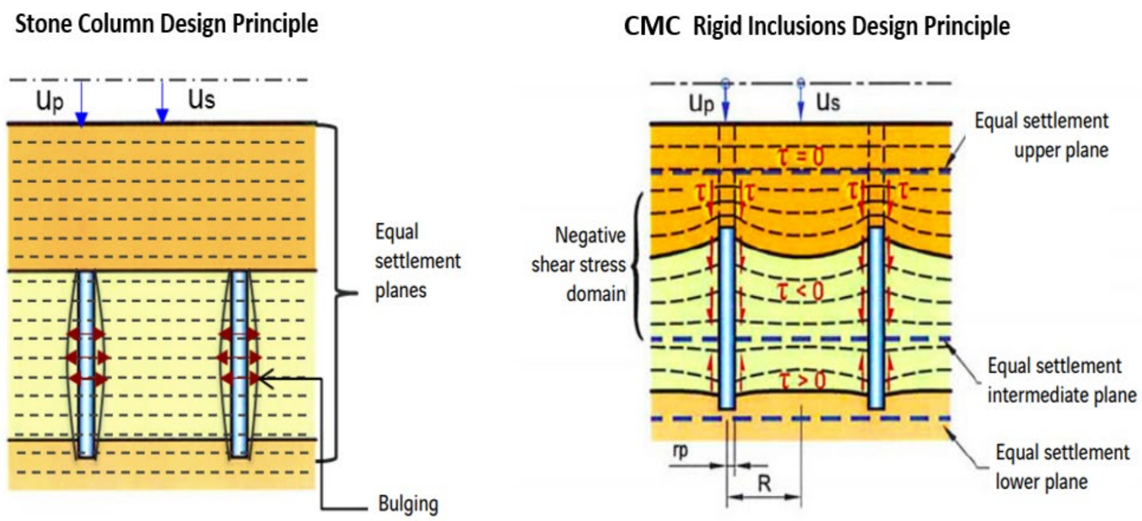


Figure 2.57: Dissimilarities in design principles of stone columns and CMC rigid inclusions (Source: Menard Oceania, 2022)

2.6.2 Ground Improvement Applications and Soil Type

Stone columns are typically utilized for soil improvement across a spectrum of classifications, ranging from fines to soft clays and silts to loose sands. Moreover, in soils with high liquefaction potential, stone columns are often the preferred soil improvement technique for three main reasons. Firstly, the columns reinforce the soil mass due to their shear strength. Secondly, installation of stone columns aids in densifying the liquefiable layers between the columns (modified CMC techniques, such as using reinforcement, can also be applied to liquefiable layers). And thirdly, the void space in the granular material of stone columns facilitates the rapid dissipation of excess pore water pressures.

On the contrary, as mentioned previously, very soft clays and silts with low shear strengths of less than 15 to 25 kPa cannot be effectively reinforced with stone columns. In such soil conditions, the inadequate stiffness of the soil results in a lack of sufficient lateral confinement for the column. Consequently, once vertical load is applied, the stone column itself is at risk of bulging and experiencing significant deformations.

CMC rigid inclusions, on the other hand, can be practically utilized in all soil types, including various fills, peat, silts, clay, sand, and gravel. In extremely soft cohesive soils where the use of aggregate-based columns is not suitable, CMC rigid inclusions appear to be the most beneficial technique. In cases where improvement is needed adjacent to vibration- and settlement-sensitive structures, CMC rigid inclusions are greatly appreciated, especially when non-vibratory techniques are necessary. However, in highly seismic areas, a hybrid approach combining earthquake drains/stone columns and structural reinforcement of CMC rigid inclusions may be needed to effectively mitigate seismic risk.

2.6.3 Construction Consideration

For the case of stone column ground improvement, when the soil condition is stiff or high area replacement ratios are required, predrilling may be necessary to achieve the design stone column depth and diameter. In very obstructed or extremely stiff layers, CMC rigid inclusions may also need to be predrilled; however, the drill rigs that install CMC rigid inclusions (with high thrust/pull-down force and high torque) are capable of penetrating much denser and stiffer ground than can be achieved with vibratory probes. Neither CMC rigid inclusions nor stone columns can penetrate obstructions such as naturally occurring boulders and cobbles or buried slabs and foundations. Predrilling using other equipment or relocating either type of ground improvement system might be necessary.

Both techniques may provide uplift resistance; however, it is more economical and simplified to use CMC rigid inclusions, as steel reinforcement can be easily set in the fresh grout upon installation of the column. Column installations to depths of over 30 m can be achieved using both techniques, but CMC rigid inclusions are typically more economical due to their significantly faster installation rates for very deep applications. Furthermore, in many cases, CMC rigid inclusions allow for tighter settlement performance and higher bearing pressures.

2.6.7 Sustainability Considerations

The most natural foundation system or ground improvement technique in existence to date is probably stone columns. As previously stated, stone columns improve the ground through the partial replacement of weak soil with stiffer resources such as granular materials, sand, or stone aggregates. Nowadays, as a potential development in terms of sustainability for stone columns, numerous studies have been carried out on the performance and behaviour of stone columns made of various column filling materials. According to Zukri and Nazir (2018), materials such as river sand, limestone, stone dust, quarry dust, Silica-Manganese slag, Pulverized Fuel Ash (PFA), tyre chips, recycled aggregate, crushed polypropylene (PP), coal bottom ash, fly ash, etc., have all been recognized to be used as replacements for traditional aggregate materials in the construction of stone columns. These alternative column filling materials, apart from being very economical, as the materials are cost-effective, environmentally friendly, and readily available, also deliver high efficiency.

In the context of ground improvement technology, Controlled Modulus Columns (CMC) represent a sustainable solution that offers several advantages over traditional methods such as piling. Notably, CMC contribute to lower carbon emissions, enhance controlled durability and quality, result in project savings through the utilization of displacement methods and load transfer layers, boast high production rates, and eliminate costs associated with soil disposal. A study conducted by Nguyen et al. (2014), delved into the sustainable development potentials of CMC, shedding light on various avenues for improvement. One significant aspect highlighted in the study is the potential for economic design enhancements through trial field tests. By optimizing the design process and conducting comprehensive field trials, it becomes possible to refine CMC applications further, ensuring cost-effectiveness and optimal performance. Additionally, the study emphasizes the importance of utilizing recycled industrial by-products for grout mixtures, which not only reduces waste but also promotes sustainability by repurposing materials that would otherwise be discarded. Furthermore, attention is drawn to the fuel consumption during CMC operations, presenting an opportunity for improvements in sustainability. Implementing measures to minimize energy consumption and exploring alternative energy sources can further enhance the environmental credentials of CMC projects. However, despite the numerous benefits offered by CMC, there are also concerns that warrant attention. One such concern is the potential impact of CMC installation on adjacent columns and existing structures. Addressing these concerns requires thorough research and careful planning to mitigate any adverse effects and ensure the structural integrity of surrounding elements. Table 2.10 summarizes the differences between these two techniques.

Table 2.10: Differences between Vibro Stone Columns and CMC Rigid Inclusions

Subject	Vibro Stone Columns	Controlled Modulus Columns
Design Approach	Equal settlement planes compatibility between columns and soil.	Very complicated, finite element analysis are mostly used.
Soil Type	Loose sands with fines to soft clays and silts with minimum shear strength of 25kPa. Excellent option for liquefiable soils.	All soil types, including gravel, sand, clay, silts, peat, organic chalk and various fills.
Construction Considerations	Predrilling may be needed to achieve the design stone column diameter and depth. Slow construction process.	Drill rigs can penetrate much stiffer/denser ground. Quick process.
Limitation of Application	Projects with extremely high loads. Environmentally sensitive projects where vibration must be avoided. Grounds made of peat, organic soil, or mixed backfill, and applications with stringent settlement criteria such as bridge abutments.	Virtually suitable for any application. In liquefiable soils must be adjoined with vertical drains or stone columns for dissipation of excess pore pressure.
Post Construction Settlement	Relatively high.	Relatively low.
Cost Effectiveness	Very cost-effective method. The columns are made of natural, easily accessible, and often local materials. Vibrating probes and machineries are available worldwide.	More economical for very deep applications and where time is of the essence due to their significantly faster installation rates.
Sustainability	Substituting aggregates with eco-friendly disposables can boost sustainability without compromising performance.	Mitigation of fuel consumption reduces CO2 emission. Recycled by-products instead of grout mix improves sustainability.

2.7 Introduction of Bi-modulus Columns (Rigid & Semi-rigid)

Bi-modulus column is regarded as a new technique in column-type ground improvement, invented to address the issues of the CMC technique and the shortcomings of the VSC method. Since the rigidity of controlled modulus columns is much greater than that of the surrounding soil, the top part of these vertical inclusions might protrude from the ground and pose challenges, typically referred to as "mushroom effects", particularly in transportation structures. Figure 2.58 illustrates an example of mushroom effects caused by CMC rigid inclusions on the surface of a low embankment in Virginia, USA.

Figure 2.58: Mushroom effects on the surface of a low embankment caused by the rigidity of controlled modulus columns, Virginia, USA

Bi-Modulus columns allow engineers to combine the benefits of extreme settlement reduction from the CMC technique with some advantages of granular columns in terrains where conventional stone columns are not typically suitable (such as very soft ground with inadequate lateral confinement, presence of organic matter in the field, or restrictive design requirements regarding settlement, etc.). Figure 2.59 illustrates the principles of achieving ground improvement using bi-Modulus columns.

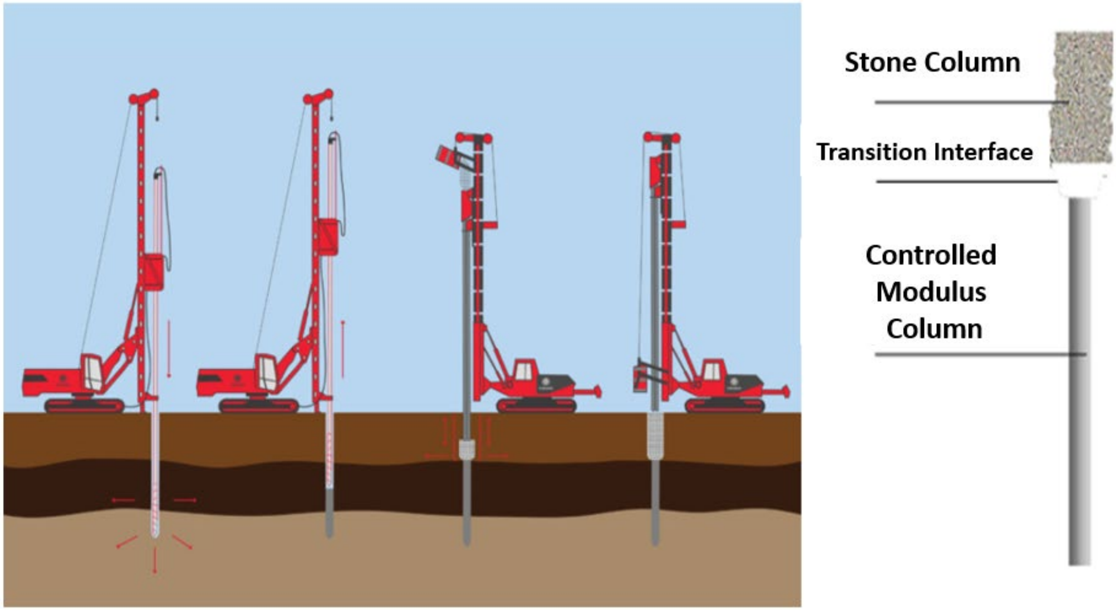


Figure 2.59: The principles of achieving ground improvement using bi-modulus columns (modified after Burtin et al. 2019)

As can be seen, the bottom part of such a column is made of concrete, and the top part is formed using aggregates. However, in rare cases, this can change based on the nature of the ground and other considerations.

Based on Menard Oceania (2022), this innovative approach can reduce the required thickness of the load transfer platform for rigid inclusions, eliminate the risk of column buckling or bulging in deeper weak soils, and enhance the overall robustness of the system. By improving the load transfer mechanism and stress distribution from the structure or building to the rigid inclusion, BMC can be a cost-effective technique that optimizes the Load Transfer Platform thickness between the structure and inclusions.

2.7.1 Application of Bi-Modulus Columns

Burtin et al. (2019), investigated the extension of a water treatment plant in Bourg d'Oisans, France, which was built in 2017. After thorough ground characterization and according to the technical specifications of the project, a combined solution of ground improvement using CMC and BMC (Bi-Modulus Column) was chosen. In this project, the upper part of the BMC was made of ballast to simplify later earthworks. The soil reinforcement design was carried out using PLAXIS software, and a second design method using an analytical approach was employed for verification. Settlements of the bi-modulus columns and the encompassing soil were computed through numerical analysis and an analytical method. The analytical approach served as a validation tool to assess the effectiveness of the PLAXIS numerical model. In both methodologies, a maximum settlement of 50 mm was observed at the surface of the columns and its surrounding soil.

Patel et al. (2018), conducted a parametric study to illustrate the effectiveness of BMCs in mitigating settlement in an embankment built on shallow clayey soil. In their study, PLAXIS 3D was utilized to model the embankment constructed on a 10 m thick clayey deposit reinforced with BMCs made of pervious concrete on top and stone columns at the bottom. Figure 2.60 depicts the embankment supported by BMCs in a 3D model.

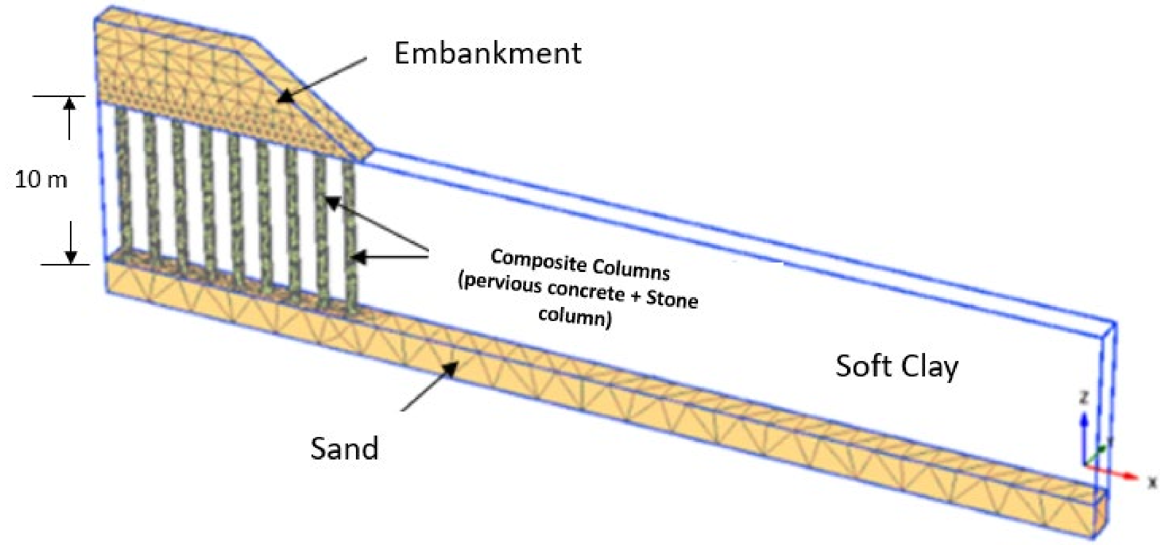


Figure 2.60: 3D model of embankment supported on bi-modulus columns (after Patel et al. 2018)

According to Patel et al. (2018), pervious concrete was found to possess greater strength and stiffness compared to stone columns while maintaining an equivalent level of permeability. Additionally, since the bearing capacity of a pervious concrete column does not depend on the confining pressure provided by the surrounding soil, it can be employed in weak soils where stone columns cannot be used. The researchers observed that the longer the pervious concrete part of the bi-modulus column, the greater the improvement in settlement behaviour of the embankment.

To date, major specialist geotechnical contractors such as Menard and Keller have successfully completed several projects using the BMC method. It has been confirmed that BMCs are particularly effective in cases of deep cut-off, to prevent unwanted moments in slabs on backfill, or in seismic zones. These factors have led to exponential growth in the use of the BMC technique since its recent development.

The adoption of this innovative technique is advisable for various projects. This method offers a promising solution for addressing mushroom effects and minimizing the thickness of LTP, thereby enhancing cost-effectiveness and resolving common LTP-related issues. However, there has been limited research conducted on this subject to date, and further exploration is needed in future studies to comprehend the impacts of both static and dynamic loading on grounds reinforced with this type of vertical inclusion.

2.8 Concluding Remarks and Recommendations

2.8.1 Conclusions

Vibro stone columns and concrete rigid inclusions are two distinct techniques known for improving ground conditions through the use of mechanically continuous columns, typically vertical and generally cylindrical in shape. Both of these methods offer cost-effective solutions to achieve satisfactory foundation conditions for a wide range of engineering works, and their utilization is increasing globally. They can provide significant benefits to both urban and rural areas in the development and maintenance of transportation infrastructures. The growing interest in these techniques can be attributed to the increasing importance of project cost optimization, as well as the scarcity of land for new projects. Based on an evaluation of available research documents and literature, and considering some of the aforementioned latest developments, the following concluding remarks can be drawn:

- Vertical inclusions as ground improvement techniques are highly beneficial in transportation structures, as they significantly increase the bearing capacity of weak ground and reduce total settlement.
- Finite element models (FEM) appear to be an accurate method for analyzing geotechnical calculations, as the results validate the experimental measurements.
- Geosynthetic encasements are useful for enhancing the performance of stone columns and addressing issues related to the lateral confinement of the columns. Furthermore, the efficiency of encased stone columns is higher when the column material is compacted well to achieve a high friction angle.

- A triangular arrangement of columns appears to achieve a slightly better pattern of deformation compared to a square pattern. However, there is a discrepancy in this matter, as some studies have reached contrary conclusions.
- The optimum spacing between the columns, ranging from 2 to 4 times the diameter of the column, produces acceptable settlement, minimum lateral deflection or bulging, and maximum factor of safety.
- The critical speed in the column length has a significant effect, where an increase in speed results in an increase in length. However, this escalation in column length is not unlimited and has a maximum. Additionally, a higher replacement ratio (De) allows the critical speed to rise to a certain extent.
- As the friction angle value of column materials increases, there is a corresponding decrease in settlement and a reduction in lateral deformation of the column. Consequently, the ratio of bearing capacity improvement will be higher.
- Stone columns facilitate the rapid dissipation of excess pore water pressure induced by the embankment load. This confirms that stone columns function as radial drainage.
- Basal reinforcement reduces settlement at the top and base of the embankment while minimizing lateral displacement at the top of the floating geosynthetic-encased stone column. However, it may increase lateral displacement at the bottom of the column. Notably, the stiffness of the basal geosynthetic reinforcement has little impact on the settlement behavior of encased stone columns.
- Rigid inclusions (CMC) are highly efficient in terms of reducing vertical stresses.
- In very sensitive structures such as already-built bridge abutments where ground vibration can be detrimental and stringent settlement reduction is required, the CMC method is preferred over conventional vibro techniques. In other words, for bridge approaches, CMC is the preferred method.
- Bi-modulus columns (BMC) consist of a rigid inclusion topped with a compacted granular column, serving as vertical ground improvement elements. These columns offer a blend of advantages found in stone columns and CMC. In regions with high liquefaction activities, BMC ensures that the upper soil remains compliant without becoming overly stiff.

In summary, after comparing the performance of three different vertical inclusions, it becomes evident that the most suitable option for a specific site depends on various criteria. These criteria may include project requirements, location, soil type, magnitudes of vertical and lateral loads, construction timeline, efficiency, allowable settlement, durability, economic considerations, and more. Generally, in Australia, qualified companies equipped with necessary machinery for conducting CMC are prevalent, whereas cost-effective materials for stone columns are lacking; hence, CMC may be a preferred method compared to stone columns. Soil stabilization through CMC is notably faster than stone columns, potentially resulting in a lower final cost. Given that seismic loads and soil liquefaction are not dominant concerns in many parts of Australia, the application of VSC may be limited. Nevertheless, stone columns offer some flexibility in accommodating settlements, making them a preferred choice in offshore projects. To prevent the mushroom effect or the need for extra adjustments and removal of top concrete under large foundations in heavy buildings, the utilization of BMCs can be considered. These recommendations can be further verified through industry and academic research.

2.8.2 Future Developments

Numerous past studies and investigations have been reviewed in this chapter, and it is gathered that the majority of previous researchers attempted to prove the efficiency of rigid and semi-rigid inclusions in terms of settlement reduction in roads and railway embankments. However, the current trend seems to primarily focus on static loading applied to a single column, and the effects of cyclic loading need to be explored extensively. To the authors' knowledge, there are no laboratory tests to evaluate the behaviour of VSC and CMC groups under dynamic loading, which can be regarded as a significant gap for future prospects. Furthermore, in addition to the settlement behaviour of composite foundations, some other topics (e.g., clogging, mushroom effects, and comparison of floating and end-bearing columns) should be given more consideration. Therefore, to extend the contents presented in this literature review, it is recommended to conduct future investigations in the following areas:

1) The performance of vertical inclusions under cyclic loading needs further study, both numerically and experimentally. Previous researchers have mainly focused on the effects of static loading in transportation structures, and there are limited studies available on the behavior of such inclusions under dynamic loading.
2) The occurrence of clogging and bulging in stone columns under cyclic or static loads is quite common. These issues can be effectively addressed by appropriately encasing the stone column material with geosynthetic materials, providing the necessary additional confinement. However, it is worthwhile to investigate the load-settlement

behavior of dual-layered geosynthetic-encased stone columns. The diameter of the second encasement layer could be much larger than the first layer and effectively penetrate into the weak soil around the encased stone column.

3) The utilization of pervious concrete as a novel method for rigid inclusion is suggested for some projects where permeability to accelerate consolidation plays a crucial role. Further exploration in future studies is needed to understand the rate of consolidation or the impact of dynamic loading on structures reinforced with such vertical inclusions.
4) A design model that only emphasizes the long-term behavior of vertical inclusions under cyclic loading can be crucially valuable for design. In such cases, an empirical or analytical equation explaining the development of excess pore water pressure caused by cyclic loading is essential. Additionally, undrained tests may be useful in establishing a cyclic excess pore water pressure model.
5) The group effect of vertical inclusions should be studied using advanced equipment such as centrifuge tests, cyclic loading actuators, and large-scale physical model boxes, as the behavior of vertical inclusions acting in a group might be very different from unit cell tests.
6) More laboratory investigations regarding the geometry of vertical inclusions, such as the ratio of column length to diameter (L/d) and the ratio of column diameter to spacing (s/d), should be conducted under cyclic loading to determine optimal design guidelines.
7) The bi-modulus column (BMC) technique can eliminate or mitigate the mushroom effects associated with the construction of controlled modulus columns. In bi-modulus columns, granular materials (VSC) are positioned above the uppermost part of the controlled modulus column (CMC), spanning a height ranging from 1 m to 1.5 m. Only a few investigations have been carried out to appreciate the efficiency of BMCs under static loading, and further exploration is needed for cyclic loading.
8) Most previous investigations have focused on the effects of end-bearing columns or vertical inclusions on stiff layers. However, there are limited studies regarding floating columns under dynamic loads. Therefore, the behavior of floating columns in transportation structures needs to be explored further.
9) A ground improvement system consisting of a combination of semi-rigid, rigid, and bi-modulus vertical inclusions for transportation structures could be an advanced topic. Thus far, there has not been sufficient research in this area, and it could be beneficial in terms of cost-effectiveness and suitability for various types of ground conditions.

10) To create vertical inclusions, the partial utilization of waste materials, including quarry dust, fly ash, bottom ash, agricultural wastes, crushed waste glass, recycled plastic, lightweight expanded clay aggregates, and construction debris, can serve as a viable solution for cost-effectiveness and sustainability. Limited research has been conducted regarding the use of marginal materials in vertical inclusions. This topic can be explored through numerical and experimental methods to assess the effectiveness of waste material utilization.

Enhancing vertical inclusion ground improvements presents a cost-effective approach for reinforcing soft soil and weak ground with limited bearing capacity. These advancements promise substantial advantages for urban areas, regional Australia, and global transportation infrastructure development and upkeep. They also render residential development projects more feasible, particularly in areas with weak ground that necessitates enhancement. Moreover, the formulation of practical guidelines for building, road, and railway foundation design on soft soil stabilized with vertical inclusions is warranted.

3

Numerical Analysis

3.1 Introduction

The design and construction of embankments over very soft, compressible alluvial deposits (e.g., clay, silty clay, clayey silt) is unavoidable for infrastructure works, especially roads and railways, and has always been a challenging task for engineers. Column-supported ground improvement techniques are utilized extensively to increase the bearing capacity of the shallow ground and reduce total settlement. Using finite element numerical modelling, this chapter compares the effects of static and dynamic loading on a road overlaying a shallow clayey deposit improved with:

1. Stone columns acting as semi-rigid vertical inclusions,
2. Controlled modulus columns functioning as rigid vertical inclusions,
3. A scenario where no ground improvement has been carried out, and
4. Bi-modulus columns as an innovative technique.

In a broader sense, numerical modelling offers a precise and cost-efficient method for understanding the behaviour of geotechnical-related designs, such as roads and embankments supported by columns. Therefore, in this chapter, to explore the behaviour of soft soil under various conditions, a simulation using the three-dimensional PLAXIS 3D software, is conducted to model an embankment constructed on shallow clayey ground. The soil behaviour in the numerical model is simulated using the Modified Cam-clay model, which is briefly introduced and explained. Subsequently, in order to ensure reliable results, the data acquired from field measurements of a real-world project are compared with the numerical analysis findings generated through the use of PLAXIS 3D, validating the adopted numerical approach. Furthermore, bi-modulus columns as a novel approach are incorporated into the design as a fourth scenario, aiming to mitigate the mushroom effects resulting from the stiffness of controlled modulus columns. The numerical findings yield valuable insights into exploring the load transfer mechanism within the composite ground, effectively capturing the response of the soil-column system.

3.2 Three-Dimensional Numerical Model Used for Vertical Inclusions

Three-dimensional numerical modelling of untreated ground, vibro stone columns, controlled modulus columns, and bi-modulus columns supporting an asphalt road was carried out with a total embankment length of 40 meters using the finite element software package PLAXIS 3D 2021. Figure 3.1 illustrates the three dimensional finite element (FE) model without inclusion of any ground improvement features. The FE model is simulated to predict the cumulative settlement of the untreated foundation. This model is further extended to study the efficacy of vertical inclusions.

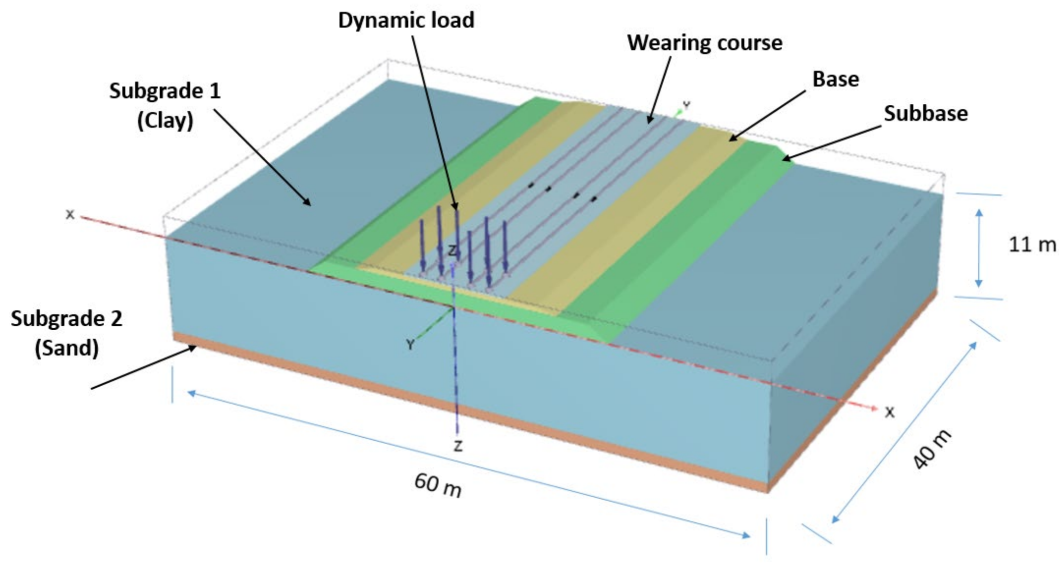


Figure 3.1: Three dimensional finite element (FE) model without inclusion of any ground improvement features

In order to ensure the accuracy and reliability of the numerical model's predictions, meticulous attention was paid to mitigating the influence of boundary conditions. Recognizing the significance of this aspect, a deliberate decision was made to adopt a total width of 60 m for the model. This width was carefully chosen to provide sufficient buffer zones around the pavement structure, minimizing the potential for boundary effects to skew the results. Not only is the validity of the numerical model strengthened through this holistic approach, but it also contributes to advancing understanding of the complex interactions within pavement structures and their response to various ground improvement and loading factors.

As depicted in Figure 3.1, the two-lane asphalt road is constructed atop the base and subbase layers, with their respective dimensions outlined in Table 3.1.

Table 3.1: Dimensions of asphalt road and its foundation

	Wearing Course (m)	**Base (m)**	**Subbase (m)**
Thickness	0.2	0.5	1.5
Width	10	20	30
Length	40	40	40

The geotechnical characteristics of the wearing course, base, and sub-base are drawn from conventional industry standards. Subgrade 1, consisting of 10 m shallow clay deposits and being a key focus of this numerical analysis, is based on the research conducted by Peric (2006). Subgrade 2, comprising of 1 m stiff sand, is recommended by PLAXIS 3D.

Table 3.2 provides an overview of the geotechnical properties for all layers except for clayey subgrade 1.

Table 3.2: the geotechnical properties for all layers except for subgrade 1 (clay) referenced from conventional industry standards and PLAXIS 3D

	γ_{sat} (kN/m^3)	**E′ (MPa)**	**ν′**	**c′ (kPa)**	**ϕ′ (deg)**
Wearing Course	20	2,100	0.4	--------	--------
Base	22	100	0.35	30	43
Subbase	20	50	0.3	40	14
Subgrade 2 (Sand)	20	75	0.3	1	31

As mentioned previously, the primary and pivotal aspect of this numerical analysis is subgrade 1, which is sourced from Peric's study in 2006, and details regarding its parameters and values can be found in Table 3.3.

Table 3.3: Detailed geotechnical parameters of subgrade 1 (clay), sourced from Peric (2006).

Parameter	**Value**
N	1.788
M	1.2
λ	0.077
k	0.0066
γ_{sat} (kN/m^3)	18
c´(kPa)	0.5

For dynamic loading, a peak dynamic load of 150 kN per wheel, which represents a potential maximum exerted on the wearing course, is utilized in this numerical analysis to ensure a conservative approach.

Following this, in order to improve the dense soft soil deposit, which spans a depth of 11 m as depicted in Figure 3.1, and comprises a surface layer (subgrade layer 1) consisting of 10 m of extremely soft clayey soil and a lower layer (subgrade layer 2) composed of 1 m of dense sand, vertical inclusions were employed independently in the subsequent scenarios:

1) Ground improvement using vibro stone columns.
2) Ground improvement using controlled modulus columns.
3) Ground improvement using bi-modulus columns.

The next stage involves mesh generation. Mesh generation is a fundamental step in the numerical modelling process within PLAXIS 3D software, as it plays a crucial role in accurately representing the geometry and behaviour of the soil or rock mass being analysed. There are several key reasons for mesh generation in PLAXIS 3D, such as spatial discretization, element connectivity, adaptation to geometry, resolution control, and boundary conditions. Simulation accuracy is typically influenced by mesh size. A finer mesh results in higher accuracy but significantly increases computational time. On the other hand, a coarser mesh reduces accuracy but allows for faster analysis. To balance accuracy and computational efficiency, a mesh sensitivity analysis is conducted to identify an optimal mesh size that delivers reasonably accurate predictions within a minimal time frame. Table 3.4 presents the mesh sensitivity analysis performed for the most basic scenario in this numerical study, which involves no ground improvement for the embankment and a stationary vehicle (static load only).

Table 3.4: Mesh sensitivity analysis for the most basic scenario in this numerical study, involving no ground improvement and a stationary vehicle

Mesh Refinement	**Relative Element Size (mm)**	**Computation Time**	**Predicted Settlement**
Very coarse	2.0	11 m 35 s	0.560 m
Coarse	1.50	11 m 48 s	0.563 m
Medium	1.0	12 m 05 s	0.569 m
<u>Fine (Adopted)</u>	0.70	14 m 03 s	0.571 m
Very fine	0.50	21 m 14 s	0.572 m

Based on Table 3.4, the computation time for a very fine mesh is nearly double that of a very coarse mesh, with the predicted settlement being 12 mm higher. Therefore, the 'Fine' mesh refinement was chosen to balance precision and computational efficiency. Table 3.5 presents the mesh sensitivity analysis for a more advanced scenario in this numerical study, where the soft clayey ground is reinforced with stone columns and subjected to dynamic loading at a speed of 60 km/h for 1 second.

Table 3.5: Mesh sensitivity analysis for reinforced soft clay with stone columns under dynamic loading at 60 km/h for 1 second

Mesh Refinement	**Relative Element Size (mm)**	**Computation Time**	**Predicted Settlement**
Very course	2.0	6 h 43 m 5 s	0.0612 m
Course	1.50	6 h 58 m 36 s	0.0621 m
Medium	1.0	8 h 18 m 19 s	0.0630 m
<u>Fine (Adopted)</u>	0.70	11 h 25 m 28 s	0.0645 m
Very fine	0.50	15 h 17 m 54 s	0.0656 m

Based on Table 3.5, the computation time for the scenario involving ground improvement and dynamic loading with a very fine mesh is approximately 8.5 hours longer than with a very coarse mesh, and the predicted settlement is 4.4 mm higher. Consequently, the 'Fine' mesh refinement was chosen in this instance as well to achieve an optimal balance between precision and computational efficiency.

According to the mesh sensitivity analysis conducted for both scenarios, a highly refined finite element mesh, featuring a relative element size of 0.5 mm and an element dimension of 1.833 mm, was selected for the three-dimensional model, illustrated in Figures 3.2a and b.

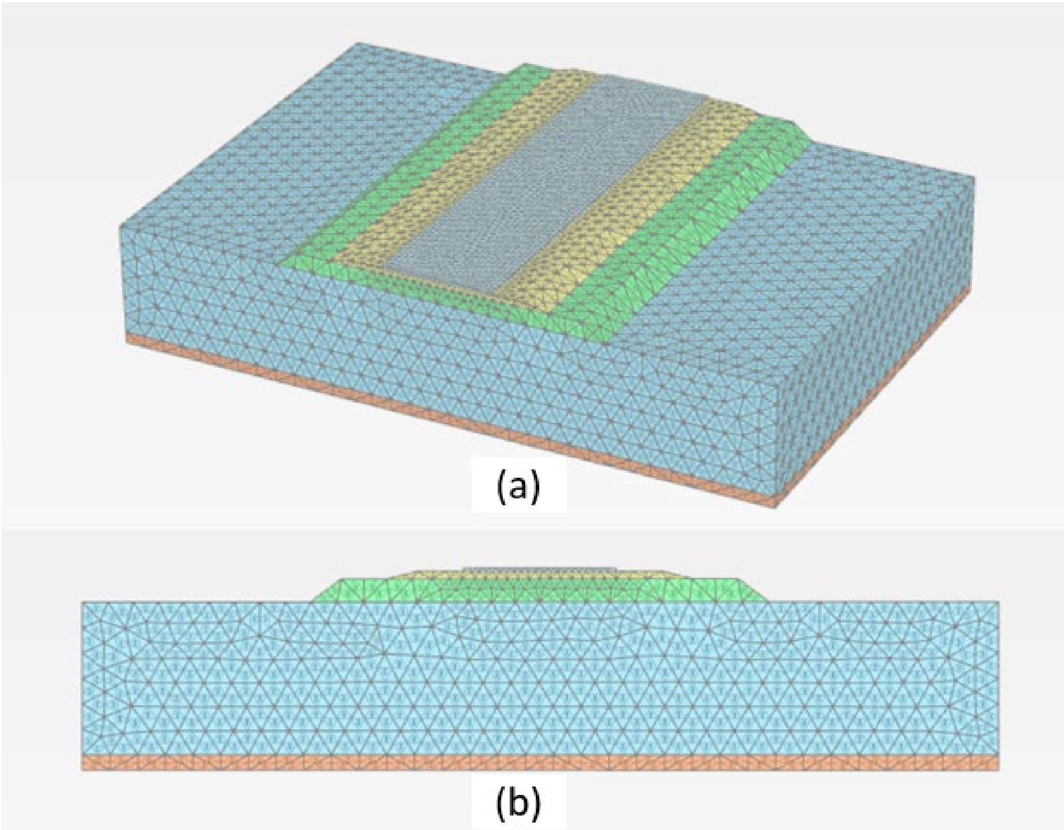


Figure 3.2: Finite element discretization, (a) three dimensional mesh (b) cross-sectional mesh

Regardless of the inclusion type, the column's diameter (D) is set at 600 mm, with a spacing between columns of 3D in square configuration. As illustrated in Figure 3.3, 391 vertical inclusions (17 along the X-axis and 21 along the Y-axis) were incorporated as embedded columns to reinforce the shallow ground. Table 3.6 outlines the geotechnical characterises (referenced from conventional industry standards) and dimensions of the vertical inclusions and LTP.

Table 3.6: The geotechnical characteristics referenced from conventional industry standards and dimensions of vertical inclusions and LTP

	Material Type	**γ (kN/m^3)**	**E (kN/m^2)**	**Thickness (mm)**
LTP	Elastic	25	30×10^6	800
VSC	Elastoplastic	18	100×10^3	600
CMC	Elastic	25	10×10^6	600

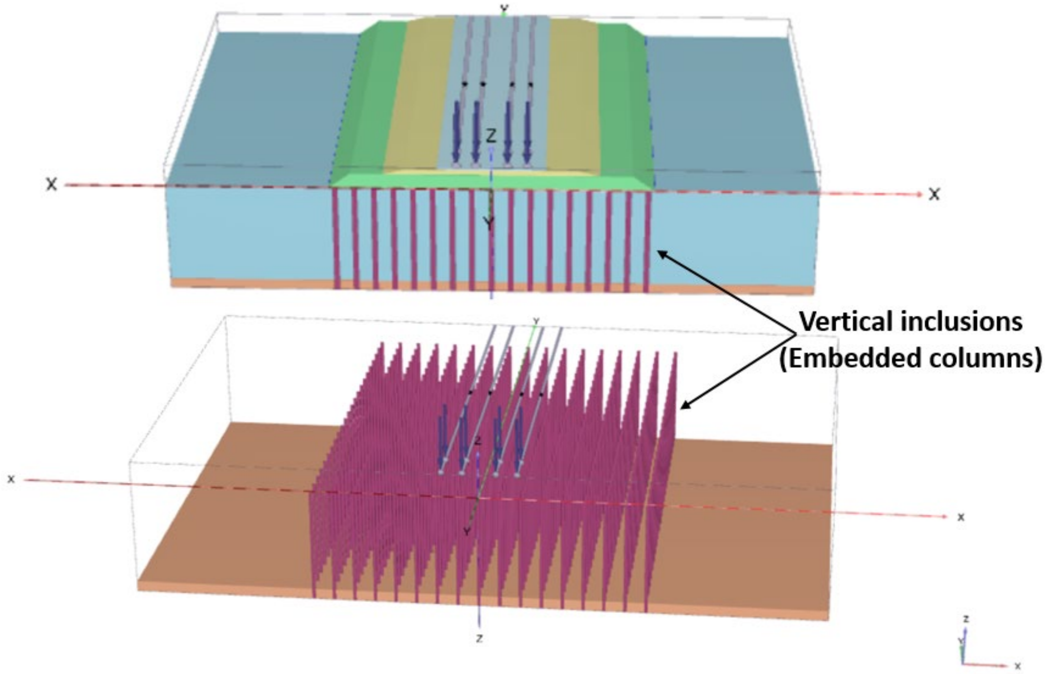


Figure 3.3: Inclusion of vertical elements into the model as embedded columns

In order to achieve the utmost accuracy in the results, a distinct constitutive model is chosen for each layer, with pertinent information input into the PLAXIS 3D software. Table 3.7 presents the constitutive models employed in this study.

Table 3.7: Employed constitutive models in this study using PLAXIS 3D

Layer	Constitutive Model
Wearing Course	Linear Elastic
Base	Mohr-Coulomb
Subbase	Mohr-Coulomb
Subgrade 1 (Soft Clay)	Modified Cam-Clay
Subgrade 2 (Stiff Sand)	Mohr-Coulomb

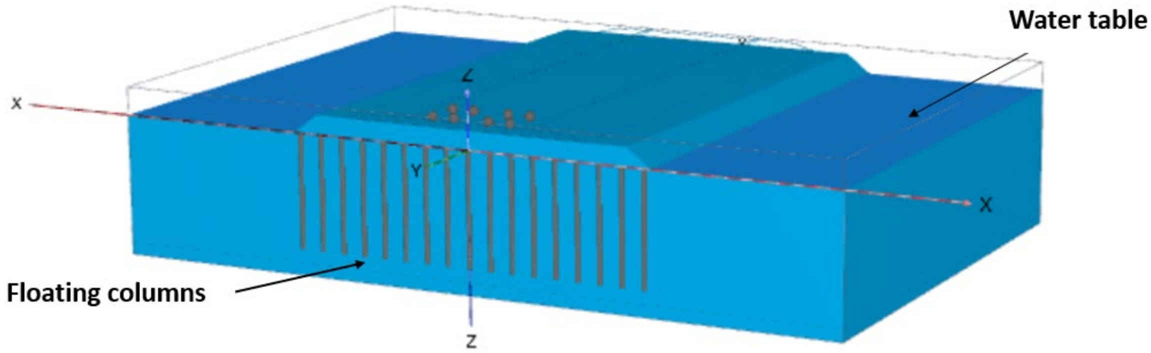
The numerical model consists of 6 stages of construction, as detailed in Table 3.8.

Table 3.8: Stages of construction of the numerical model

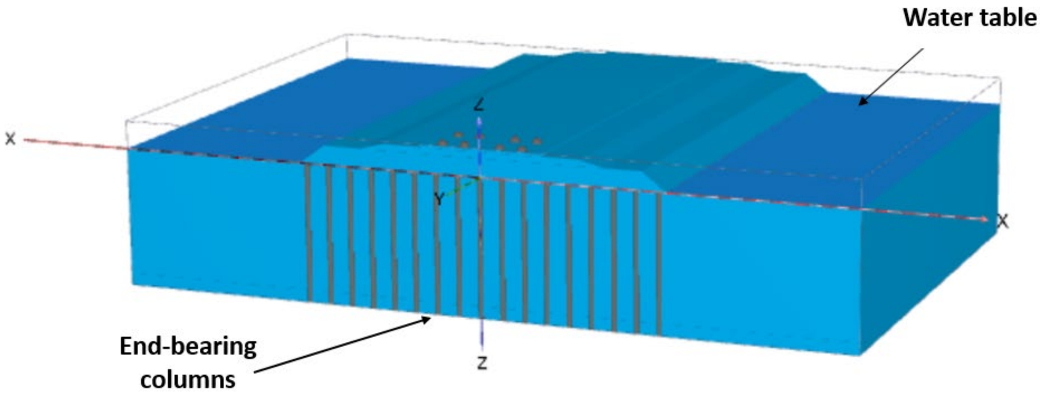
Stages of Construction	Development of the Numerical Model
Phase 1	Initial condition of the ground
Phase 2	Construction of the vertical inclusions and the LTP
Phase 3	Construction of the sub-base
Phase 4	Construction of the base
Phase 5	Construction of the waring course
Phase 6	Application of the dynamic loading on the wearing course

To ensure a conservative approach and yield the most significant outcomes concerning ground settlement for the ground treated with floating and end-bearing columns, this study considers the worst-case scenario by assuming the water table is at the ground surface.

Figures 3.4 (a) and (b) show the location of the water table at the ground surface for both floating columns and end-bearing columns respectively.



a)



b)

Figure 3.4: Location of the water table in the numerical model; (a) floating vertical inclusions. (b) end-bearing vertical inclusions

3.3 Constitutive Models Employed in This Study

In this section, the Modified Cam-Clay model, which is employed to simulate the behaviour of a 10 m thick layer of soft clay (referred to as subgrade 1), is briefly introduced and explained.

The Cam-Clay and Modified Cam-Clay models are elastic-plastic strain hardening models based on Critical State theory and the fundamental assumption of a logarithmic relationship between mean stress and void ratio. Originating from research at Cambridge University, these models, namely Cam-Clay (CC) and Modified Cam-Clay (MCC), represent pioneering critical state models designed to describe the behaviour of soft soils, particularly clay. They encompass three crucial aspects of soil behaviour: strength, compression or dilatancy (the volume change accompanying shearing), and the Critical State, where soil elements undergo unlimited distortion without altering stress or volume.

A significant portion of the volume within a soil mass comprises voids, which may contain fluids, primarily air and water. Consequently, soil deformations often involve substantial, and sometimes irreversible, volume changes. Cap plasticity models, including the CC and MCC formulations, possess a notable advantage in realistically modelling such volume changes, which underscores the choice of employing the MCC in this numerical investigation.

The primary assumptions of the CC and MCC models are detailed subsequently. In critical state mechanics, the state of a soil sample is characterized by three parameters: mean stress, deviatoric stress, and specific volume. Specific volume is defined as $v = V_v/V_s$ where V_v is the volume of voids and V_s is the volume of solids.

3.3.1 Virgin Consolidation Line and Swelling Line

The fundamental concept behind these models is rooted in the understanding that when subjected to gradual compression and isotropic stress in ideal drainage conditions, soft soil behaves according to specific relationships between its volume and the applied stress. These relationships are characterized by a primary linear trend known as the virgin consolidation line, representing the normal compression of the soil. Additionally, a series of linear swelling lines, termed unloading-reloading lines, illustrate the soil's behaviour during swelling and subsequent unloading/reloading cycles. This depiction, as showcased in Figure 3.5, serves as a visual aid to grasp the underlying principles driving the behaviour of soft soils under such conditions.

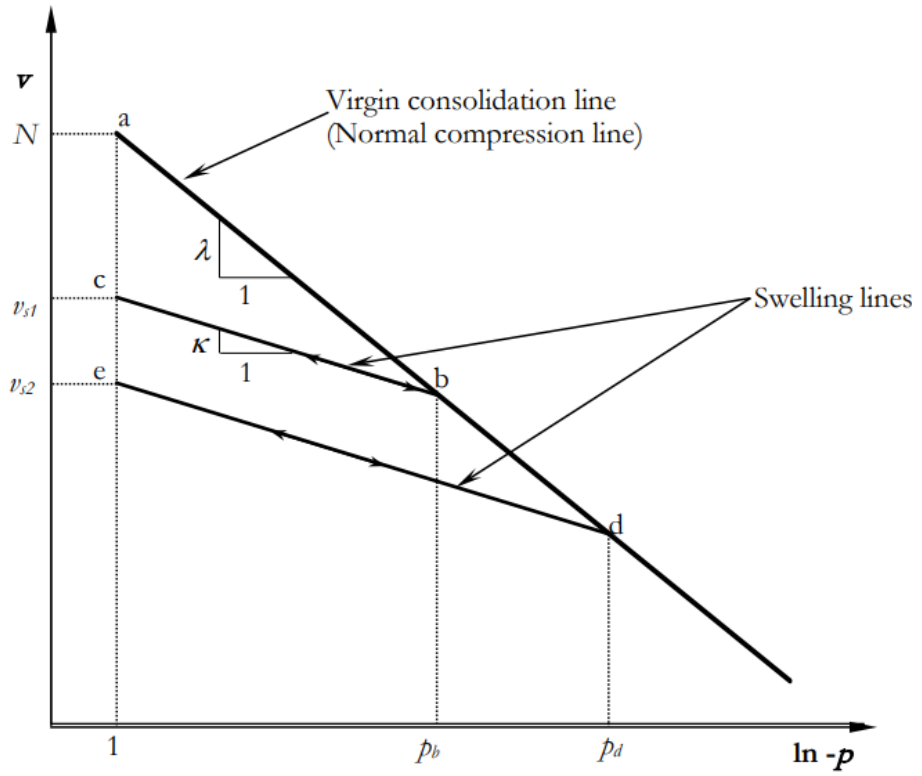


Figure 3.5: Typical behaviour of clays in consolidation (oedometer) test (after Peric 2006)

The virgin consolidation line in Figure 3.5 is defined by the equation:

$$v = N - \lambda \ln(-p) \tag{3.1}$$

while the equation for a swelling line has the form:

$$v = v_s - \kappa \ln(-p) \tag{3.2}$$

The values λ, κ and N are characteristic properties of a particular soil. λ represents the slope of the normal compression (virgin consolidation) line on $v - \ln p$ plane, while κ is the slope of swelling line. N is known as the specific volume of normal compression line at unit pressure, and is dependent on the units of measurement. As can be seen in Figure 3.5, v_s differs for each swelling line and depends on the loading history of a soil.

If the current state of soil lies on the virgin consolidation line, it is described as being normally consolidated. When the stress state falls below this line, the soil is deemed over consolidated. Typically, soil does not exist beyond the virgin consolidation line, and if it does, that state is considered unstable. The hardening behaviour of the CC and MCC models is formulated based on the virgin consolidation line. In contrast, the swelling line is utilized in calculations concerning elastic properties.

3.3.2 The Critical State Line

Sustained shearing of a soil sample eventually leads to a state where further shearing can occur without any changes in stress or volume. This condition, known as the critical state, signifies that the soil distorts at a constant state of stress with no volume change. It is characterized by the Critical State Line (CSL). In the $p' - q$ plane, the CSL is represented as a straight line passing through the origin with a slope equal to M, one of the material's characteristic parameters crucial in defining the yield surface (refer to Figure 3.7).

The location of this line relative to the normal compression line is shown in Figure 3.6. As depicted in the figure, the CSL is parallel to the virgin consolidation line in the $\upsilon - \ln p$ space. The parameter Γ represents the specific volume of the CSL at unit pressure. Similar to N the value of Γ depends on the units of measurement.

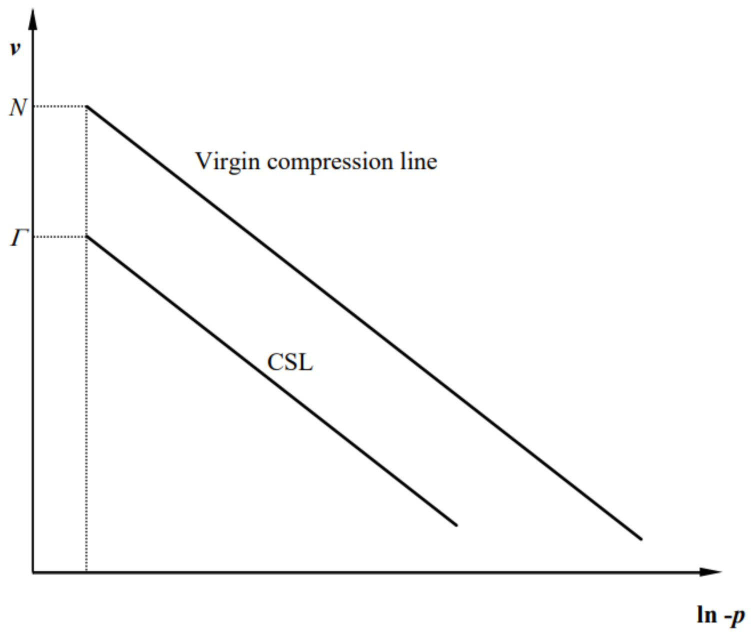


Figure 3.6. Typical Critical State Line and Virgin Compression Line of clays (after Peric 2006)

There is a relationship between the parameter N of the normal compression line and Γ. For the Cam-Clay model, these two parameters are related by the equation:

$$\Gamma = N - (\lambda - \kappa) \tag{3.3}$$

while for the Modified Cam-Clay model the relationship is:

$$\Gamma = N - (\lambda - \kappa) \ln 2 \tag{3.4}$$

Due to the relationship between N and Γ, only one of them needs to be specified when describing a Cam-Clay or Modified Cam-Cam material.

3.3.3 Yield Functions

The yield functions of the Cam-Clay model is:

$$F_c = q + Mp \ln\left(\frac{-p}{P_c}\right) = 0 \tag{3.5}$$

And the yield function for modified Cam-Clay is:

$$F_c = q^2 + M^2 p\,(p + p_c) = 0 \tag{3.6}$$

As shown in Figure 3.7, in p-q space, the CC (Cam-Clay) yield surface appears as a logarithmic curve, while the MCC (Modified Cam-Clay) yield surface is represented by an elliptical curve. The parameter P_c (known as the yield stress or pre-consolidation pressure) determines the size of the yield surface. The parameter M represents the slope of the CSL (Critical State Line) in p-q space. A key characteristic of the CSL is that it intersects the yield curve at the point where the maximum value of q is achieved.

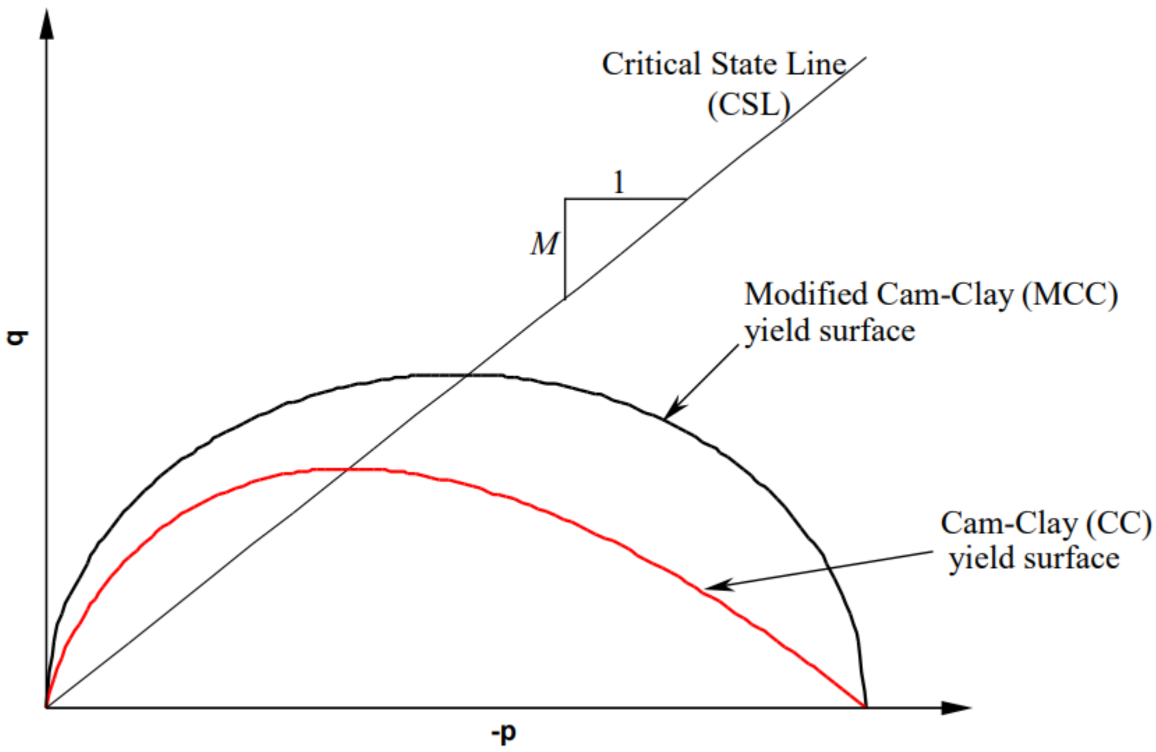


Figure 3.7: Yield surfaces of the Cam Clay and Modified Cam Clay models in p-q plane (after Peric 2006)

In three-dimensional υ–p–q space, the yield surface defined by the CC or MCC formulation is known as the State Boundary Surface. The State Boundary Surface for the Modified Cam-Clay model is shown in Figure 3.8.

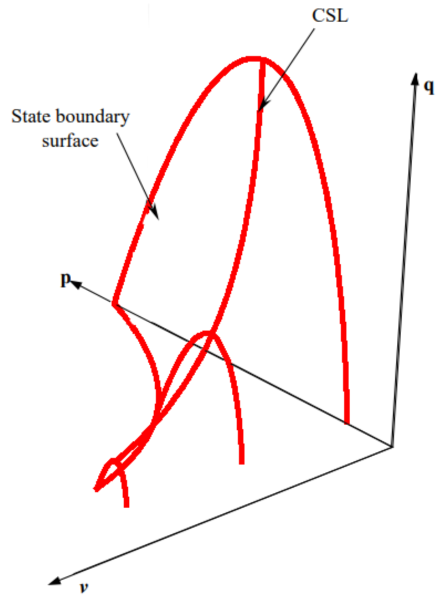


Figure 3.8: State Boundary Surface for MCC model (after Peric 2006)

3.3.4 Elastic Material Constants for Cam-Clay and Modified Cam-Clay

Based on Peric (2006), for Cam-Clay and Modified Cam-Clay soils, the bulk modulus is not constant; rather, it depends on the mean stress, specific volume, and the slope of the swelling line:

$$K = -\frac{\upsilon\, p}{\kappa} \tag{3.7}$$

Furthermore, the Cam-Clay and Modified Cam-Clay formulations necessitate the precise determination of either the shear modulus (G) or Poisson's ratio (v).

3.3.5 The Over Consolidation Ratio (OCR) and Initial State

The current state of soil can be described by its stress state (p and q), specific volume (υ), and yield stress, p_c (also known as pre consolidation pressure, which measures the highest stress level the soil has ever experienced). The ratio of pre consolidation pressure to current pressure is known as the over consolidation ratio (OCR).

The in-situ distribution of pre consolidation pressure for a Cam-Clay or Modified Cam-Clay material can be determined using the OCR. An OCR value of 1 represents a normal consolidation state, indicating that the maximum stress level previously experienced by a material is not greater than the current stress level. An OCR greater than 1 describes an over consolidated state, indicating that the maximum stress level experienced by the material exceeds the present stress level. The OCR=1 is selected for this study indicating a normal consolidation state.

To compute models involving Cam-Clay or Modified Cam-Clay materials (such as this numerical investigation), non-trivial initial effective stresses must be specified. The initial yield surfaces for all stress states must be specified by determining the corresponding p_c. This can be achieved by directly assigning the pre consolidation pressure or by specifying the OCR.

If the current stress state fully resides within a defined yield surface, the soil will initially exhibit elastic behaviour under loading. This suggests that it is over consolidated. However, if the initial stress state is situated on the yield surface, the soil will display elasto-plastic behaviour upon loading, indicating normal consolidation. Since initial stress states lying outside yield surfaces lack physical significance for Cam-Clay and Modified Cam-Clay models, the finite element programs such as PLAXIS will adjust the pre consolidation pressure to align with the current stress level.

3.3.6 Hardening and Softening Behaviour

According to Peric (2006), the hardening of the material is attributed to plastic volumetric strain or the compaction of the material, which is equivalent to a reduction in void ratio and specific volume. Considering an increment of load from step (n) to (n +1), the expansion of the yield surface is defined by the increase in pre consolidation pressure, as:

$$(p_c)_{n+1} = (p_c)_n \exp\left[\frac{V_n \Delta\, \varepsilon_v^p}{\lambda - \kappa}\right] \tag{3.8}$$

If yielding occurs to the right of the point where the CSL intersects a yield surface, the material exhibits hardening behaviour, accompanied by compression. This side of the yield surface is known as the wet or subcritical side. On the other hand, if yielding occurs to the left of the intersection of the CSL and yield surface (referred to as the dry or supercritical side), the soil material exhibits softening behaviour, accompanied by dilatancy (an increase in volume). In the softening regime, the yield stress curve decreases after the stress state touches the initial envelope. Additional constitutive models employed in this numerical analysis encompass the Mohr-Coulomb and Linear Elastic models. However, owing to their straightforward nature and given that this study primarily concentrates on the MCC model, they are not elaborated upon in this context.

3.4 Results and Discussion

A thorough numerical investigation was undertaken to examine the behaviour of vertical inclusions, including VSC, CMC, and bi-modulus, within a 3D model using PLAXIS finite element software under both static and dynamic loading conditions. More than 1000 models were examined systematically to explore various scenarios. The findings are presented through graphical representations and discussed in detail. In the subsequent sections, the effects of dynamic loading (speed) on both the asphalt road with and without ground improvement are initially discussed, followed by additional parametric investigations.

3.4.1 Effects of Dynamic Loading on Ground Settlement

In this segment of the numerical investigation, a series of models were generated for speeds ranging from 40 to 150 km/h to comprehend the consequential settlement effects caused by vehicles in motion on the shallow ground atop the constructed embankment and asphalt road. Both static and dynamic loadings were applied simultaneously.

According to Transport Certification Services, the maximum weight contribution to axles in trucks is 7,374 kg, which is equivalent to 72.3 kN per wheel. In contrast, Koffman (1972) notes that a dynamic load of 150 kN per wheel can be considered the maximum potential load exerted on tracks by locomotives, which are the heaviest moving structures. Thus, a value of 150 kN per wheel, exceeding 72.3 kN by more than a factor of two, is utilized in this numerical analysis to ensure a high degree of conservatism. This cautious approach is crucial, especially for critical infrastructure systems where safety and reliability are essential. By applying such conservative measures, engineers can better manage the risks associated with dynamic loading effects, thereby improving the stability and performance of the infrastructure.

Figure 3.9 displays the maximum weight contribution to axles with 10,000 kg central payload on tray and rear mounted crane sourced from Transport Certification Services.

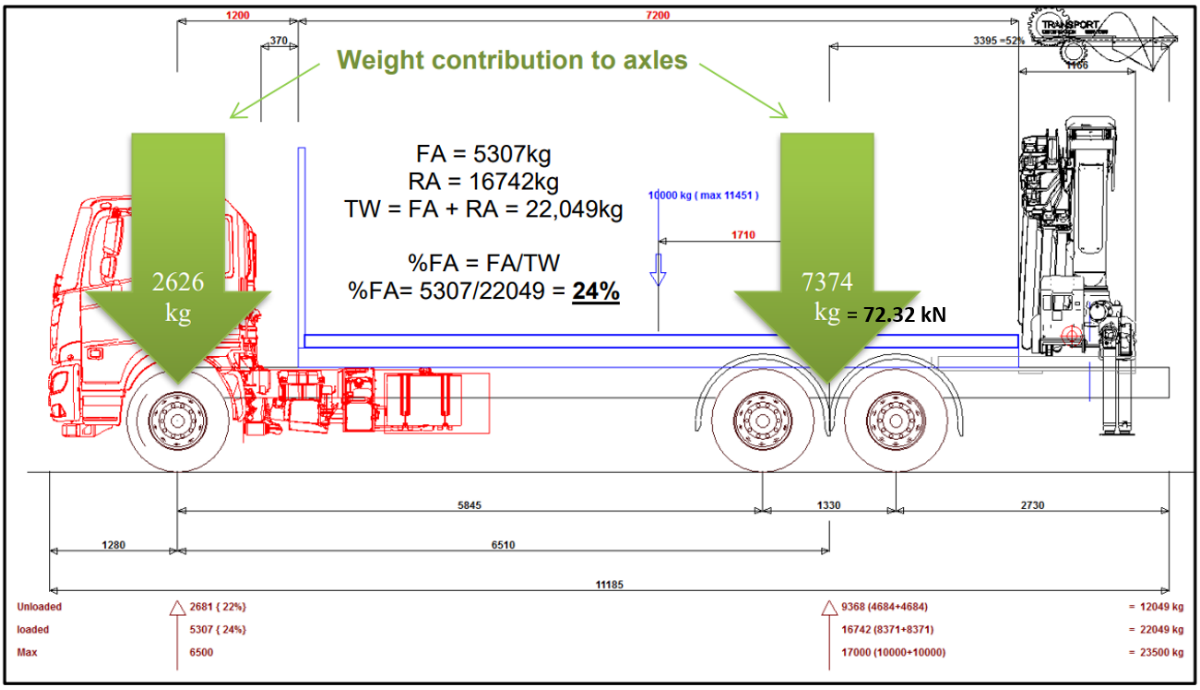


Figure 3.9: The maximum weight contribution to axles with 10,000 kg central payload on tray and rear mounted crane sourced from Transport Certification Services

Figure 3.10 illustrates the modelling of the dynamic load of 150 kN per wheel in PLAXIS 3D for this numerical analysis.

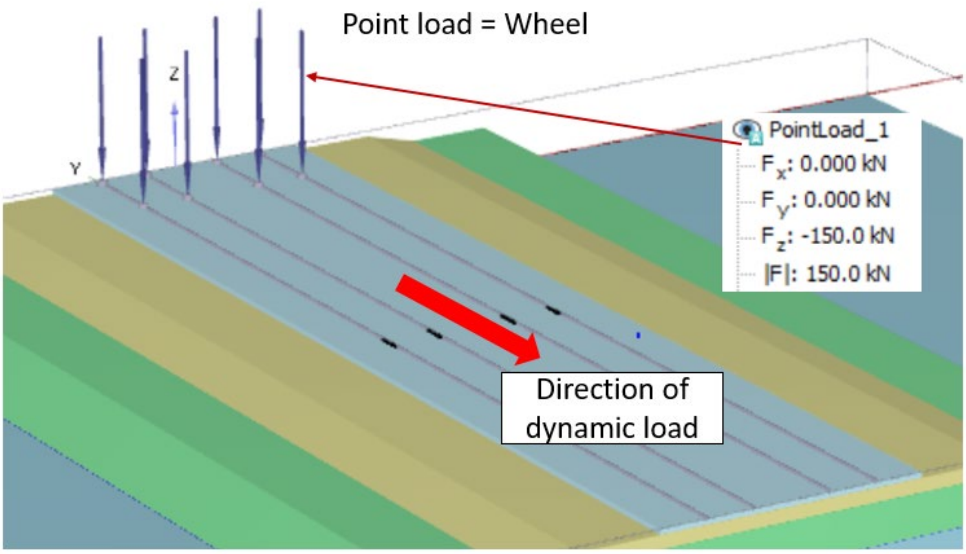


Figure 3.10: Description of the dynamic load of 150 kN per wheel and its orientation in this numerical analysis conducted with PLAXIS 3D

As shown in Figure 3.10, the moving load was modelled as 150 kN per wheel. The axle connects one wheel on one side to another on the opposite side. Given that cars have four wheels, the modelling accounts for two axles. In this numerical model, the distance between the two axles is 3 m, and the distance between the wheels is 1.8 m, which aligns with the standard car dimensions.

Approximately 200 numerical models were generated in PLAXIS 3D to investigate the impact of dynamic loading on a very shallow ground, predominantly composed of clay, across various scenarios:

1. Without any ground improvements.
2. Ground improvement using end-bearing vibro stone columns (VSC).
3. Ground improvement using end-bearing controlled modulus columns (CMC).
4. Ground improvement using end-bearing bi-modulus columns.

3.4.1.1 Effects of Dynamic Loading on Shallow Ground without Ground Improvements

The results obtained from the numerical models are summarised in Figure 3.11.

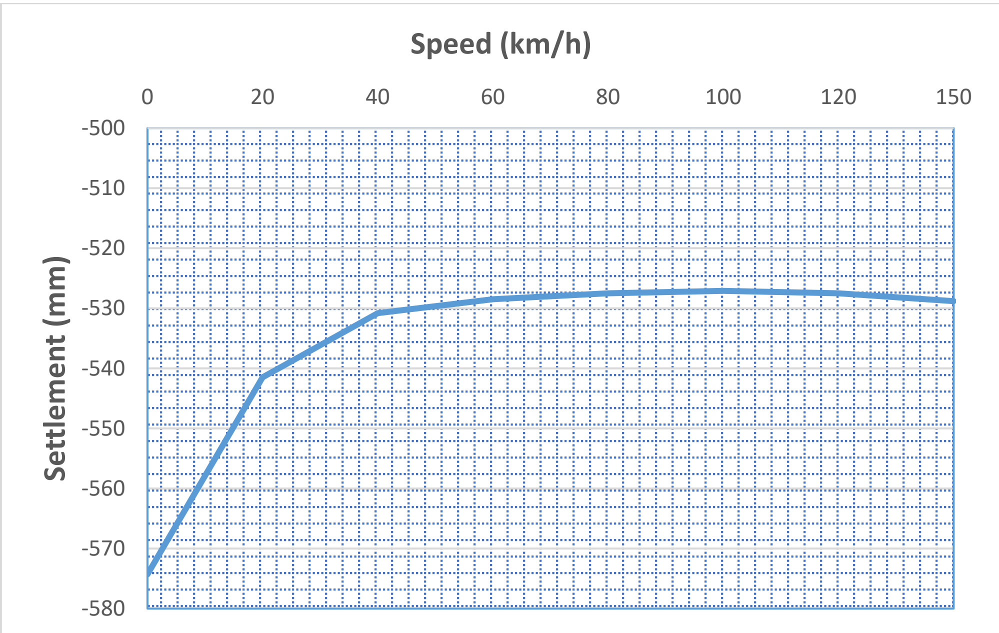


Figure 3.11: Speed-Settlement graph for the scenario without ground improvement

According to the graph, it can be observed that the maximum settlement of 573 mm is recorded under static loading conditions. An increase in speed to 40 km/h reduces the settlement to 530 mm, and beyond this point, vehicle speed appears to have negligible effects on the settlement behaviour of the shallow ground.

3.4.1.2 Effects of Dynamic Loading on Shallow Ground Improved with Vibro Stone Columns (VSC)

The results derived from numerical models are depicted in Figure 3.12.

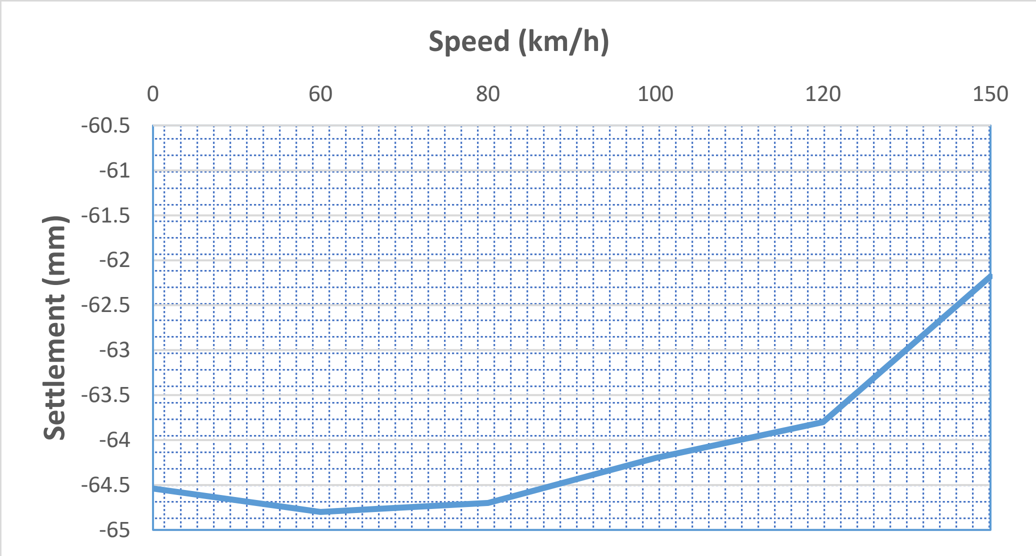


Figure 3.12: Speed-settlement graph for the scenario where the shallow clayey ground is reinforced with vibro stone columns (VSC)

Figure 3.12 suggests that the peak settlement occurs within the speed range of 0 to 80 km/h, and beyond this range, further increases in speed lead to a gradual decrease in ground settlement. This could be attributed to the dynamic interaction between the vehicle and the ground. At lower speeds, the load exerted by the vehicle has more time to transfer and affect the ground, resulting in greater settlement. As the speed increases, the duration of load application decreases, reducing the time for the ground to settle under the load. Additionally, higher speeds may induce dynamic effects such as vibrations that can help dissipate the energy more quickly, leading to less settlement.

3.4.1.3 Effects of Dynamic Loading on Shallow Ground Improved with Concrete Modulus Columns (CMC)

The findings from numerical simulations are outlined in Figure 3.13.

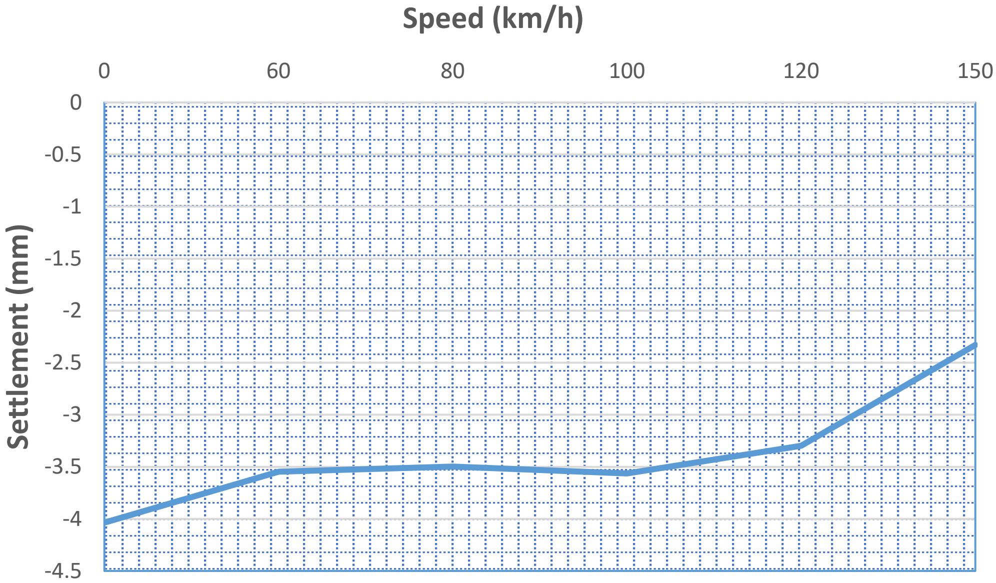


Figure 3.13: Speed-settlement graph for the scenario where the shallow clayey ground is reinforced with concrete modulus columns (CMC)

This Figure indicates that the highest settlement is observed when the dynamic load is stationary. As the speed increases, ground settlement decreases from 4 mm to 2.5 mm. Thus, as explained previously, it can be inferred that a greater speed of the moving vehicle results in reduced ground settlement.

3.4.1.4 Effects of Dynamic Loading on Shallow Ground Improved with Bi-Modulus Columns (BMC)

The outcomes derived from numerical modelling are encapsulated in Figure 3.14.

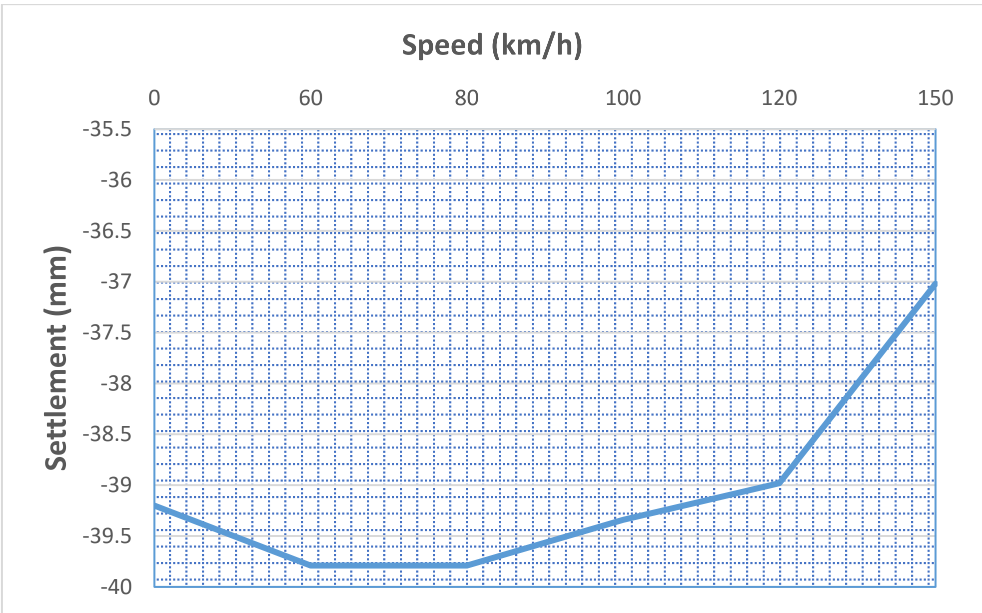


Figure 3.14: Speed-settlement graph for the scenario where the shallow clayey ground is reinforced with bi-modulus columns (BMC)

Referring to Figure 3.14, it can be seen that, similar to other scenarios, raising the speed of the dynamic load tends to decrease settlement when shallow ground is reinforced with bi-modulus columns. However, in this case, the maximum settlement occurs within the speed range of 60 to 80 km/h; beyond this range, increasing speed continues to diminish settlement.

3.4.1.5 Comparison between Speed-Settlement Behaviours Induced by Various Vertical Inclusions

The analysis conducted on speed-settlement behaviours of different vertical inclusions offers valuable insights into ground improvement techniques. In this part of the study, the aim was to examine the effectiveness of various methods such as vibro stone columns (VSC), controlled modulus columns (CMC), and bi-modulus columns under constant static loading and vehicles in motion. By comparing their performance under varying dynamic loading conditions, the impact of speed on ground settlement is deciphered.

Figure 3.15 illustrates the comparison of speed-settlement behaviour generated by different types of vertical inclusions (VSC, CMC, bi-modulus).

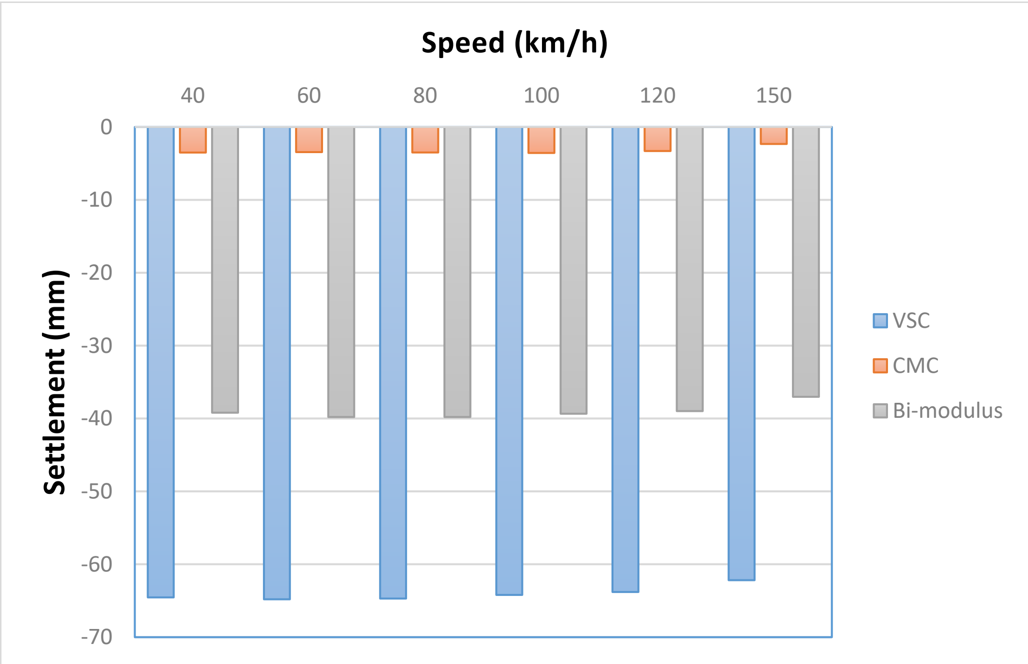


Figure 3.15: Speed-settlement comparison induced by various vertical inclusions

The findings depicted in Figure 3.15 suggest that regardless of the specific type of vertical inclusions utilized, an increase in speed leads to a reduction in settlement. However, it is noteworthy that these changes in settlement are minimal, indicating limited sensitivity to speed variations. This observation underscores the stability and effectiveness of the vertical inclusion techniques across different dynamic loading scenarios.

3.4.2 Dynamic Loading's Impact on Effective Stress

In this phase of the study, PLAXIS 3D was employed to compute the ground's effective stress induced by the construction of asphalt roads and dynamic loading. This analysis covered a range of scenarios and speeds, spanning from zero to 150 km/h:

1) Unimproved ground.
2) VSC treated ground.
3) CMC treated ground.
4) Bi-modulus treated ground.

Figure 3.16 illustrates the comparison of speed-effective stress outcomes derived from numerical analyses, aimed at discerning the most critical conditions.

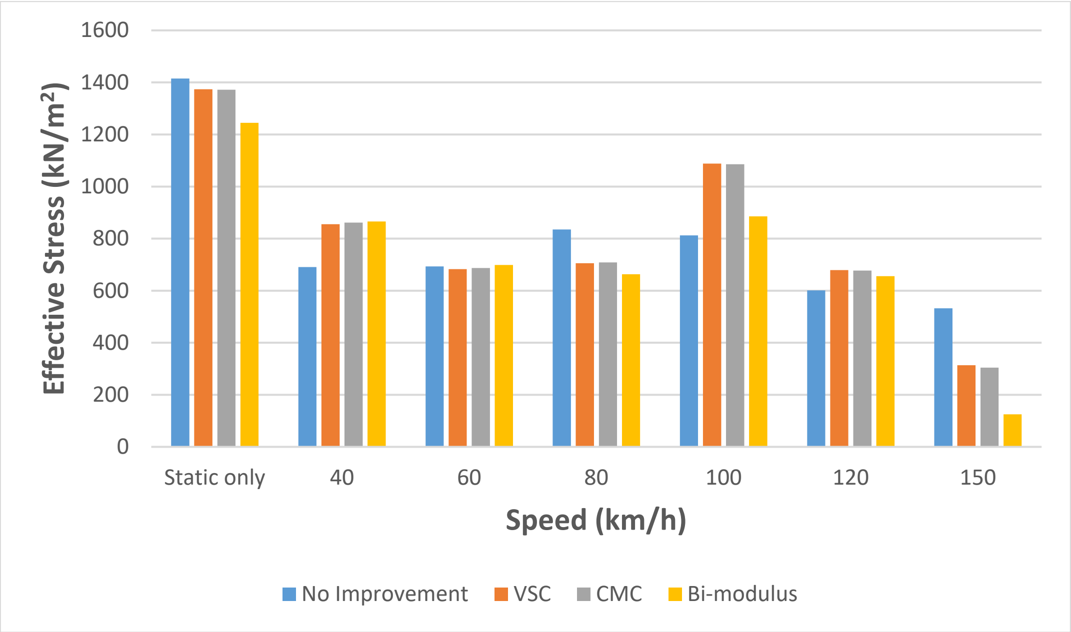


Figure 3.16: Effective stress-speed behaviour of the ground surface treated by various vertical inclusions

As evident, irrespective of the application or absence of ground improvement techniques, the highest effective stress occurs when the vehicle is stationary. Across all instances, at speeds of 40, 60, 80, and 120 km/h, the computed effective stress ranges from 600 to 850 kN/m^2. Additionally, a speed of 100 km/h consistently leads to the highest effective stress, while a speed of 150 km/h consistently results in the lowest effective stress.

3.4.3 Dynamic Loading's Impact on Lateral Displacement

In this part of the speed parametric analysis, the lateral displacement due to the construction of an asphalt road and the application of dynamic loads was assessed using PLAXIS 3D. In the context of embankments and pavements, lateral displacement affects how loads are distributed across the ground. This is important for understanding settlement patterns and preventing uneven settlement that can damage infrastructure. Various scenarios and speeds ranging from zero to 150 km/h were considered for this evaluation:

1) Ground without improvement.
2) VSC treated ground.
3) CMC treated ground.
4) Bi-modulus treated ground.

Figure 3.17 presents a comparison of the results from numerical analyses regarding speed and lateral displacement, aiming to identify the most critical scenario.

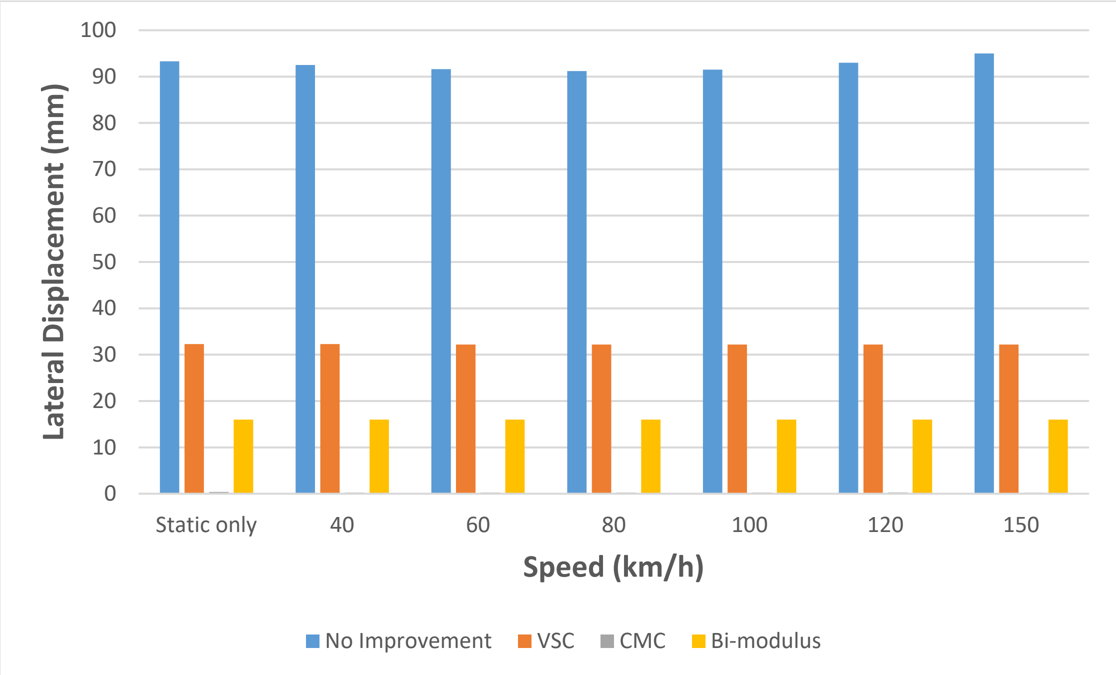


Figure 3.17: Lateral displacement-speed behaviour of the ground surface treated by various vertical inclusions

According to the results shown in Figure 3.17, it can be concluded that the maximum lateral displacement is observed for the scenario where there is no ground improvement, and variation of speed has a negligible effect on generating lateral displacement. Furthermore, as can be seen, CMC ground improvement is the most effective technique in mitigating lateral displacement to almost zero, followed by bi-modulus and VSC techniques, which are both consequential ways of reducing lateral displacement, respectively.

3.4.4 Dynamic Loading's Impact on Cartesian Strain

The term "Cartesian strain" refers to the deformation of soil material and/or structures measured in terms of displacements along Cartesian coordinates (x, y, and z axes). It quantifies how much a material deforms (stretches, compresses, or shears) in each direction of a Cartesian coordinate system. In this segment of the speed parametric investigation, Cartesian strain induced by the construction of an asphalt road and dynamic loading was computed using PLAXIS 3D across various scenarios and speeds ranging from zero to 150 km/h:

1) Ground without improvement.
2) VSC treated ground.
3) CMC treated ground.
4) Bi-modulus treated ground.

Figure 3.18 illustrates the comparison of the speed-Cartesian strain results obtained from numerical analyses to understand the most critical situation.

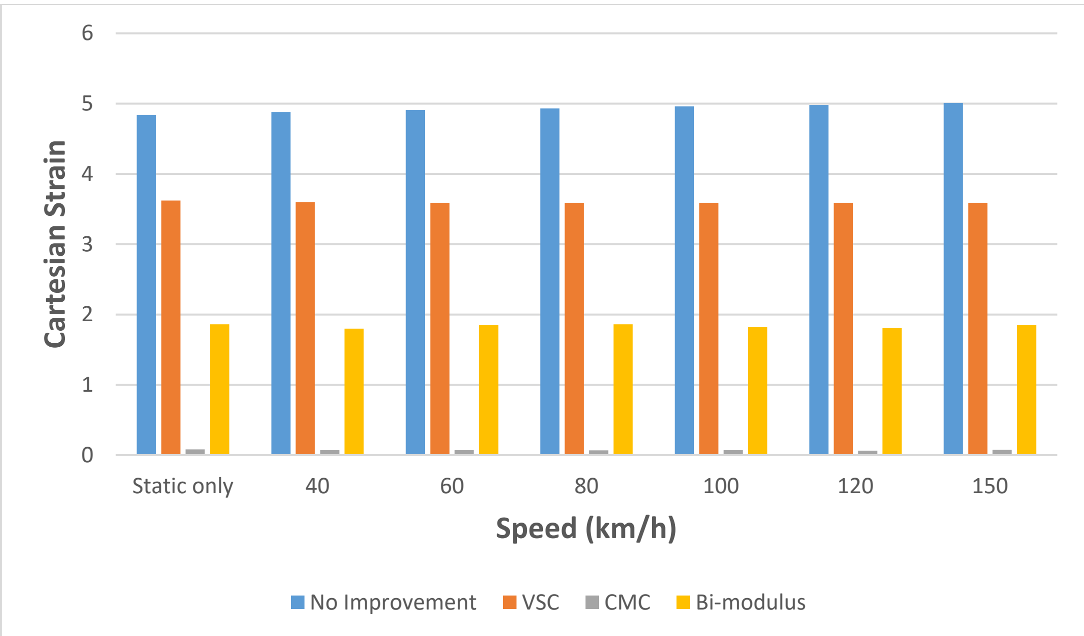


Figure 3.18: Cartesian strain-speed behaviour of the ground surface treated by various vertical inclusions

Based on the findings depicted in Figure 3.18, it can be inferred that the highest Cartesian strain occurs in the scenario without ground improvement, with speed variation having minimal impact on this strain. Additionally, due to its high rigidity compared to other techniques, CMC ground improvement emerges as the most effective method for reducing Cartesian strains to nearly zero. This is followed by the bi-modulus and VSC techniques, which also significantly reduce Cartesian strains.

3.4.5 Dynamic Loading's Impact on Volumetric Strain

In this section of the speed parametric analysis, volumetric strain resulting from the construction of an asphalt road and dynamic loading was computed using PLAXIS 3D across various scenarios and speeds ranging from zero to 150 km/h:

1) Ground without improvement.
2) VSC treated ground.
3) CMC treated ground.
4) Bi-modulus treated ground.

Figure 3.19 depicts the comparison of numerical analyses results on speed-volumetric strain, considering different scenarios.

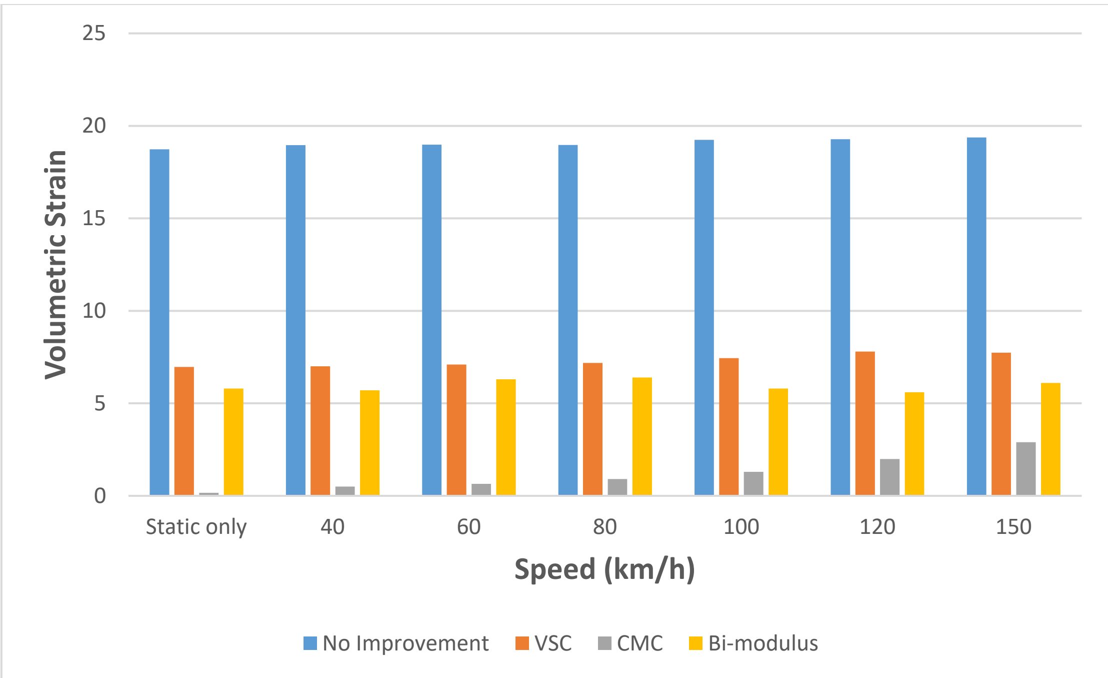


Figure 3.19: Volumetric strain-speed behaviour of the ground surface treated by various vertical inclusions

Based on Figure 3.19, it is evident that the highest volumetric strain occurs in the scenario without ground improvement, while CMC ground improvement proves highly effective in reducing the volumetric strain nearly to zero when the vehicle is stationary. However, as speed increases, the volumetric strain also rises significantly. Following the CMC method, both bi-modulus and VSC techniques emerge as significant approaches to reducing volumetric strain, respectively.

3.4.6 Impact of Dynamic Loading Moving in Different Directions and at Different Speeds on the Overall Ground Settlement of Untreated Soil

In this situation, two vehicles are traveling in opposite directions: one at a speed of 150 km/h (on the left) and the other at 80 km/h (on the right). When stationary, the initial distance between the two vehicles is 40 m. Figure 3.20 illustrates the numerical model representing this scenario.

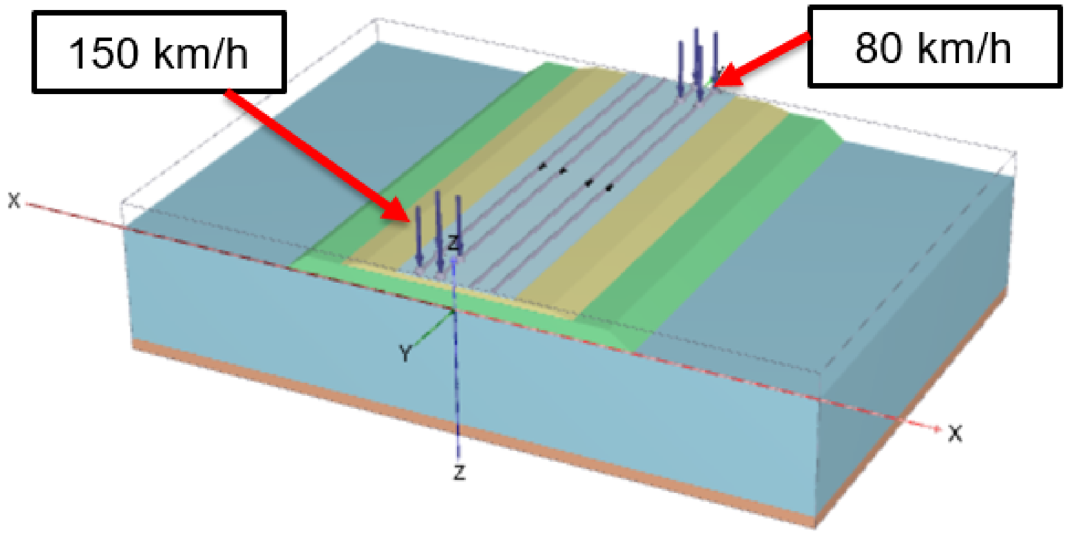


Figure 3.20: Simulation of vehicles in motion traveling in opposite directions modelled using PLAXIS 3D

Figure 3.21 displays the settlement profile resulting from the passage of vehicles (dynamic load), as calculated using PLAXIS 3D.

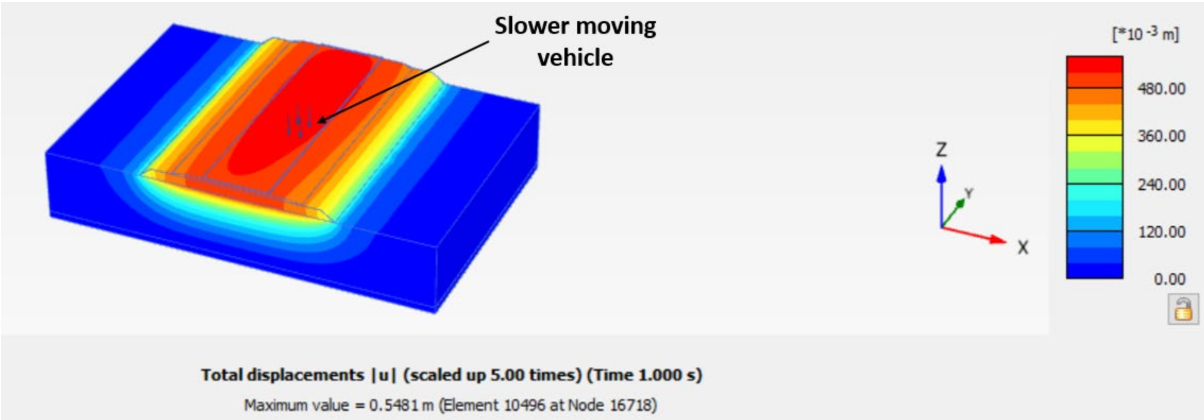


Figure 3.21: Displacement contours induced by passing vehicles computed using PLAXIS 3D

Figure 3.21 illustrates that the highest settlement, reaching 548 mm, occurs along the right lane where the load moving at a slower speed of 80 km/h travels. This observation aligns with the findings of Shahraki and Witt (2015), who noted that in trains traveling in opposite directions, the maximum deformation tends to occur where slower-moving trains pass.

This finding once more validates the results obtained from this numerical study and confirms the influence of speed on settlement patterns.

3.4.7 Comparison between Floating and End-bearing Columns

In this segment of the numerical investigation, the behaviour of floating and end-bearing vertical inclusions is compared to understand their respective characteristics. Figure 3.22 illustrates 3D finite element models employing floating and end-bearing vertical inclusions.

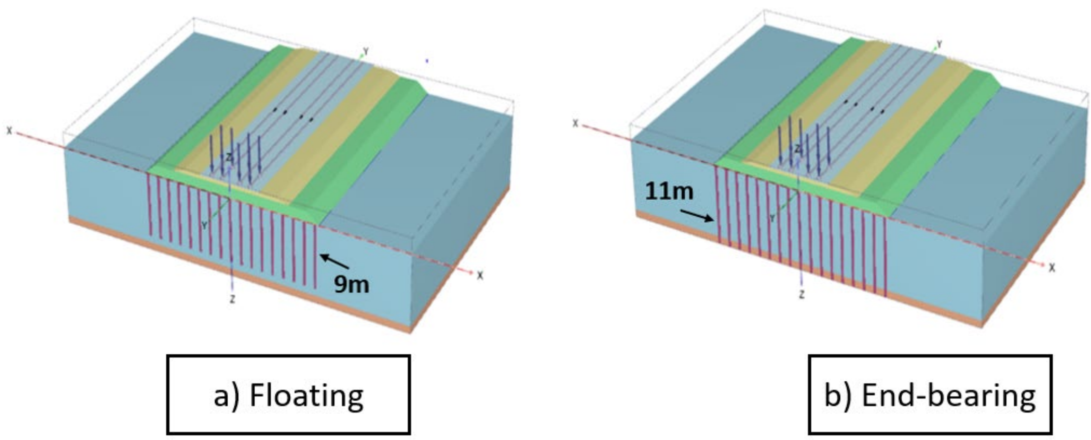


Figure 3.22: Employment of vertical inclusions within the numerical modelling; a) Floating, b) End-bearing

Numerical models were created for all three vertical inclusions (VSC, CMC and bi-modulus columns) in both floating and end-bearing conditions, and comparisons were made. Figure 3.23 illustrates the comparison between floating and end-bearing vertical inclusions in terms of settlement control obtained from numerical analysis.

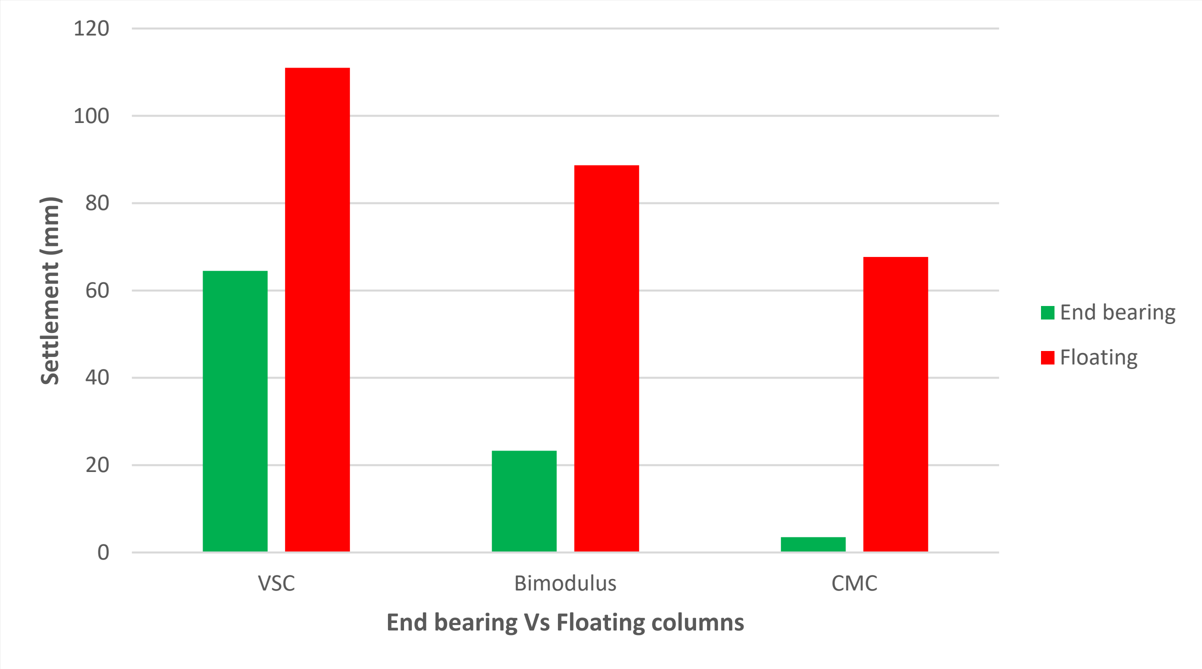


Figure 3.23: Comparison of settlement control between floating and end-bearing vertical inclusions at ground surface

Figure 3.23 confirms the anticipated effectiveness of end-bearing columns over floating columns in settlement mitigation. Notably, for CMC and bi-modulus columns, especially CMC, there's a distinguished contrast in settlement reduction between end-bearing and floating solutions. This suggests that, when feasible in terms of cost and ground conditions, end-bearing is the preferred choice. Particularly evident with CMC inclusions, the floating option results in exponentially higher ground settlement. This is because in end-bearing CMCs, the load from structures or vehicles is efficiently transferred downwards due to their extreme material rigidity. However, this is not the case in the floating option, resulting in much more noticeable and potentially problematic settlement at the ground surface.

On the other hand, as shown in Figure 3.22, end-bearing columns are 11 m long, while floating columns are chosen to be 9 m. Despite this relatively minor difference, PLAXIS simulations compute a significant variation in ground settlement, likely due to substantial support from the bedrock and subgrade 2 (sand). To investigate this discrepancy further, an additional case was analysed in which subgrade 1 was replaced with sand and subgrade 2 with clay. Figure 3.24

presents the comparison of the deformed mesh and the accompanying maximum settlement for a scenario where floating and end-bearing stone columns are utilized to reinforce subgrade 1 (sand) and subgrade 2 (clay).

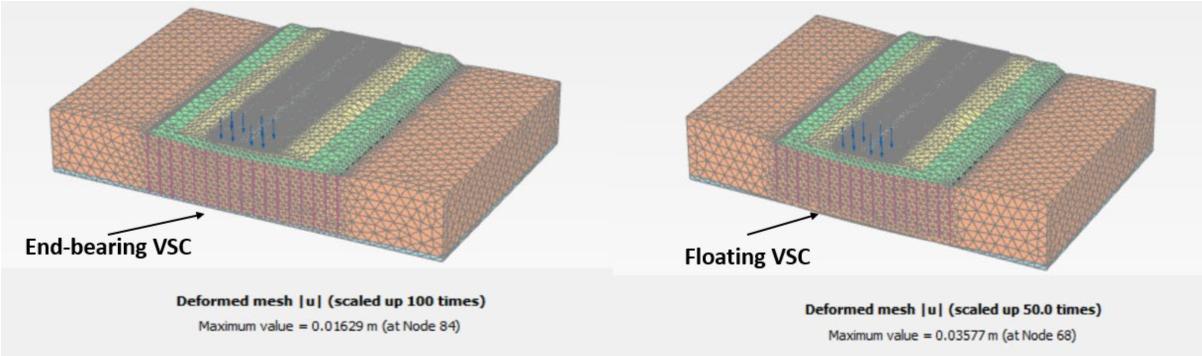


Figure 3.24: The comparison of the deformed mesh and the accompanying maximum settlement for a scenario where floating and end-bearing stone columns are utilized to reinforce subgrade 1 (sand) and subgrade 2 (clay)

Based on Figure 3.24, it is evident that for floating VSC, the maximum settlement is 35.7 mm, whereas for end-bearing VSC, the maximum settlement is 16.2 mm, which is less than half that of the floating scenario. Similar to the findings in Figure 3.23, which demonstrate that end-bearing VSC is approximately twice as effective as floating VSC when subgrade 1 consists of clay, it can be concluded that regardless of the soil material, end-bearing columns are significantly more efficient than floating columns. This increased efficiency is primarily due to the support provided by the bedrock to which they are anchored, and secondly, because of the stiffer layers below the columns.

3.4.8 Extension of Floating Columns to a Stiffer Layer

To gain a clearer understanding of the functionality of floating columns, this segment of the numerical study involved creating a model where floating vertical inclusions were extended to a significantly stiffer layer.

Figure 3.25 demonstrates the extension of floating stone columns to a more rigid layer, simulated using PLAXIS 3D.

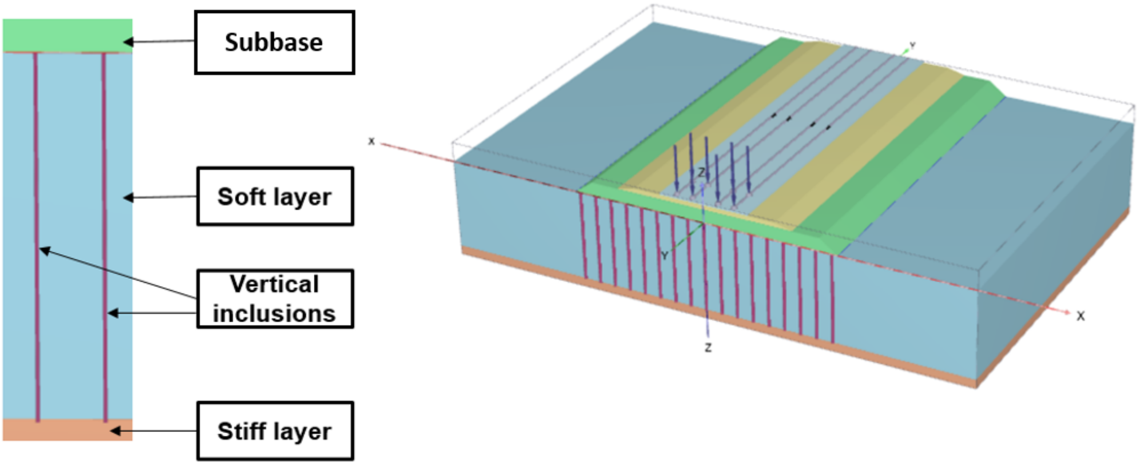


Figure 3.25: Extension of floating stone column to a stiffer layer

The numerical analysis results for floating stone columns in both soft and stiff layers were compared in relation to ground settlement, as depicted in Figure 3.26.

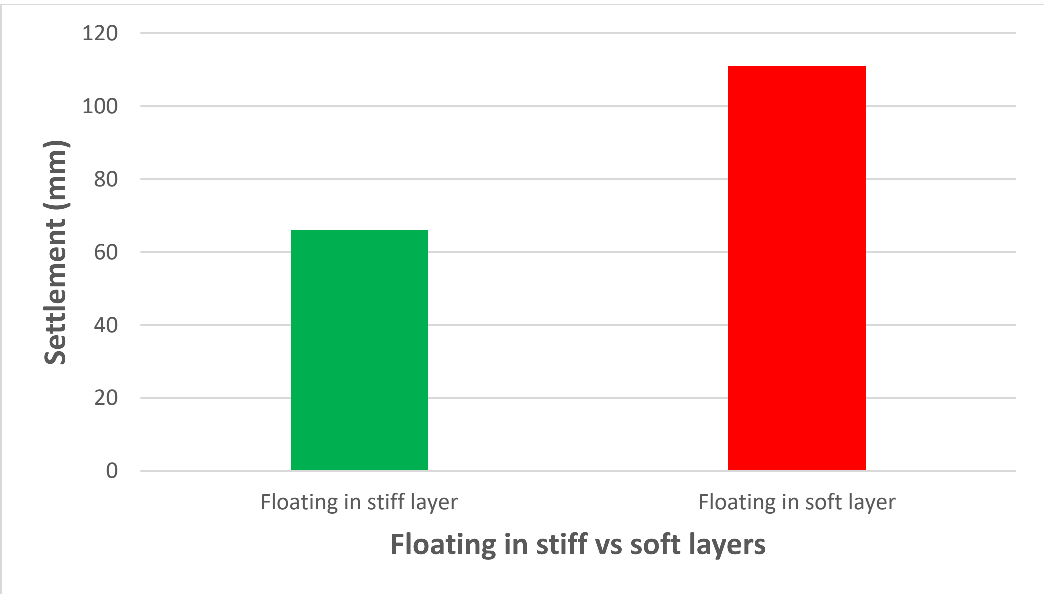


Figure 3.26: Comparison of settlement mitigation at the ground surface between floating columns in soft and stiff layers

Figure 3.26 indicates that extending the vertical inclusions to a stiff layer leads to approximately a 25% reduction in overall settlement compared to floating vertical inclusions in a soft layer, because it improves load transfer efficiency and encounters less compressible soil. However, extending the inclusions to a stiffer layer entails higher material, force, and machinery requirements, resulting in increased costs compared to floating in a soft layer.

Additionally, thorough investigation of ground conditions is necessary to determine the feasibility of extending the columns to a stiffer layer.

3.4.9 Effect of Groundwater Level on the Overall Settlement of the Treated Ground

In all numerical models in this study, the water table was set at the ground surface to ensure maximum potential ground settlement and the most conservative results possible. However, to examine the impact of groundwater on the overall settlement of the treated ground, numerical models were created in this section with the water table positioned at three different levels:

1) Ground surface.
2) Model bottom. (at 11 m below the ground surface)
3) Model midpoint. (at 5.5 m below the ground surface)

Figure 3.27 illustrates the fluctuation of the groundwater level in three different models generated using PLAXIS 3D for the ground treated with floating stone columns.

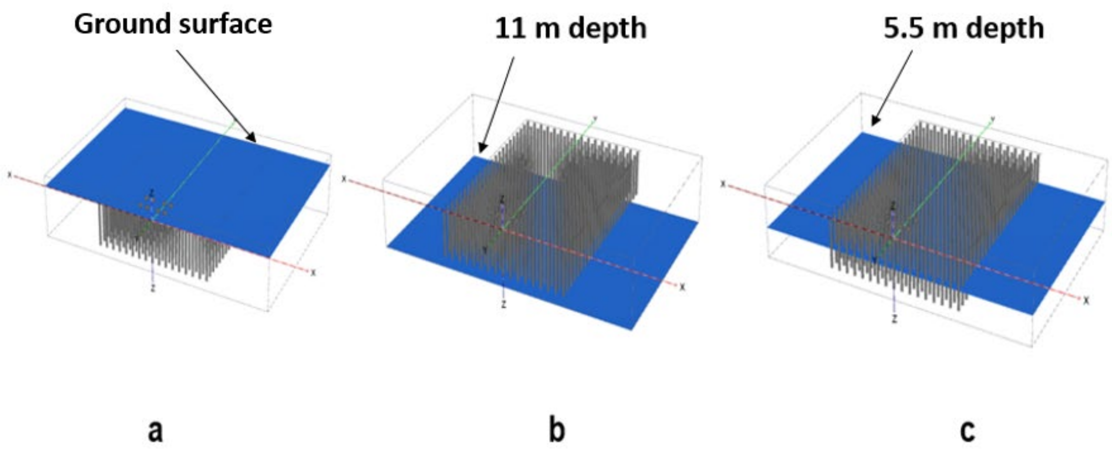


Figure 3.27: Location of the water table at: a) Ground surface; b) Model bottom; c) Model midpoint

After completing the numerical analysis of these three identical models, where the only varying factor was the groundwater level, the results from PLAXIS 3D were compared to understand the influence of groundwater level on overall settlement. Figure 3.28 presents the comparison between the results.

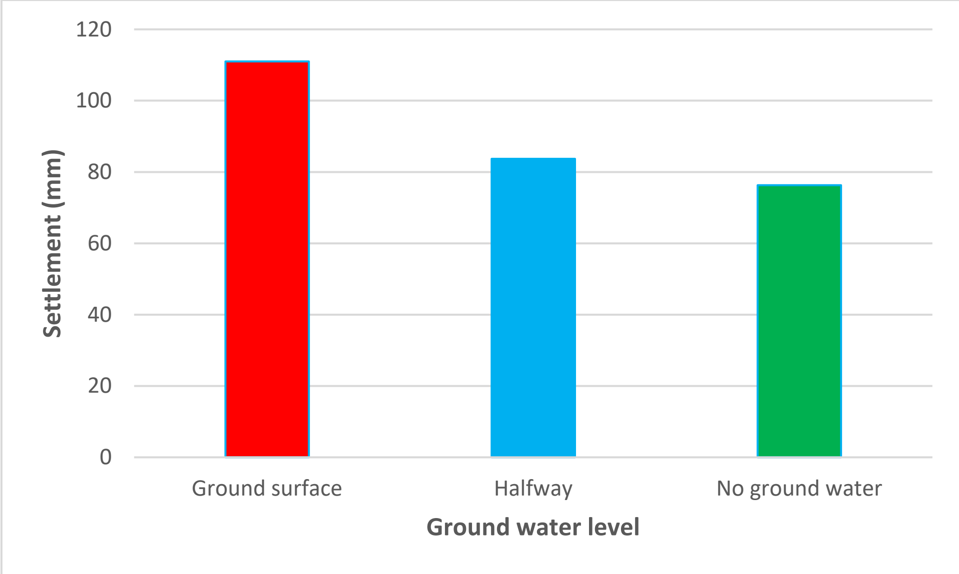


Figure 3.28: The impact of the groundwater level on total ground settlement for ground treated with floating stone columns

The findings depicted in Figure 3.28 indicate that as anticipated, the scenario with the water table at the ground surface results in the highest overall settlement. Moreover, the other two scenarios, where the water table is either at the middle or significantly below the base of the columns, yield very similar outcomes in terms of ground settlement. However, it is still noticeable that there are minimal effects on overall ground settlement when the water table is at the midpoint. The negligible effects on ground settlement when the water table is at the midpoint indicate that the hydraulic and mechanical conditions of the soil are relatively stable, supporting uniform and consistent behaviour in terms of settlement.

3.4.10 Effect of LTP and its Thickness on the Overall Settlement of the Treated Ground

In this section of the numerical analysis, recognizing the significant role of the Load Transfer Platform (LTP) in ground improvement endeavours, a study was undertaken to examine the impact of the LTP and its thickness on the overall settlement of the treated ground. This investigation encompasses both floating and end-bearing stone columns utilized as ground improvement techniques. Figure 3.29 illustrates the positioning of the LTP atop the vertical inclusions modelled in PLAXIS 3D.

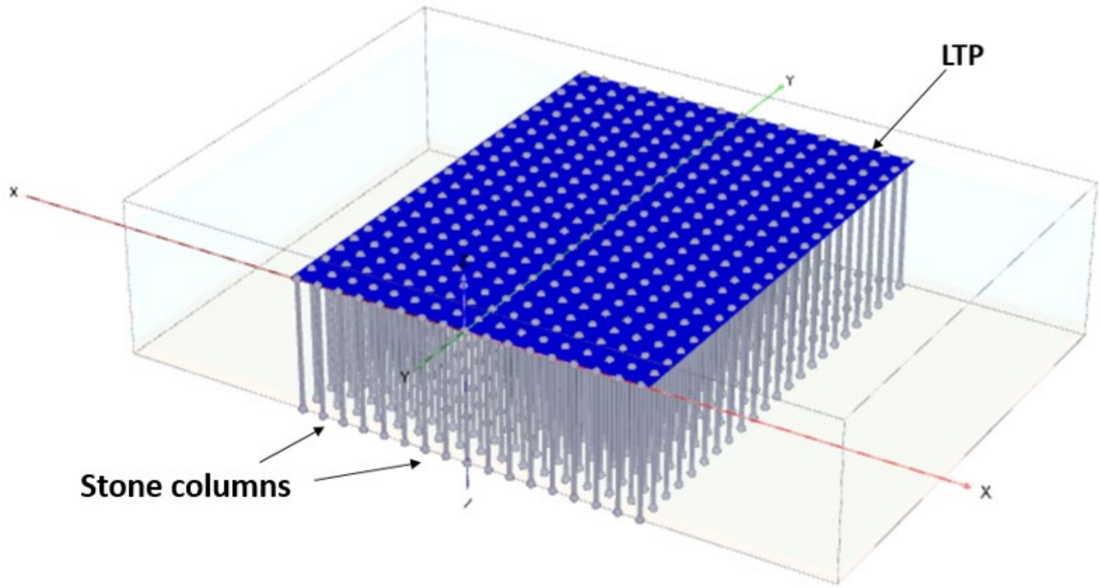


Figure 3.29: The positioning of the LTP atop the vertical inclusions modelled in PLAXIS 3D

As established in the previous chapter, the thickness of the LTP is a critical parameter, as it directly influences its load distribution capability. A sufficiently thick LTP ensures that the loads are spread over a wider area, reducing the stress on individual columns and preventing excessive settlement or failure. Therefore, optimizing the thickness of the LTP is essential for achieving the desired performance in ground improvement projects, ensuring both safety and cost-effectiveness.

In this study, the thickness of the Load Transfer Platform (LTP) was considered:

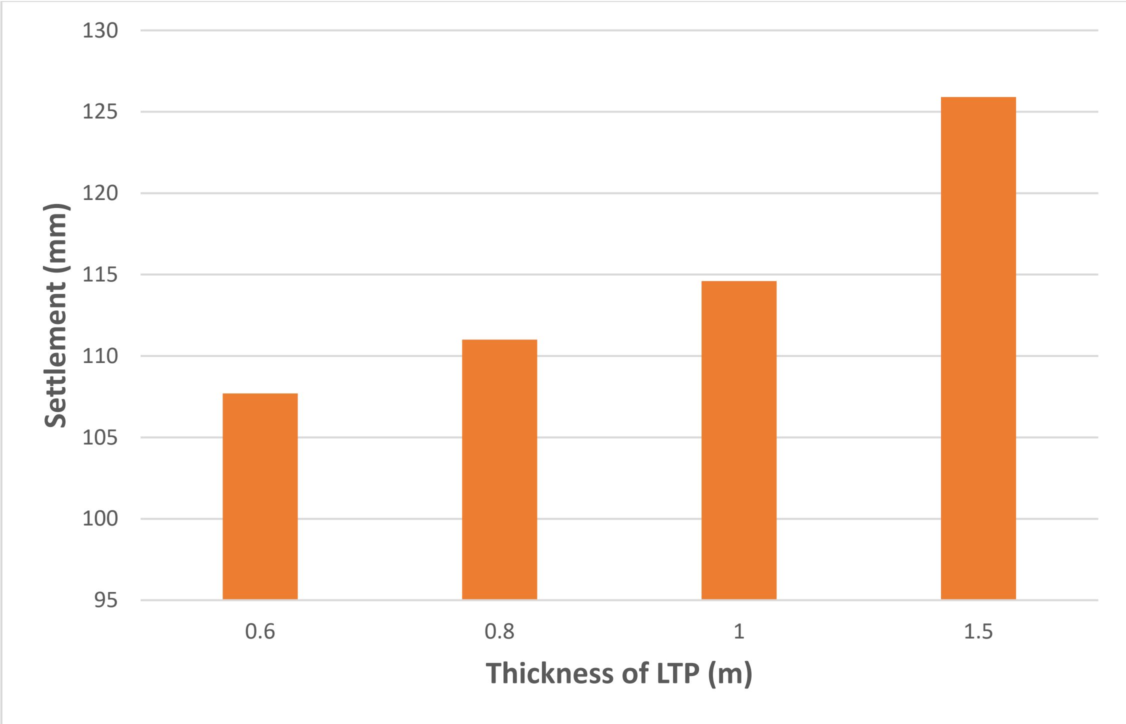
a) 0.6 m,

b) 0.8 m,

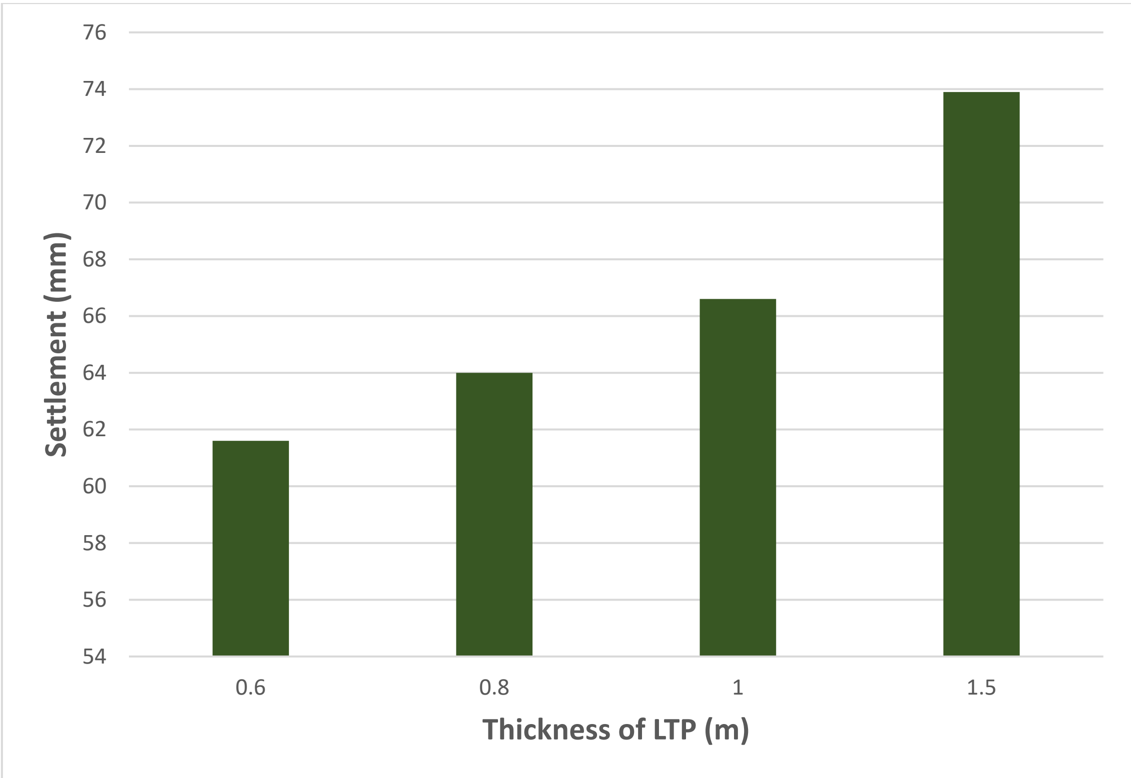
c) 1 m, and

d) 1.2 m.

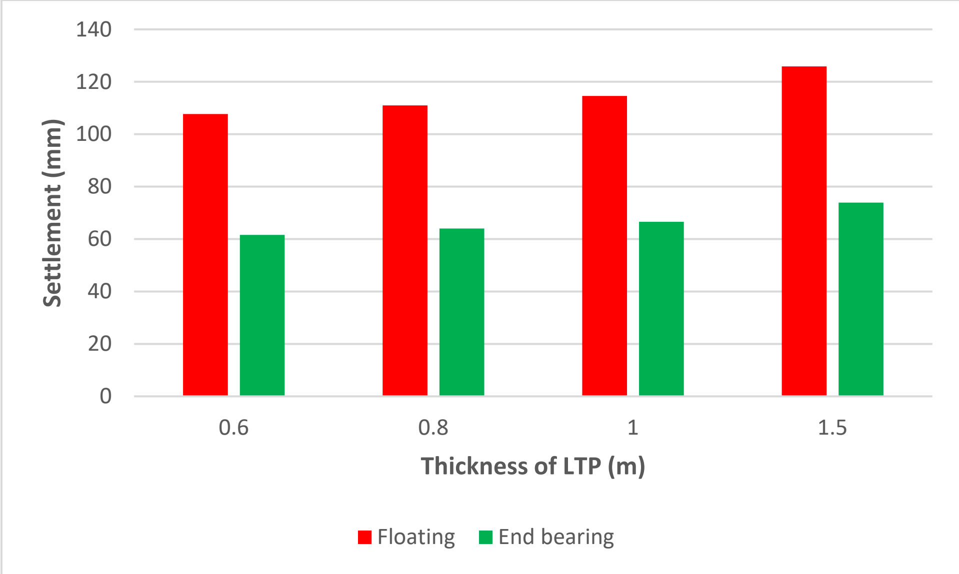
Following the conclusion of the numerical analysis, the findings are presented and compared in Figure 3.30.



a) Floating stone columns



b) End-bearing stone columns



c) Comparison between Floating and End-bearing stone columns

Figure 3.30: The impact of the thickness of the LTP on ground settlement in a) Floating stone columns, b) End-bearing stone columns, c) Floating vs. End-bearing stone columns

Figure 3.30 reveals that for both floating and end-bearing VSC inclusions, an increase in LTP thickness correlates with an increase in settlement at the ground surface. Interestingly, it appears that a 0.6 m thick LTP offers the most effective settlement mitigation. Consequently, if design criteria permit, opting for LTPs with thinner thicknesses proves more favourable in terms of cost-effectiveness and settlement management. This finding underscores the importance of considering both engineering requirements and economic factors when designing ground improvement projects.

3.4.11 Impact of Partially Failed Vertical Inclusions on Ground Settlement

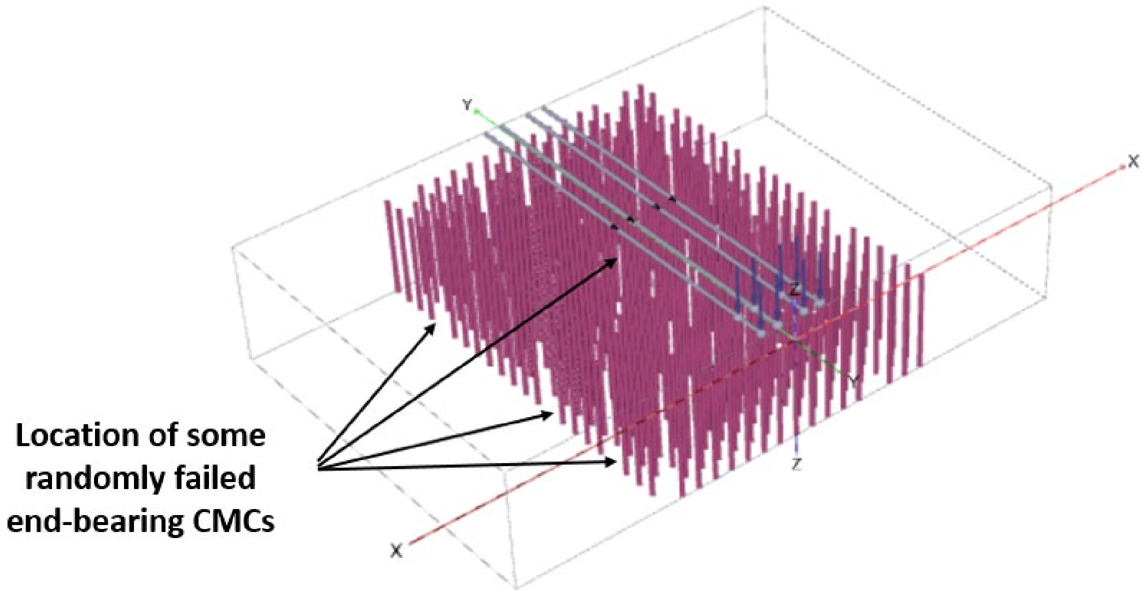
Industry experts suggest that there is a possibility for 10 to 15% of all installed columns (both rigid and semi-rigid vertical inclusions) in a ground improvement project to fail either during construction or afterward. To comprehend the repercussions of such failures on ground settlement, a numerical investigation was conducted using PLAXIS 3D, exploring the following scenarios:

1) Failure of some end-bearing CMC inclusions randomly.
2) Failure of some floating stone columns locally with LTP.
3) Failure of some floating stone columns locally without LTP.

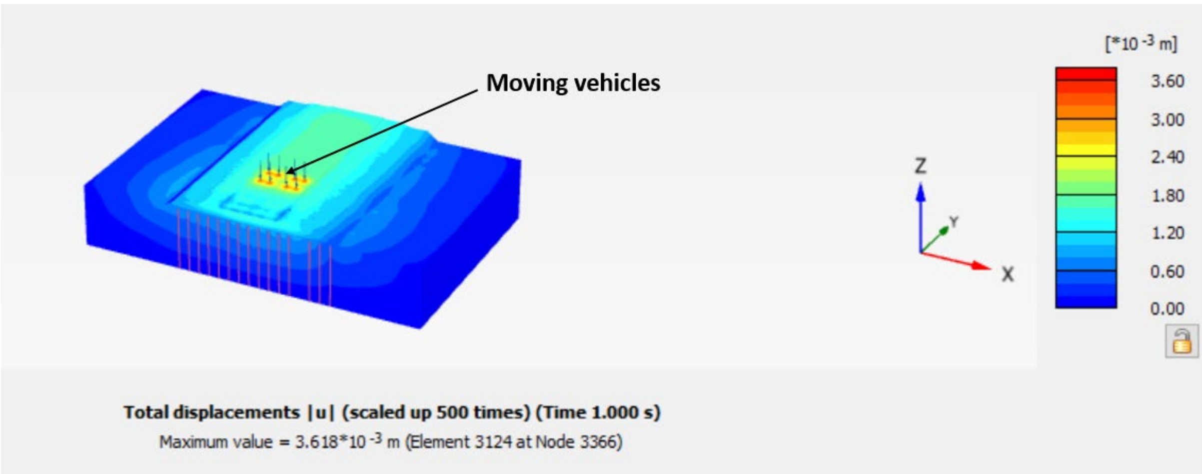
3.4.11.1 Random Failure of Some End-bearing CMC Inclusions

Approximately 30 CMC inclusions, which account for 10% of the total CMC, were randomly chosen across the entire model and deleted to simulate failure at those locations.

Figure 3.31a demonstrates the modelling of randomly failed CMC inclusions in PLAXIS 3D, while Figure 3.31b displays the settlement profile for this model recorded under both static and dynamic loading conditions.



a)



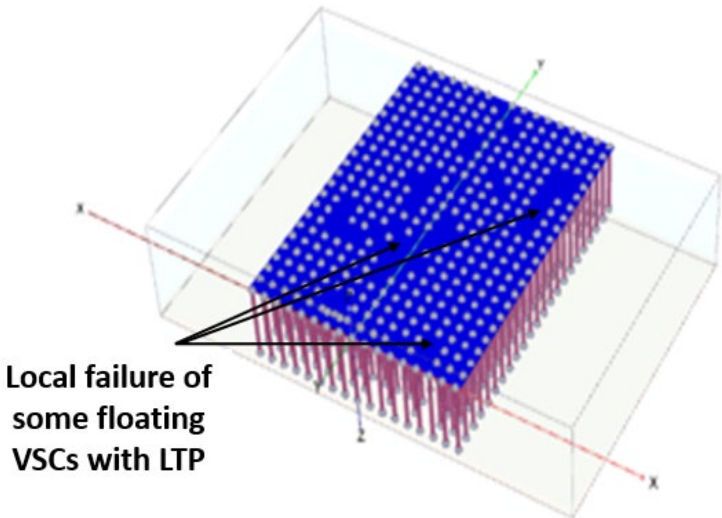
b)

Figure 3.31: Numerical model; a) Randomly failed CMC inclusions; b) Relevant settlement profile

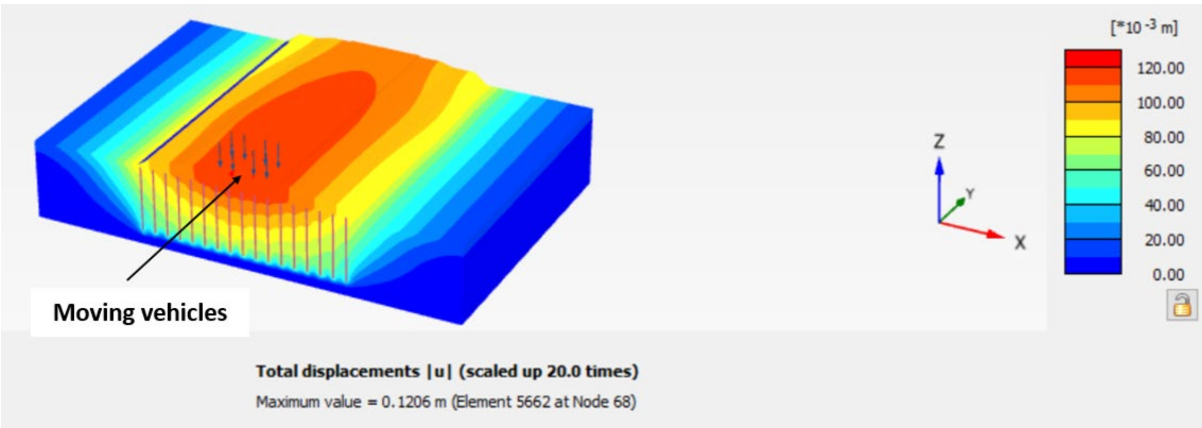
Based on the settlement profile and comparison with a scenario where all columns are installed perfectly without any failures, the maximum recorded settlement at the ground surface remained at 3.6 mm, unchanged. Thus, it can be inferred that random failure of some columns for end-bearing CMC inclusions has negligible effects on the settlement of the treated ground.

3.4.11.2 Local Failure of Some Floating Stone Columns with LTP

Figure 3.32a illustrates the modelling of locally failed stone columns with LTP in PLAXIS 3D, while Figure 3.32b displays the settlement profile for this model calculated under static and dynamic loading conditions.



a)



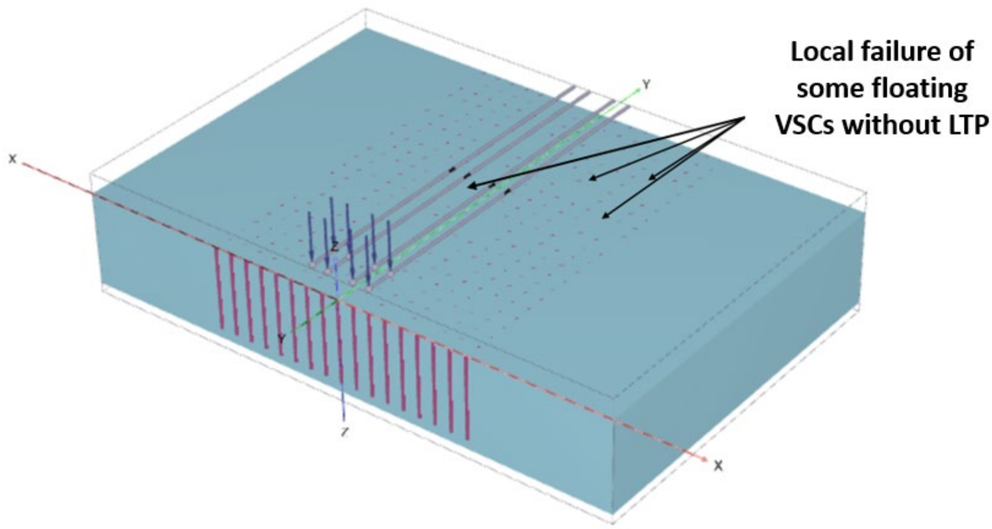
b)

Figure 3.32: Numerical model; a) Locally failed stone columns with LTP; b) Relevant settlement profile

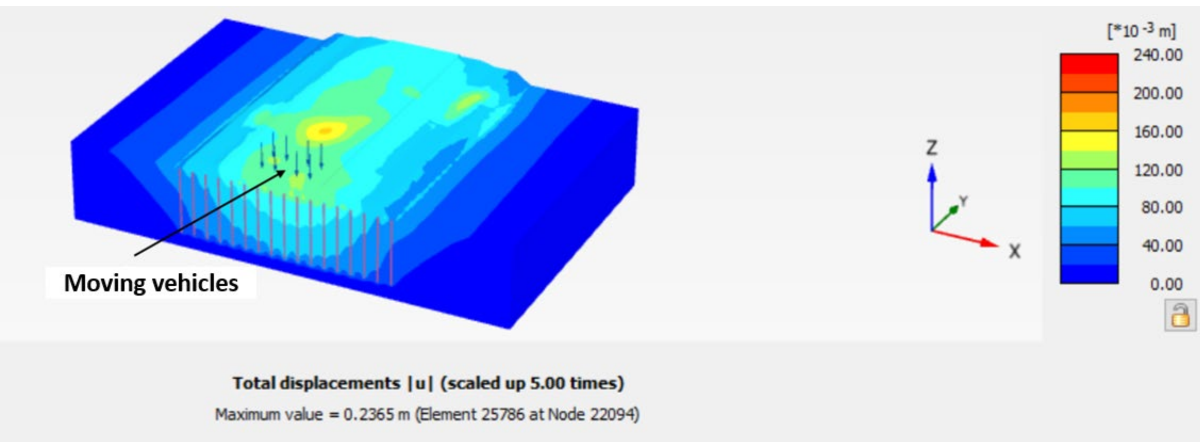
Upon examining the settlement profile and comparing the results with a scenario where all floating stone columns are flawlessly installed, a 12 mm rise in total settlement is noted, from 176 mm to 188 mm. Consequently, it can be inferred that local failure of stone columns does indeed marginally contribute to the overall settlement increase.

3.4.11.3 Local Failure of Some Floating Stone Columns without LTP

Figure 3.33a illustrates the modelling of locally failed stone columns lacking LTP in PLAXIS 3D, while Figure 3.33b depicts the settlement profile of this model observed during both static and dynamic loading conditions.



a)



b)

Figure 3.33: Numerical model; a) Locally failed stone columns without LTP; b) Relevant settlement profile

Based on the settlement profile, in a situation where there's local failure of stone columns and absence of LTP, the total settlement rises from 176 mm to 270 mm, highlighting the crucial role of LTP in load transfer and stress distribution.

Table 3.9 outlines the findings derived from this aspect of the numerical analysis, focusing on the failed vertical inclusions during construction and their influence on ground settlement.

Table 3.9: Impact of partially failed vertical inclusions on ground settlement

Failure	Outcome in Terms of Ground Settlement
Random failure of some vertical inclusions	Negligible
Local failure of some vertical inclusions with LTP	Minor
Local failure of some vertical inclusions without LTP	Major

3.4.12 Effect of Spacing between Vertical Inclusions on the Overall Settlement of the Treated Ground

In this segment of the numerical investigation, numerical models were generated to explore the importance of the spacing between columns, considering the following scenarios:

1) VSC columns:
   a) 2D, 3D and 4D for floating columns
   b) 2D, 3D and 4D for end bearing columns
2) CMC columns:
   a) 2D, 3D and 4D for floating columns
   b) 2D, 3D and 4D for end bearing columns
3) Bi-modulus columns:
   a) 2D, 3D and 4D for floating columns
   b) 2D, 3D and 4D for end bearing columns

Following the numerical analysis, the settlement responses for each vertical inclusion were compared between floating and end-bearing conditions. Figure 3.34 illustrates how spacing affects the settlement of ground treated with floating and end-bearing stone columns.

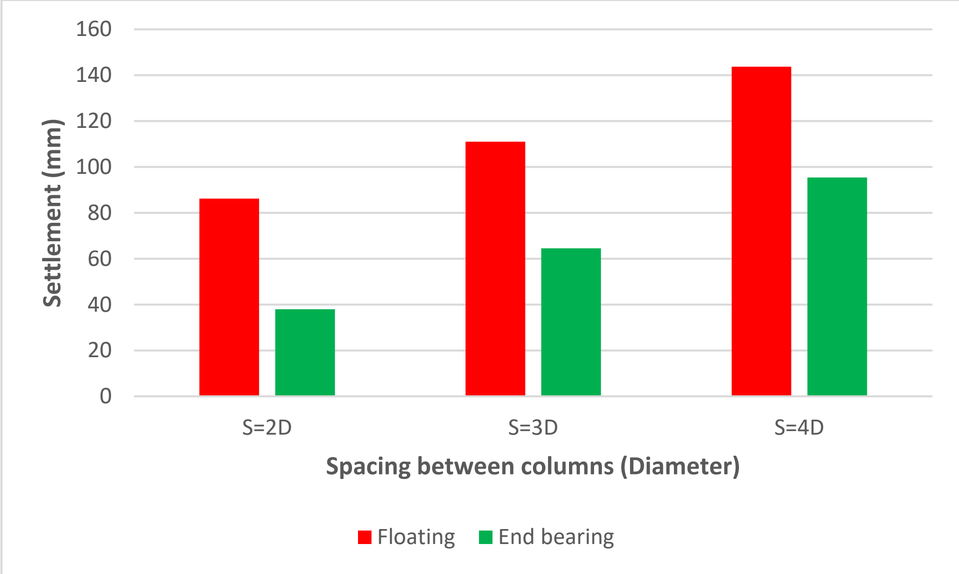


Figure 3.34: The impact of spacing on settlement of ground treated with floating and end-bearing stone columns at ground surface

Figure 3.34 indicates that reducing the spacing between the stone columns, for both floating and end-bearing configurations, results in a more significant reduction in settlement. As expected, the S = 2D option emerges as the most effective choice for mitigating settlement.

Additionally, it is evident that in the case of VSC inclusions, the settlement control results are consistently within a similar range, with the end-bearing solution remaining the preferable choice. This observation underscores the robustness and reliability of the end-bearing technique in effectively mitigating settlement issues within treated ground conditions.

Figure 3.35 illustrates how spacing influences the settlement of ground treated with floating and end-bearing controlled modulus columns.

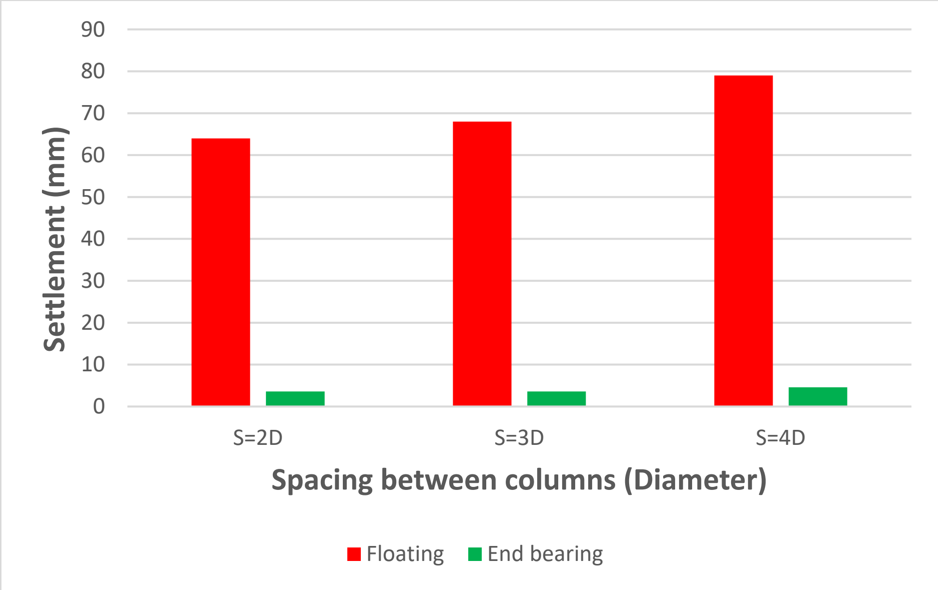


Figure 3.35: The impact of spacing on settlement of ground treated with floating and end-bearing concrete modulus columns at ground surface

As per the graph in Figure 3.35, significant disparities exist in settlement reduction between end-bearing and floating options for CMC inclusions. Additionally, it is apparent that for floating CMC inclusions, S=2D is more effective for settlement mitigation, whereas for end-bearing CMC inclusions, spacing has minimal impact on settlement reduction which is attributed to their high rigidity, direct load transfer to a solid underlying layer, and the limited influence of the compressibility of the soil between the columns. Figure 3.36 demonstrates how spacing affects the settlement of ground treated with floating and end-bearing bi-modulus columns.

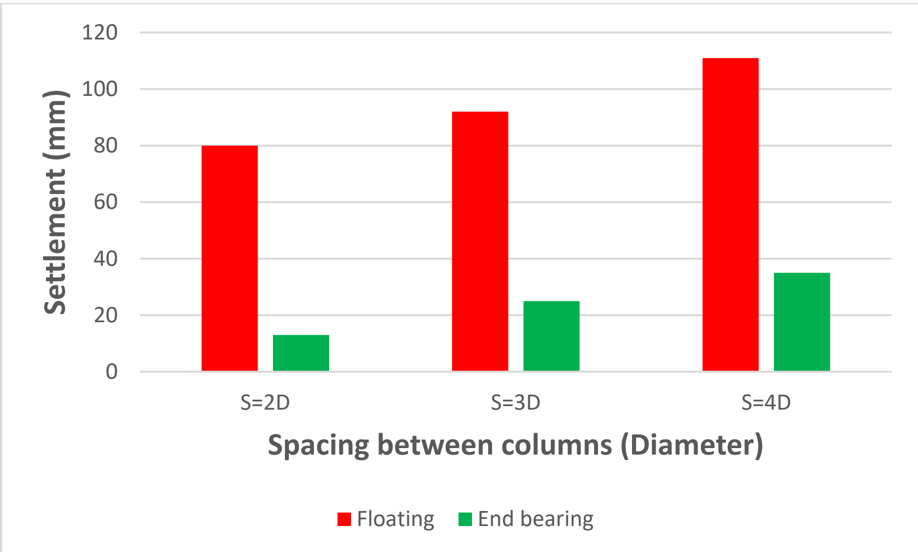


Figure 3.36: The impact of spacing on settlement of ground treated with floating and end-bearing bi-modulus columns

The graph in Figure 3.36 highlights a notable contrast in settlement reduction between end-bearing and floating options for bi-modulus inclusions. End-bearing bi-modulus columns demonstrate considerable effectiveness in reinforcing the ground and settlement mitigation. Table 3.10 provides a summary of the results obtained from the spacing parametric study.

Table 3.10: The summary of the results obtained from the spacing parametric study

	VSC	**CMC**	**Bi-modulus**
Most Influential Configuration	End-bearing	End-bearing	End-bearing
Effects of Spacing Variation for End-bearing Configuration	Major	Marginal	Major
Effects of Spacing Variation for Floating Configuration	Major	Marginal	Relatively consequential
Differences in Settlement Mitigation Between Two Configurations	Medium	Large	Large

It is important to highlight that in practical applications and real-world projects, the spacing between vibro stone columns typically falls within the range of 2 to 3 times the diameter (2-3D), while for controlled modulus columns, the spacing is usually set at 4 times the diameter (4D). Designers face limitations in selecting the spacing between vertical inclusions due to various factors such as soil heaving, cost-effectiveness, workability, and the generation of excess pore pressure from ground compaction. In this numerical study, the objective was to demonstrate the significance of spacing as one of the most critical aspects of vertical inclusion design.

3.4.13 Parametric Study on the Length of CMC Vs VSC Section of the Bi-Modulus Columns

In this section, a parametric study was undertaken to explore the significance of the transition zone in bi-modulus columns and to determine the optimal combination of CMC and VSC sections that lead to the most effective settlement mitigation.

Figure 3.37 illustrates the 3D FE models of bi-modulus columns developed using PLAXIS 3D.

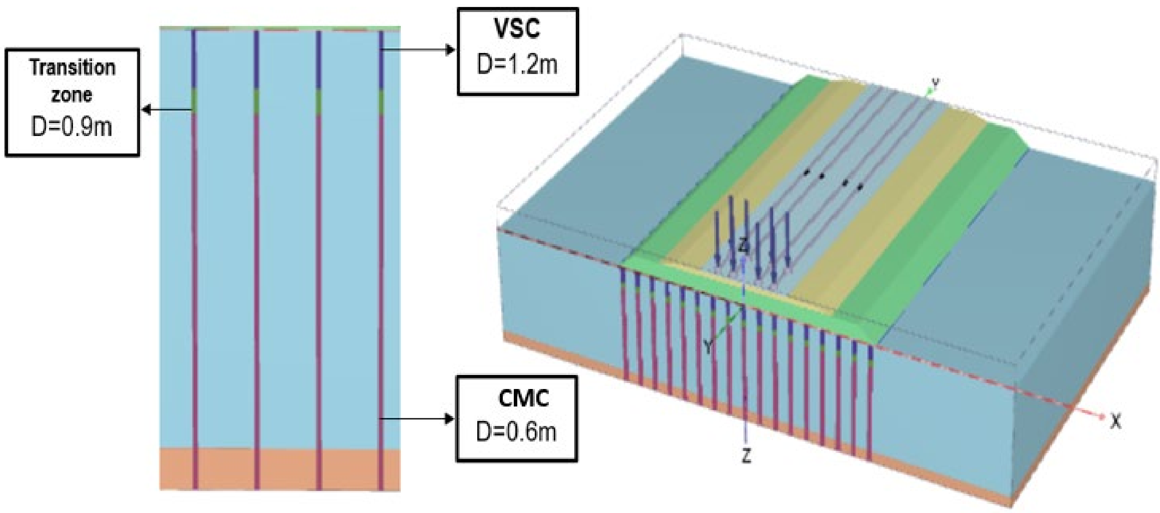


Figure 3.37: 3D FE models of bi-modulus columns developed using PLAXIS 3D

As evident, the VSC section occupies the uppermost position with a diameter of 1.2 m, followed by the transition zone in the middle with a diameter of 0.9 m, and finally, at the base lies the CMC section with a diameter of 0.6 m.

In the numerical model, the overall length of the bi-modulus columns is 11 m, with a constant transition zone length of 0.6 m across all scenarios. In the transition zone, materials were carefully chosen to closely match those used in the VSC section of the bi-modulus column, with a slight increase in stiffness of approximately 15%.

This nuanced adjustment in material properties aims to ensure a smooth transition between different sections of the bi-modulus column, maintaining structural integrity and enhancing overall performance. Table 3.11 presents the range of options for constructing bi-modulus columns in the numerical model, focusing on variations in VSC/CMC length.

Table 3.11: Parametric investigation on bi-modulus column construction: variation in VSC/CMC lengths

Bi-modulus Column Options	Length of Transition Zone (m)	Length of VSC Section (m)	Length of CMC Section (m)
1	0.6	9.4	1
2	0.6	9	1.4
3	0.6	8.4	2
4	0.6	8	2.4
5	0.6	7.4	3
6	0.6	7	3.4
7	0.6	6.4	4
8	0.6	6	4.4

Figure 3.38 presents a comparison of the results obtained from the PLAXIS 3D software for this parametric investigation.

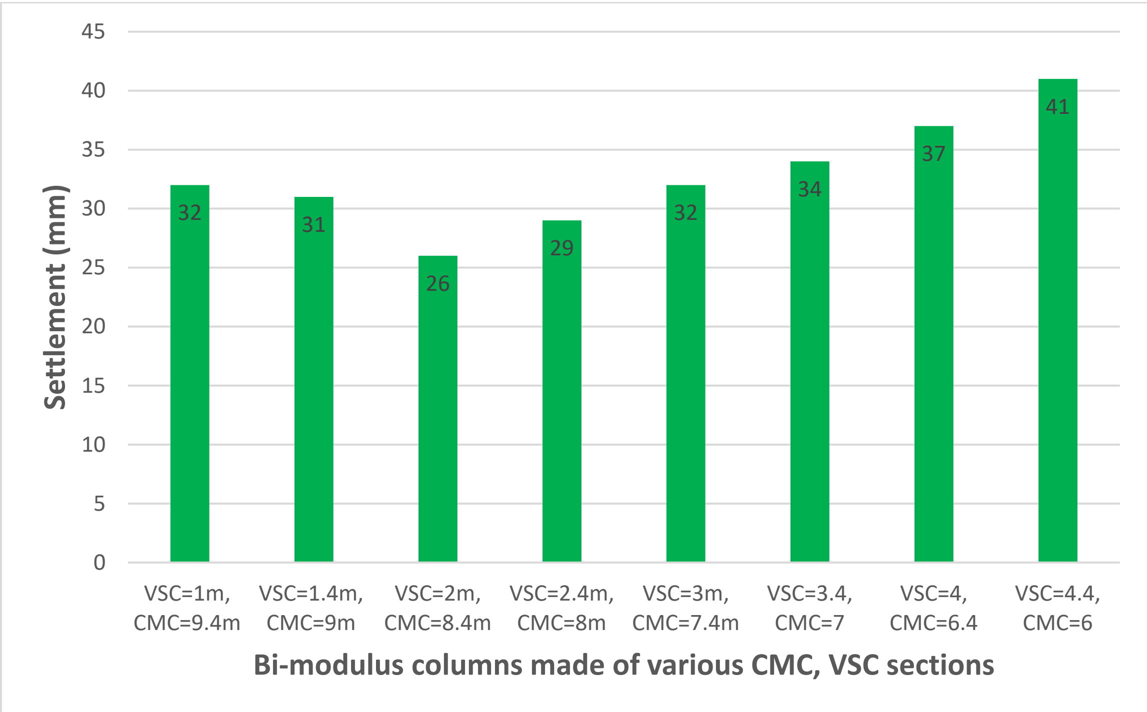


Figure 3.38: Settlement behaviour of the ground at its surface treated with various configurations of bi-modulus columns

Based on the findings of this parametric study, the optimal configuration for settlement mitigation appears to be a bi-modulus column consisting of a 2 m VSC section at the top, a 0.6 m transition zone in the middle, and an 8.4 m CMC section at the bottom. Conversely, bi-modulus columns with very small VSC sections (1 and 1.4 m), as well as those with VSC sections exceeding 2 m, are less advantageous for ground settlement mitigation. It seems that beyond the optimal scenario, an increase in the length of the VSC section of the column correlates with a corresponding increase in observed settlement. The explanation for this finding is that a VSC section equal to 2 m appears to be sufficient to effectively transfer loads across the entire ground. It acts as an additional load transfer platform (LTP) and eliminates the mushroom effects caused by the rigidity of the CMC. Any VSC section less than 2 m is inadequate for sufficient load transfer, while any VSC section greater than 2 m decreases the rigidity effect obtained from the CMC section. In summary, the most effective configuration of bi-modulus column for reducing settlement involves a VSC/CMC arrangement where the VSC measures 2 m (18%), the transition zone is 0.6 m (5.5%), and the CMC spans 8.4 m (76.5%). As anticipated, any increase in the VSC section beyond this optimal configuration results in greater ground settlement.

3.4.14 Ground Improvement beneath the Batter Slopes

In this segment of the study, bi-modulus columns (excluding the transition zone) of different CMC and VSC lengths are analysed to grasp the significance of ground improvement beneath the batter of embankment in the scenarios outlined below:

- Vertical inclusions are extended to batters.
- Vertical inclusions support the asphalt road only.

Due to the presence of minimal sections referred to as "transition zones" in bi-modulus columns, PLAXIS 3D is incapable of computing results in instances where there are no columns beneath the batters. Consequently, models encounter significant convergence issues. Figure 3.39 demonstrates the modelling of vertical inclusions in PLAXIS 3D for both a) extended to batter slopes and b) non-extended configurations.

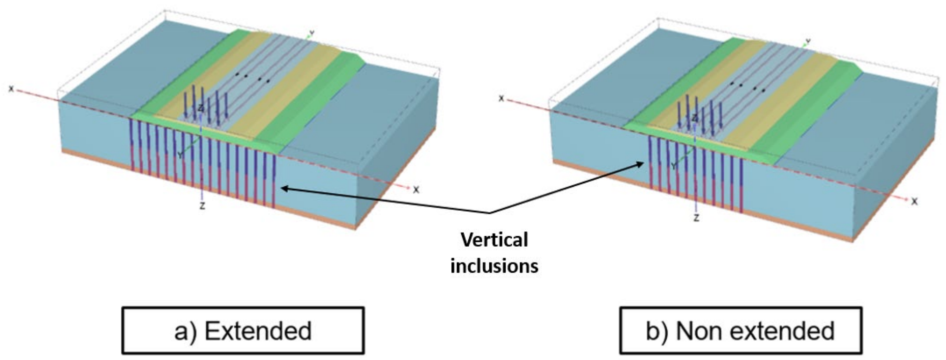


Figure 3.39: Modelling of vertical inclusions in PLAXIS 3D for a) extended to batter slopes and b) non-extended configurations

The different lengths of the CMC and VSC sections of the 11 m bi-modulus columns installed beneath the asphalt road and the batter of the embankments are detailed in Table 3.12.

Table 3.12: Length variations of the CMC and VSC sections of 11-meter bi-modulus columns

Bi-modulus Column Options	Length of VSC Part (m)	Length of CMC Part (m)
1	1.5	9.5
2	2.5	8.5
3	3.5	7.5
4	4.5	6.5
5	5.5	5.5

Figure 3.40 illustrates a comparison of settlement behaviour derived from numerical analysis, examining and comparing bi-modulus vertical inclusions extended to batter slopes and those not extended.

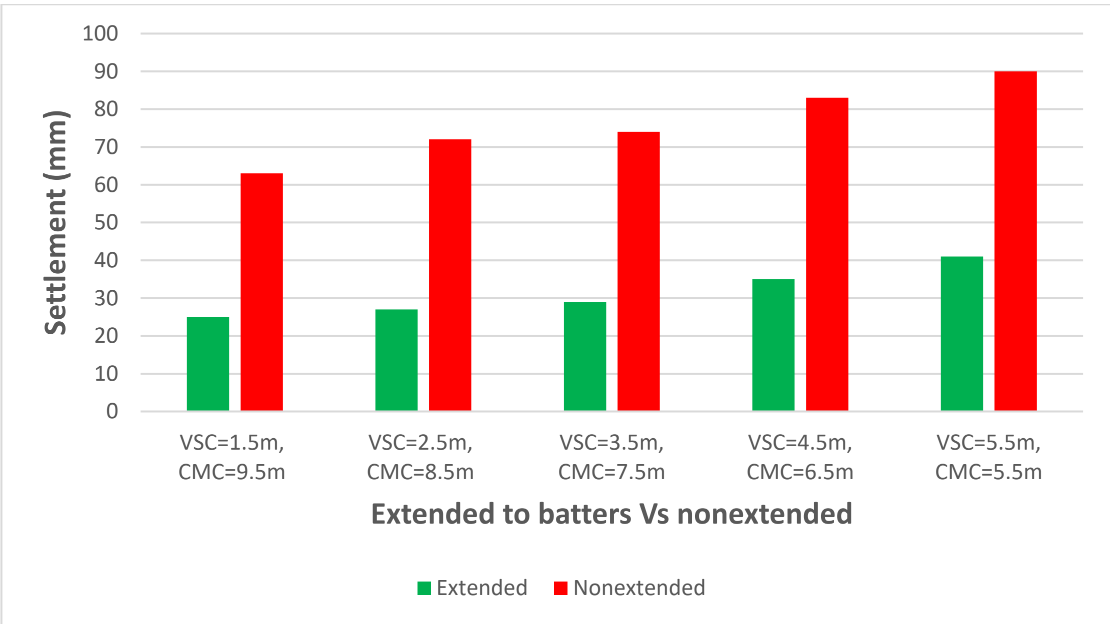


Figure 3.40: Settlement comparison at the ground surface between bi-modulus columns extended to batter and those not extended to batter, with various lengths of VSC and CMC sections

From Figure 3.40, it is evident that irrespective of the lengths of the VSC/CMC sections, extending vertical inclusions to batter slopes yields significantly better outcomes in terms of settlement reduction. In contrast to the previous section, where the transition zone was considered, this study finds that the longer the CMC section of the bi-modulus columns, the lower the observed settlement.

Table 3.13 offers a concise overview regarding the advantages and disadvantages associated with employing the extended or non-extended to batter vertical inclusion ground improvement method.

Table 3.13: Benefits and drawbacks of utilizing vertical inclusions extended or not extended to batter slopes

Outcome	Extended	Non Extended
Total settlement	Less	More
Creation of differential settlement	No	Yes
Creation of cracks due to settlement differences	No	Yes
Number of vertical inclusions	More	Less
Cost effectiveness	Less	More

Given that cost-effectiveness is a pivotal consideration in any project, a set of models was generated and evaluated, wherein the lengths of the columns supporting the embankment batter were decreased to 8 m and 6 m. This was based on the assumption that in this section of the embankment (batter), the load is lighter, necessitating fewer reinforcements. Figure 3.41 depicts this case.

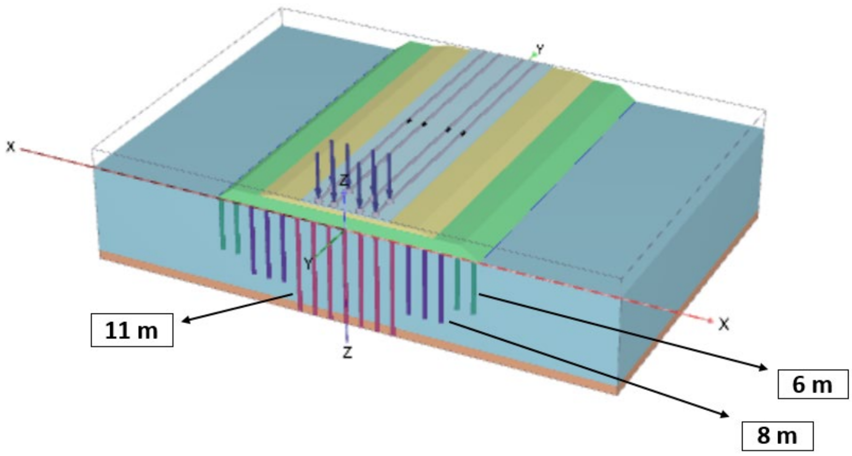


Figure 3.41: 3D FE model created in PLAXIS 3D to demonstrate the reduction in length of the vertical inclusions supporting the batter slopes

It is notable that the length of the vertical inclusions supporting the asphalt road remains constant (11 m for end-bearing columns), while for areas farther from the asphalt road, floating vertical inclusions were modelled with lengths of 8 m and 6 m, respectively, to the edges of the batters.

Upon completing the numerical analysis, it was determined that further research and comprehension are needed for the following two reasons:

- For the case of VSC, the models failed due to insufficient lateral and base confinement of floating columns.
- For the case of CMC, settlement profile shows a noticeable differential settlement between the edges of the batters and the buffer zone.

Figure 3.42 shows the settlement profile for the case involving CMC.

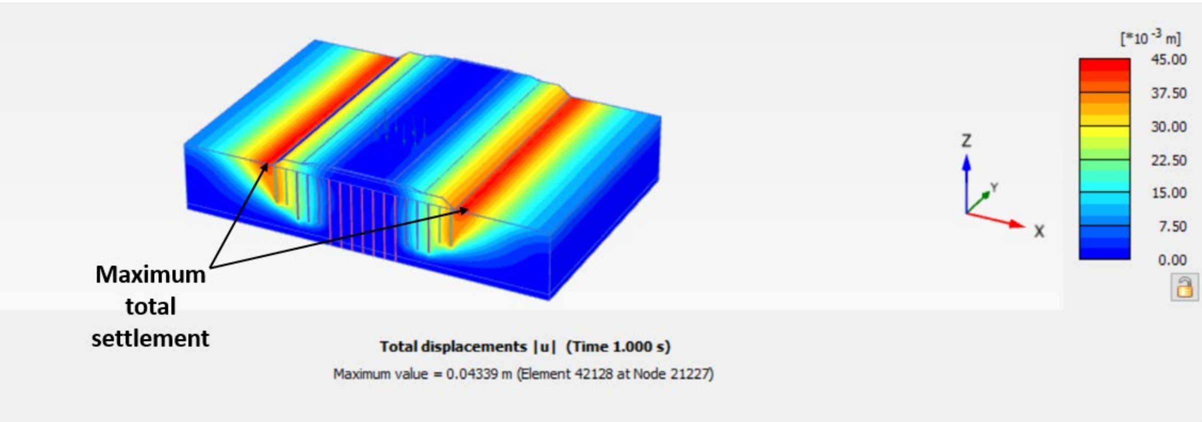


Figure 3.42: Settlement profile for the numerical model with varying lengths of CMC inclusions under the batter slopes

As can be seen, a maximum total settlement of approximately 45 mm is observed at the edges of the batters, which can lead to cracks and thus, requires further investigation.

3.4.15 Effects of the Modulus of Elasticity (E) of Materials Used for Vertical Inclusions

In this section, an investigation was carried out to examine the impact of the modulus of elasticity (E) on vertical inclusions under both end-bearing and floating conditions. For Vibro Stone Column (VSC) scenarios, a reference modulus of elasticity of E = 100 kPa was used. Numerical models were developed with a range of E values from 60 kPa to 160 kPa to comprehensively analyse the variations in behaviour. Figure 3.43 illustrates the effects of changes in the modulus of elasticity of the used aggregates for end-bearing and floating VSC, as well as their comparison.

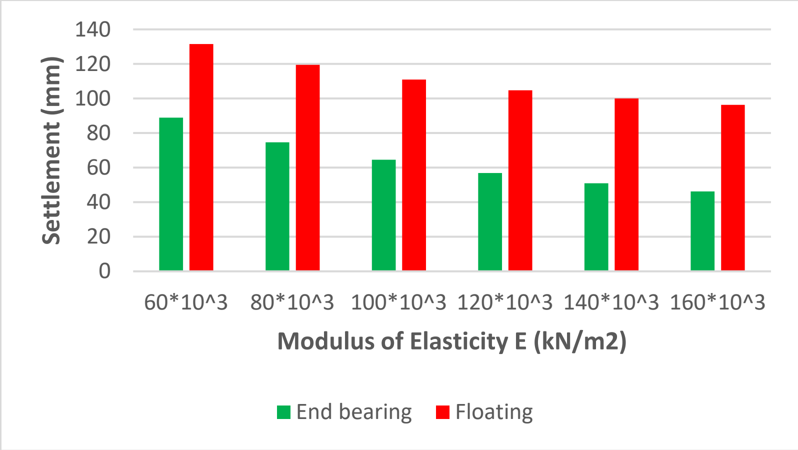


Figure 3.43: The effects of changes in the modulus of elasticity of the used aggregates for end-bearing and floating VSC, as well as their settlement comparison at the ground surface

According to the results shown in Figure 3.43, increasing the modulus of elasticity significantly reduces overall settlement for both end-bearing and floating VSC. As expected, floating VSC are less effective in reducing settlement. Notably, the settlement reduction achieved by a floating VSC with E = 160 kPa is approximately equivalent to that of an end-bearing VSC with E = 60 kPa. This finding indicates that in situations where end-bearing options are impractical due to ground conditions or cost considerations, increasing the modulus of elasticity of the aggregates can be highly beneficial in mitigating settlement and meeting design requirements. For the case of Controlled Modulus Columns (CMC), an investigation was conducted under both end-bearing and floating conditions. A reference modulus of elasticity of E = 10 MPa was used. Numerical models were developed with a range of E values from 5 MPa to 20 MPa to thoroughly analyse the effects. Figure 3.44 illustrates the effects of changes in the modulus of elasticity of the used concrete for end-bearing and floating CMC, as well as their comparison.

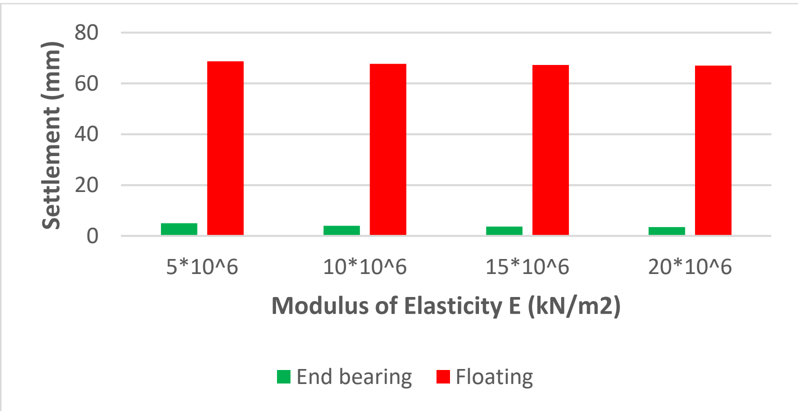


Figure 3.44: The effects of changes in the modulus of elasticity of the used concrete for end-bearing and floating CMC, as well as their settlement comparison at the ground surface

The results presented in Figure 3.44 indicate that for both end-bearing and floating CMC, increasing the modulus of elasticity has a negligible effect on overall ground settlement. Notably, floating CMCs are significantly less effective in reducing settlement compared to end-bearing solutions. For instance, when E = 10 MPa, end-bearing CMC reduces ground settlement to just 4 mm, whereas floating CMC with the same modulus mitigate settlement to 68 mm. This demonstrates that end-bearing CMCs are 17 times more efficient than floating CMC in this particular scenario.

The investigation of bi-modulus columns (BMC) considered both end-bearing and floating scenarios of the optimal BMC configuration. This configuration, as determined previously, consists of a 1.5 m section of vibro stone column (VSC) at the top and an 8.5 m section of concrete modulus column (CMC) at the bottom. For the VSC portion, an elastic modulus (E) of 100 kPa was used as a reference. Various numerical models were developed with E values ranging from 60 kPa to 160 kPa to explore different conditions. Figure 3.45 illustrates the effects of changes in the modulus of elasticity of the VSC section on end-bearing and floating BMC, as well as their comparison.

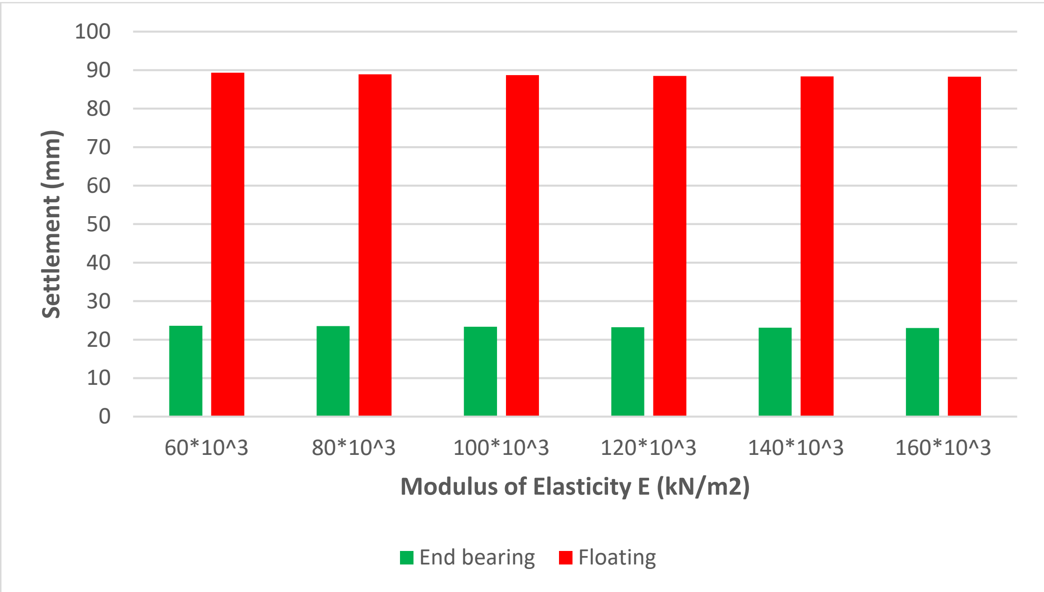


Figure 3.45: The effects of changes in the modulus of elasticity of the VSC section on end-bearing and floating BMC, as well as their settlement comparison at the ground surface

The results depicted in Figure 3.45 indicate that for both end-bearing and floating bi-modulus inclusions, increasing the modulus of elasticity of the VSC section has a minimal impact on overall ground settlement. This is likely because the VSC section constitutes only 1.5 m, or 14%, of the total 11 m bi-modulus inclusion. Furthermore, it is evident that floating bi-modulus columns are considerably less effective in reducing settlement compared to end-bearing solutions, being 3.8 times less efficient in this specific instance.

For the CMC section, an elastic modulus (E) of 10 MPa was used as the reference. To investigate different conditions, various numerical models were developed with E values ranging from 5 MPa to 20 MPa. Figure 3.46 shows the impact of changes in the modulus of elasticity of the CMC section on both end-bearing and floating BMC, along with a comparison of these effects.

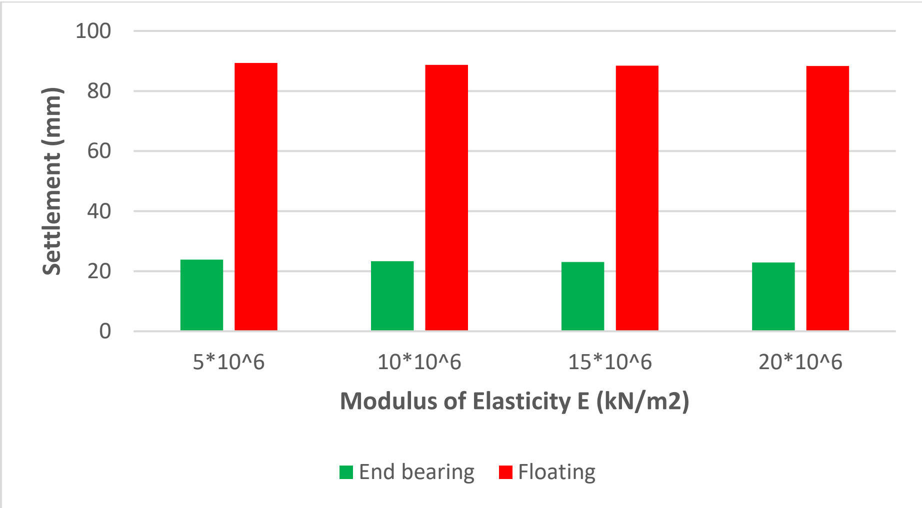


Figure 3.46: The impact of changes in the modulus of elasticity of the CMC section on both end-bearing and floating BMC, along with a settlement comparison at the ground surface

The results shown in Figure 3.46 indicate that for both end-bearing and floating bi-modulus inclusions, increasing the modulus of elasticity of the CMC section has a negligible effect on overall ground settlement. This minimal impact is likely due to the fact that, unlike VSC inclusions, variations in the modulus of elasticity for the CMC section are insignificant.

3.4.16 Effects of the Density (γ) of Materials Used for Vertical Inclusions

This section investigates the impact of the density (γ) of materials used in vertical inclusions under both end-bearing and floating conditions. For Vibro Stone Column (VSC) scenarios, a reference density of $\gamma = 18$ kN/m³ was used. Numerical models were developed with γ values ranging from 16 kN/m³ to 20 kN/m³ to thoroughly analyse behavioural variations. Figure 3.47 illustrates the effects of changes in the density of the used aggregates for both end-bearing and floating VSC, along with a comparison of these effects.

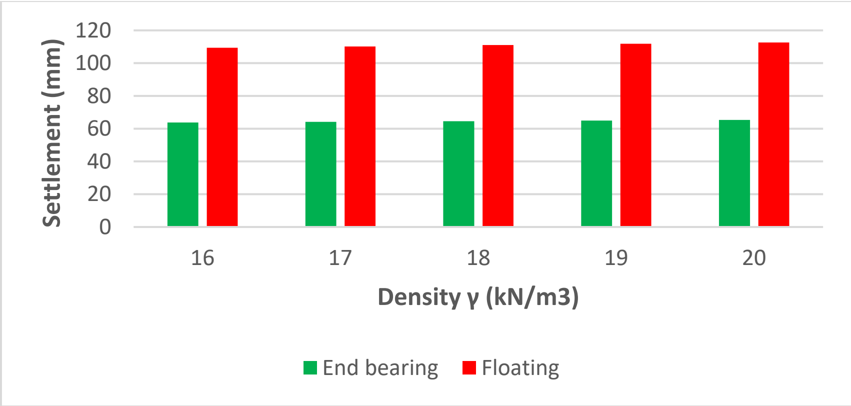


Figure 3.47: The effects of changes in the density of the used aggregates for both end-bearing and floating VSC, along with a settlement comparison at the ground surface

The results shown in Figure 3.47 indicate that for both end-bearing and floating VSC, increasing the density of the materials has a negligible effect on overall ground settlement. As anticipated, floating VSC are less efficient in reducing settlement. Interestingly, since variations in the density of VSC aggregates do not improve column efficiency, less dense and more cost-effective materials, such as quarry dust or disposable tire waste, can be used to construct VSCs without sacrificing performance compared to more expensive alternatives.

For the case of Controlled Modulus Columns (CMC), an investigation was conducted under both end-bearing and floating conditions, utilizing a reference density of γ = 25 kN/m³. Numerical models were developed with γ values ranging from 21 kN/m³ to 26 kN/m³ to comprehensively analyse the effects. Figure 3.48 illustrates the impact of changes in the density of the concrete used for both end-bearing and floating CMC, along with a comparative analysis of these effects.

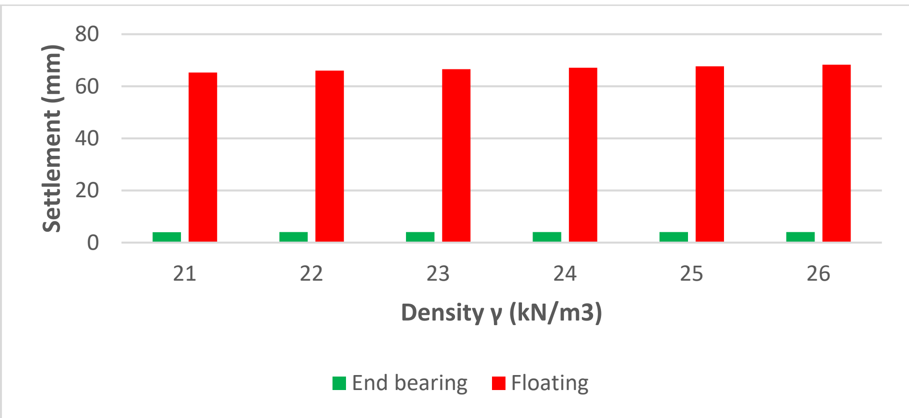


Figure 3.48: The impact of changes in the density of the concrete used for both end-bearing and floating CMC, along with a comparative settlement analysis at the ground surface

The findings depicted in Figure 3.48 suggest that increasing the density value has minimal impact on overall ground settlement for both end-bearing and floating CMC configurations. It is evident that floating CMCs are considerably less effective in reducing settlement. Given that adjustments in concrete density do not enhance the efficiency of CMC columns, employing less dense and more cost-effective concrete could be a viable option without compromising the achieved settlement reduction by CMC.

The investigation into bi-modulus columns (BMC) examined both end-bearing and floating scenarios to determine the optimal BMC configuration. This configuration comprises a 1.5 m vibro stone column (VSC) section at the top and an 8.5 m concrete modulus column (CMC) section at the bottom. For the VSC section, a density (γ) of 18 kN/m³ was used as a reference. Various numerical models were developed, with γ values ranging from 16 kN/m³ to 20 kN/m³, to investigate different conditions. Figure 3.49 illustrates the impact of changes in the density of the VSC section on both end-bearing and floating BMC, alongside a comparison of their effects.

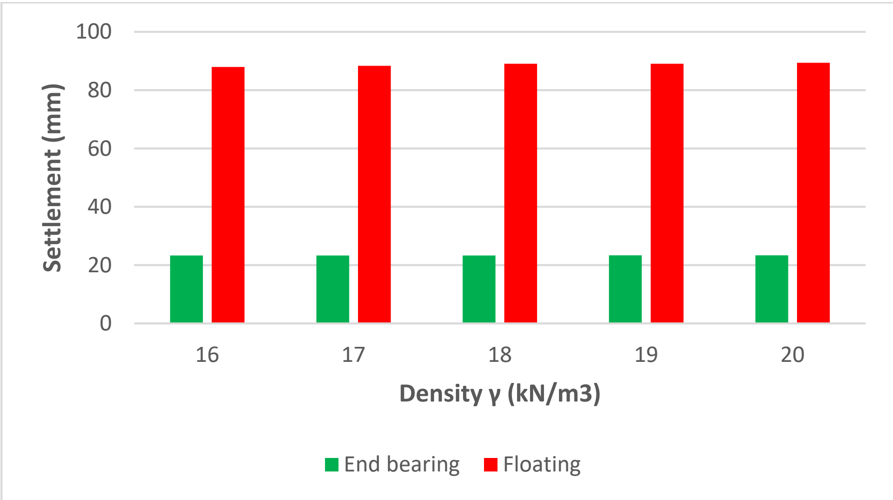


Figure 3.49: The impact of changes in the density of the VSC section on both end-bearing and floating BMC, alongside a settlement comparison at the ground surface

Based on the findings presented in Figure 3:49, it is apparent that elevating the density of the VSC section has minimal impact on overall ground settlement for both end-bearing and floating bi-modulus inclusions. As expected, floating bi-modulus inclusions demonstrate notably lower efficiency in reducing settlement compared to the end-bearing solution.

For the CMC section, a density (γ) of 25 kN/m³ was used as the reference. To explore various conditions, several numerical models were developed with γ values ranging from 21 kN/m³ to 26 kN/m³. Figure 3.50 illustrates the influence of variations in the density of the CMC section on both end-bearing and floating BMC, along with a comparative analysis of these effects.

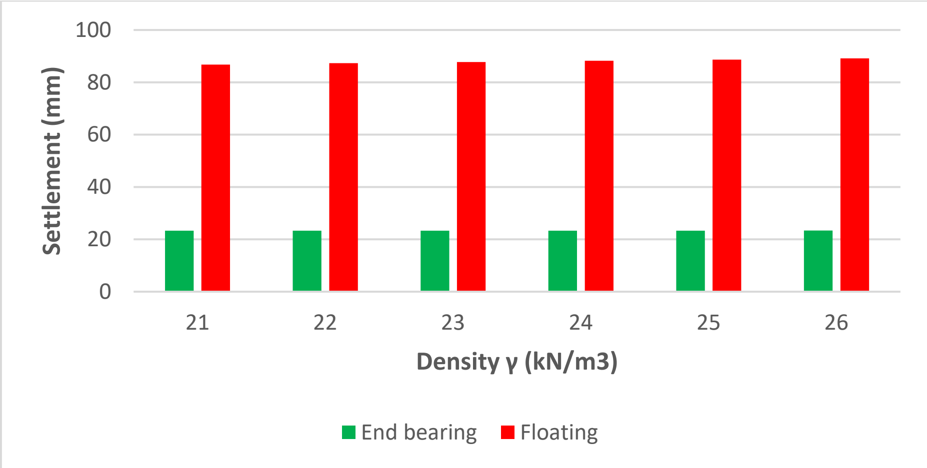


Figure 3.50: The influence of variations in the density of the CMC section on both end-bearing and floating BMC, along with a comparative settlement analysis at the ground surface

The findings depicted in Figure 3.50 indicate that elevating the density value of the CMC section has minimal impact on overall ground settlement for both end-bearing and floating bi-modulus inclusions.

3.4.17 Effect of the Degree of Friction (M) of Soil Particles Reinforced by Vertical Inclusions on the Overall Settlement of the Treated Ground

In this section, the investigation delves into the impact of the degree of friction (M) of soil particles reinforced by vertical inclusions, considering both end-bearing and floating scenarios. A reference degree of friction (M) equal to 1.2 was utilized. Numerical models were meticulously crafted, encompassing a range of M values from 0.5 to 1.5 to comprehensively assess behavioural nuances. Figure 3.51 portrays the impacts of altering the degree of friction (M) within clayey soil reinforced by both end-bearing and floating VSC, offering a comparative analysis of these effects.

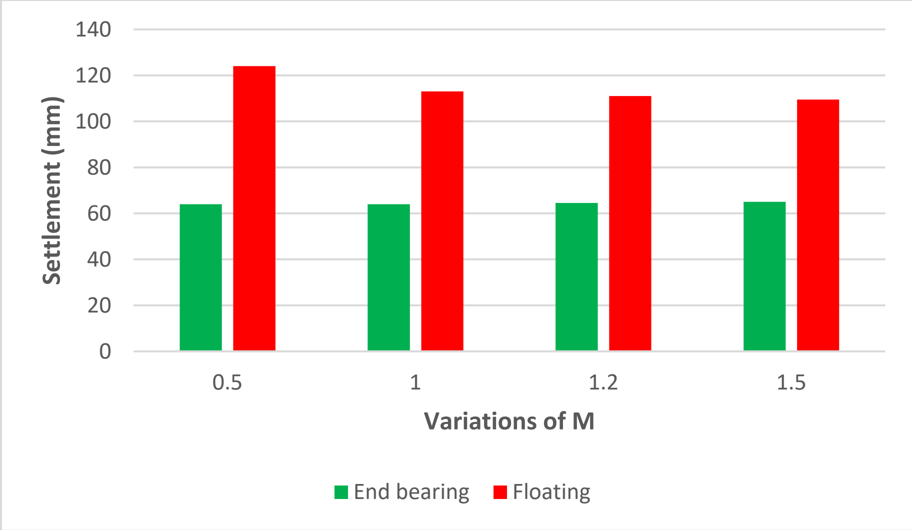


Figure 3.51: The impacts of altering the degree of friction (M) within clayey soil reinforced by both end-bearing and floating VSC, along with a comparative settlement analysis at the ground surface

The findings depicted in Figure 3.51 indicate that raising the value of M for floating VSC leads to a slightly lower ground settlement. In contrast, for end-bearing VSC, the variation in M values appears to be insignificant.

Figure 3.52 illustrates the impacts of altering the degree of friction (M) within clayey soil reinforced by both end-bearing and floating CMC, offering a comparative analysis of these effects.

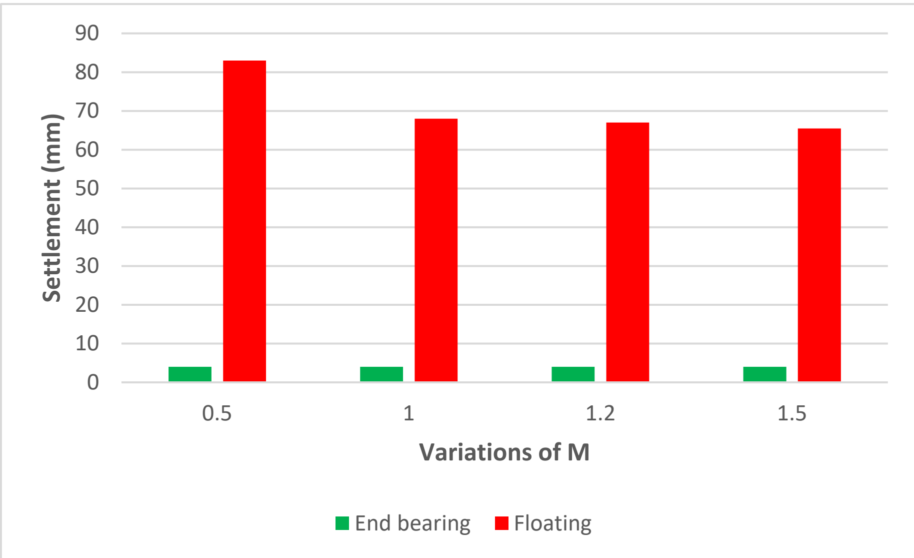


Figure 3.52: The impacts of altering the degree of friction (M) within clayey soil reinforced by both end-bearing and floating CMC, along with a comparative settlement analysis at the ground surface

Based on the findings presented in Figure 3.52, it is evident that augmenting the value of M for floating CMC leads to a reduction in ground settlement. However, for end-bearing CMC, variations in M values appear to have negligible impact. As anticipated, regardless of the degree of friction of the soil, floating CMCs demonstrate significantly lower efficiency in settlement reduction compared to the end-bearing solution (Approximately 21 times less effective in this particular example).

Figure 3.53 presents the effects of modifying the degree of friction (M) in clayey soil reinforced by both end-bearing and floating BMC, providing a comparative assessment of these effects.

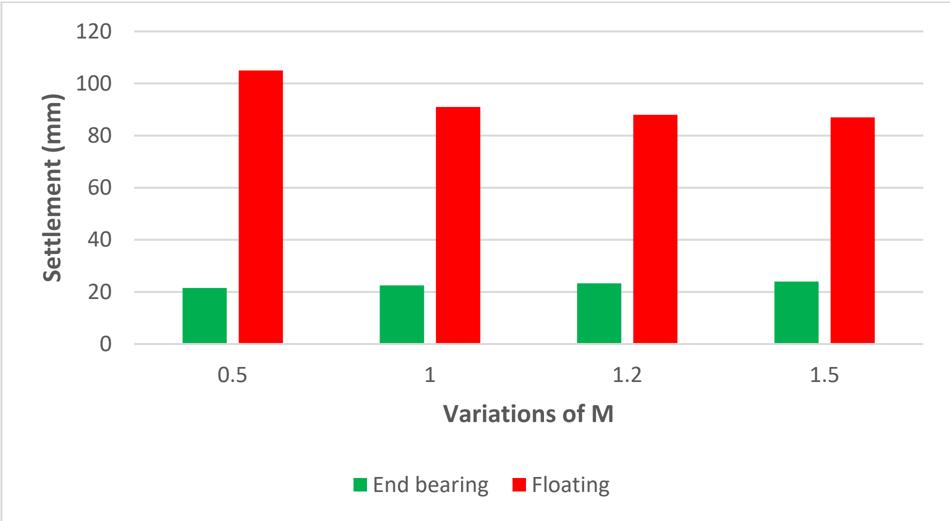


Figure 3.53: The effects of modifying the degree of friction (M) in clayey soil reinforced by both end-bearing and floating BMC, along with a comparative settlement analysis at the ground surface

Based on the findings depicted in Figure 3.53, it is apparent that elevating the value of M for floating bi-modulus inclusions leads to reduced ground settlement. Conversely, for end-bearing bi-modulus inclusions, the variation in M values appears to marginally increase ground settlement, albeit to a negligible extent.

3.4.18 Effect of Lambda (λ) (Compression Index) and Kappa (κ) (Swelling Index) of the Soft Clay Layer Reinforced by Vertical Inclusions on the Overall Settlement of the Treated Ground

This section investigates the impact of Lambda (λ) (Compression Index) and Kappa (κ) (Swelling Index) of the soft clay layer reinforced by both floating and end-bearing vertical inclusions on the overall settlement of the treated ground. $\lambda=0.8$ was used as a reference. Additionally, λ was taken to be 5 times greater than κ, irrespective of the value of λ. Numerical models were developed with λ values ranging from 0.6 to 3 to thoroughly analyse behavioural variations. Figure 3.54 illustrates the effects of changes in the compression index (λ) of the clayey soil reinforced by both end-bearing and floating VSC, along with a comparison of these effects.

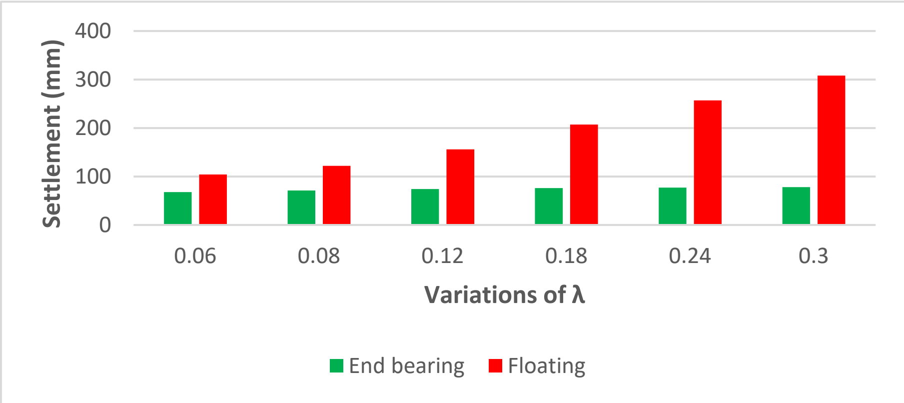


Figure 3.54: The effects of changes in the compression index (λ) of the clayey soil reinforced by both end-bearing and floating VSC, along with a settlement comparison at the ground surface

According to the findings depicted in Figure 3.54, it is apparent that raising the value of λ for floating VSC results in a significant increase in ground settlement. In contrast, for end-bearing VSC, variations in λ values appear to have minimal effects on overall settlement (approximately 10%).

Figure 3.55 presents the impacts of altering the compression index (λ) of the clayey soil reinforced by both end-bearing and floating CMC, providing a comparative analysis of these effects.

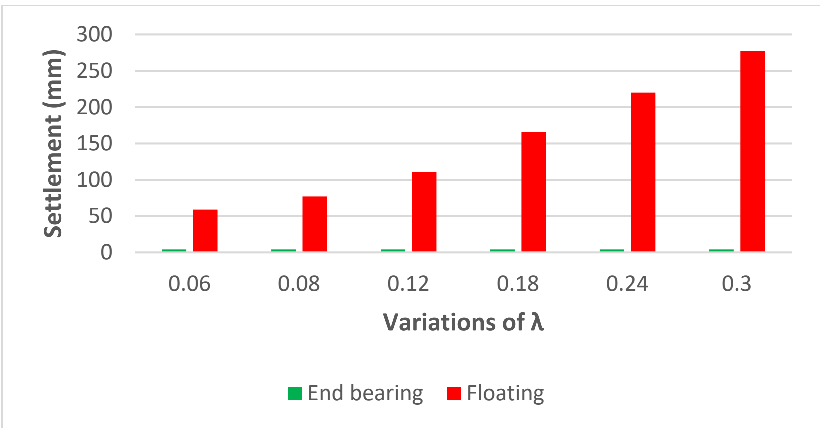


Figure 3.55: The effects of changes in the compression index (λ) of the clayey soil reinforced by both end-bearing and floating CMC, along with a settlement comparison at the ground surface

The findings illustrated in Figure 3.55 reveal that elevating the value of λ for floating CMC results in a substantial increase in ground settlement. Conversely, for end-bearing CMC, variations in λ values appear to have no major impact. It is evident that floating CMC exhibit significantly lower efficiency in reducing settlement compared to the end-bearing solution (Approximately 69 times less effective in this particular example).

Figure 3.56 presents the impacts of altering the compression index (λ) of the clayey soil reinforced by both end-bearing and floating CMC, providing a comparative analysis of these effects.

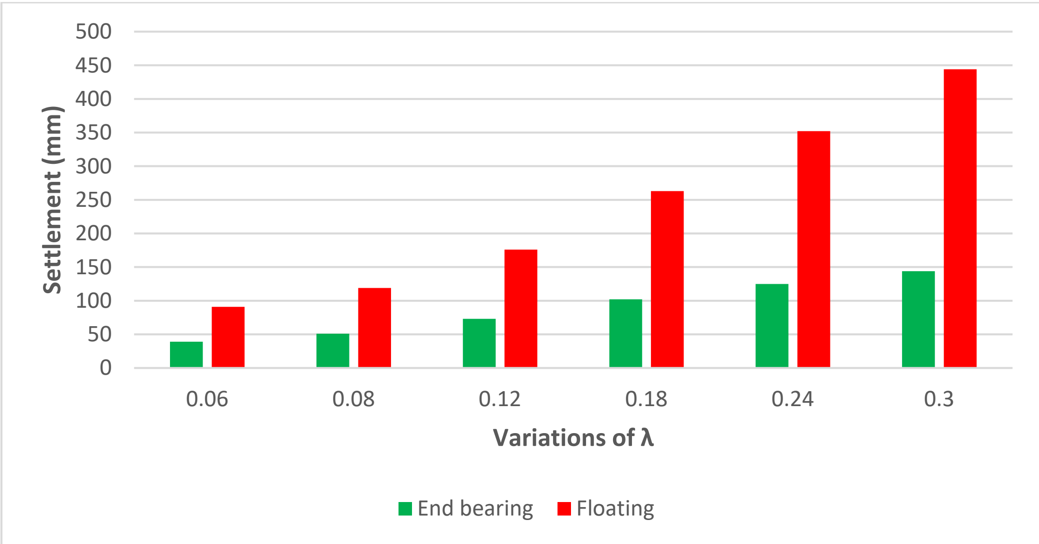


Figure 3.56: The effects of changes in the compression index (λ) of the clayey soil reinforced by both end-bearing and floating BMC, along with a settlement comparison at the ground surface

According to the results shown in Figure 3.56, it is obvious that increasing the value of λ for floating bi-modulus inclusions greatly increases the ground settlement to a massive extent. For end-bearing bi-modulus inclusions, unlike the VSC and CMC scenarios, the variation of λ does have a major effect on ground settlement but less than the floating bi-modulus scenario.

3.5 Validation of the Adopted Numerical Method

In this section, in order to ensure reliable results, the data acquired from field measurements of a real-world project are compared with the numerical analysis findings. To delve into the load-settlement characteristics of reinforced soft ground, an extensive study was conducted in a specific geological setting. The investigation took place within a soft, compressible marine clay deposit situated along the north-eastern coastal region of New South Wales, Australia. This region was chosen due to its relevance in understanding the behaviour of such ground formations, particularly concerning infrastructure development and stability. The study commenced with the installation of a group of stone columns within the soft clay deposit. These columns, totalling 50 in number (5 × 10), were meticulously installed by Keller Ground Engineering, a renowned firm known for its expertise in ground reinforcement techniques. The columns were arranged in a square grid pattern, strategically placed to reinforce the ground effectively. The dimensions of the stone columns were carefully selected to optimize their reinforcement capabilities. Three target diameters were employed: 0.8 m, 1 m, and 1.2 m. These variations in diameter were intended to investigate their respective impacts on the overall performance of the reinforced ground system. Subsequently, the focus of the study shifted towards the construction of a square eastern embankment atop the reinforced ground surface. This embankment was constructed in several stages, allowing for a comprehensive analysis of the load-settlement characteristics at various points during the construction process. Figure 3.57 provides a visual representation of the layout and arrangement of the stone columns within the reinforced ground area.

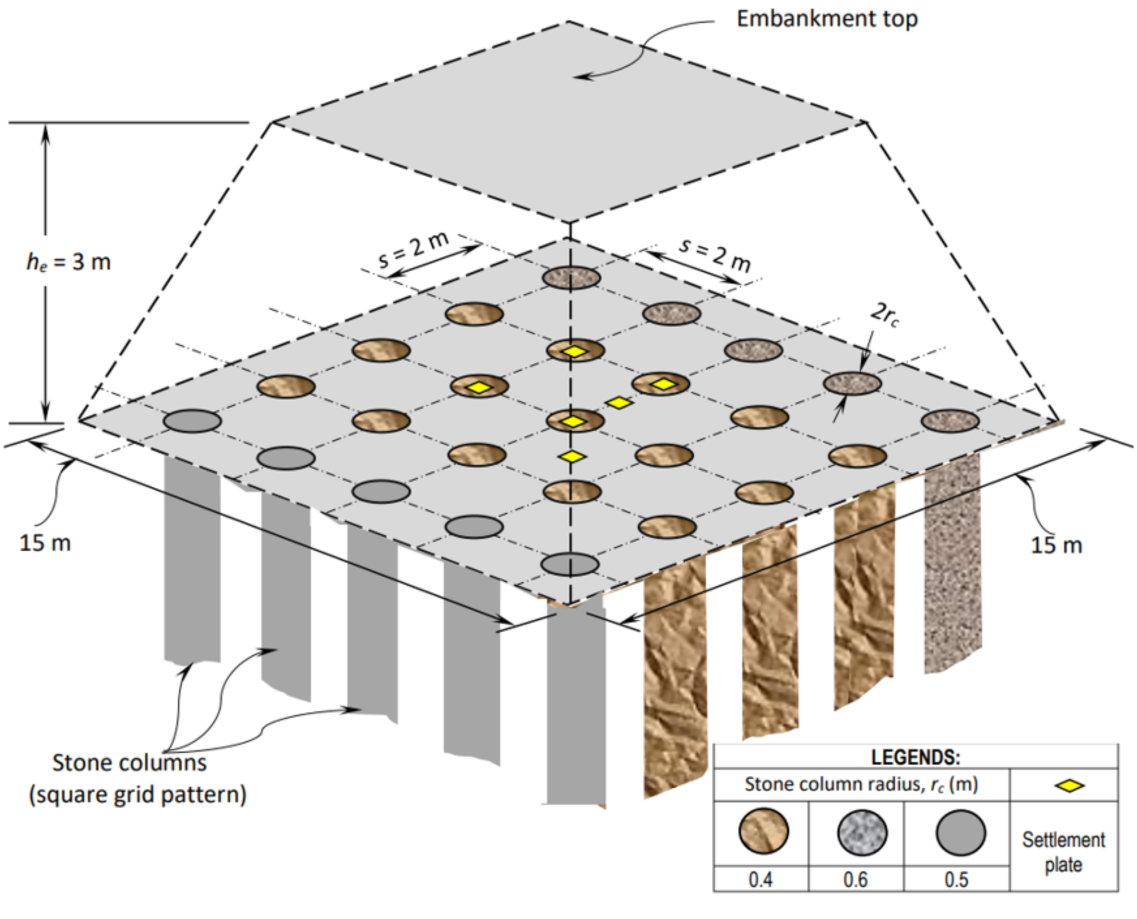
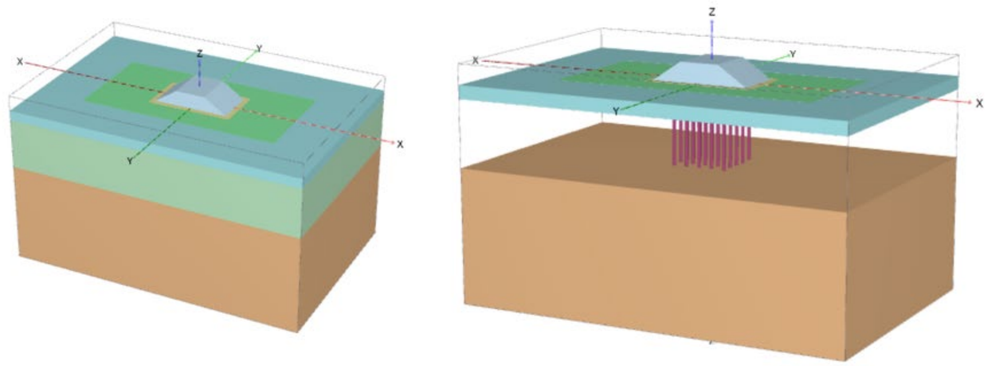


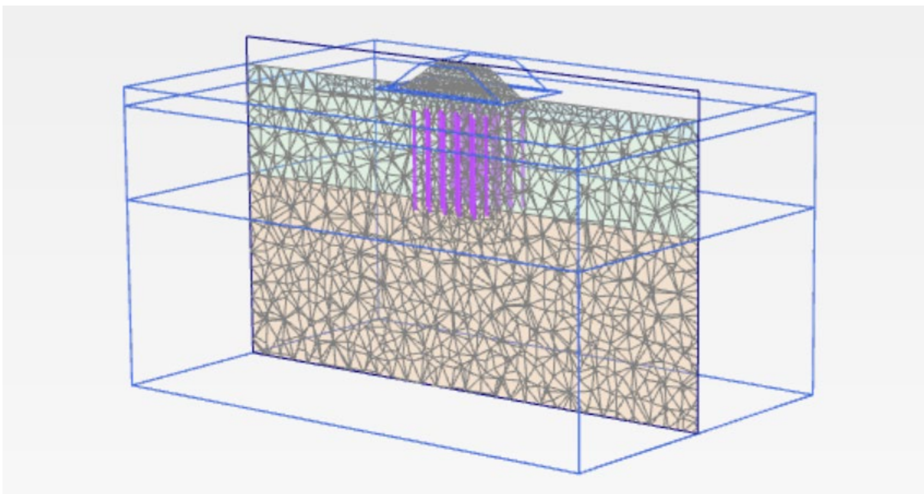
Figure 3.57: Sketch of stone column reinforcement and embankment of a ground improvement project in NSW, Australia

The stone columns were installed up to a depth of 10.5 m below the ground surface. A layer of angular railway ballast, with an average size of 40-80 mm, was placed and compacted on top of the stone columns, resulting in a finished ballast layer with an average thickness of 1 m. Thereafter, a sand blanket with an average thickness of 50 mm was placed on top of the finished ballast layer. The embankment was then constructed using silty sand reclaimed from a nearby local site and compacted at an optimum moisture content.

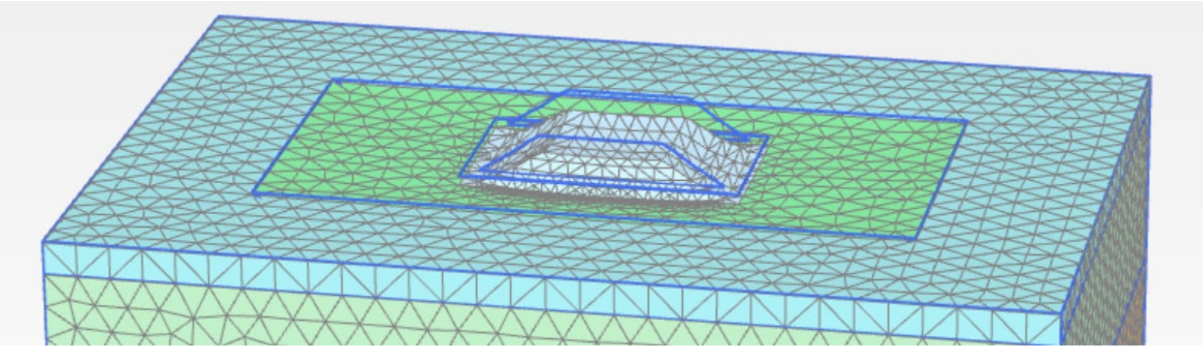
The resulting ground settlement was measured using a number of settlement plates installed for on-site monitoring during construction. To validate the numerical analysis presented in this thesis, a three-dimensional finite element analysis was conducted utilizing PLAXIS 3D to generate a precise 3D model of the ground improvement project. Figure 3.58 shows: a) The precisely simulated numerical model of the project in PLAXIS 3D; b) The three-dimensional mesh cross-section before settlement; c) The deformed mesh after embankment's settlement; and d) The settlement profile of the numerical model.



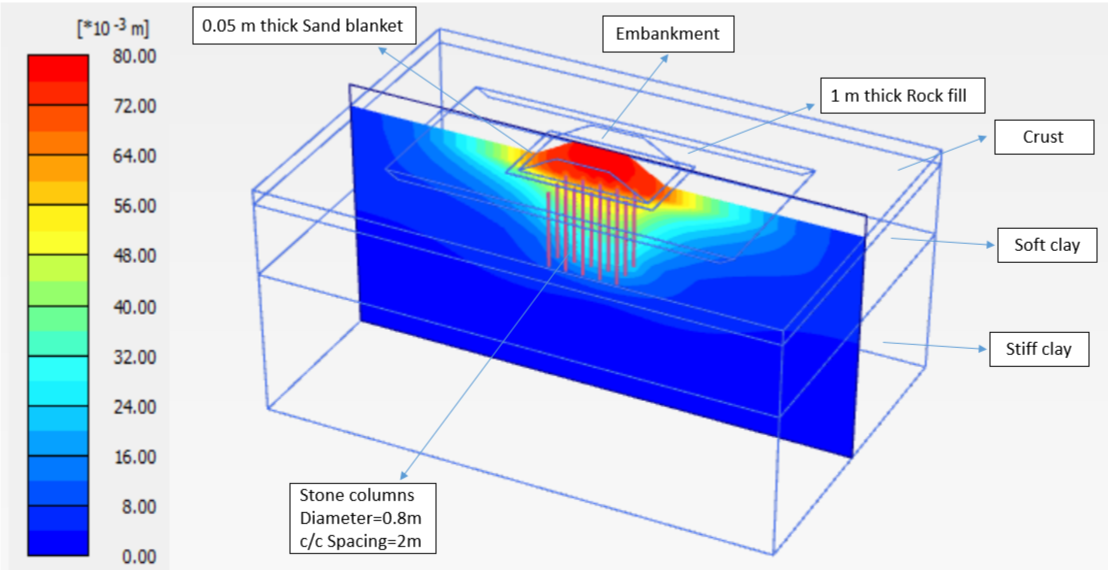
a)



b)



c)



d)

Figure 3.58: a) 3D finite element model of the embankment constructed on stone column reinforced soft soil; b) Model cross section; c) Deformed mesh after embankment's settlement; d) The three dimensional settlement profile of the numerical model calculated by PLAXIS 3D

According to Figure 3.58d, it can be seen that the maximum settlement of approximately 80 mm occurs at the centre of the embankment area, with a reduction pattern towards the edges of the embankment. The effectiveness of the stone columns in settlement control is evident. The numerical findings are then compared with field measurements to validate the accuracy of FE predictions. Figure 3.59 illustrates the correlation between the predicted results and the actual field data.

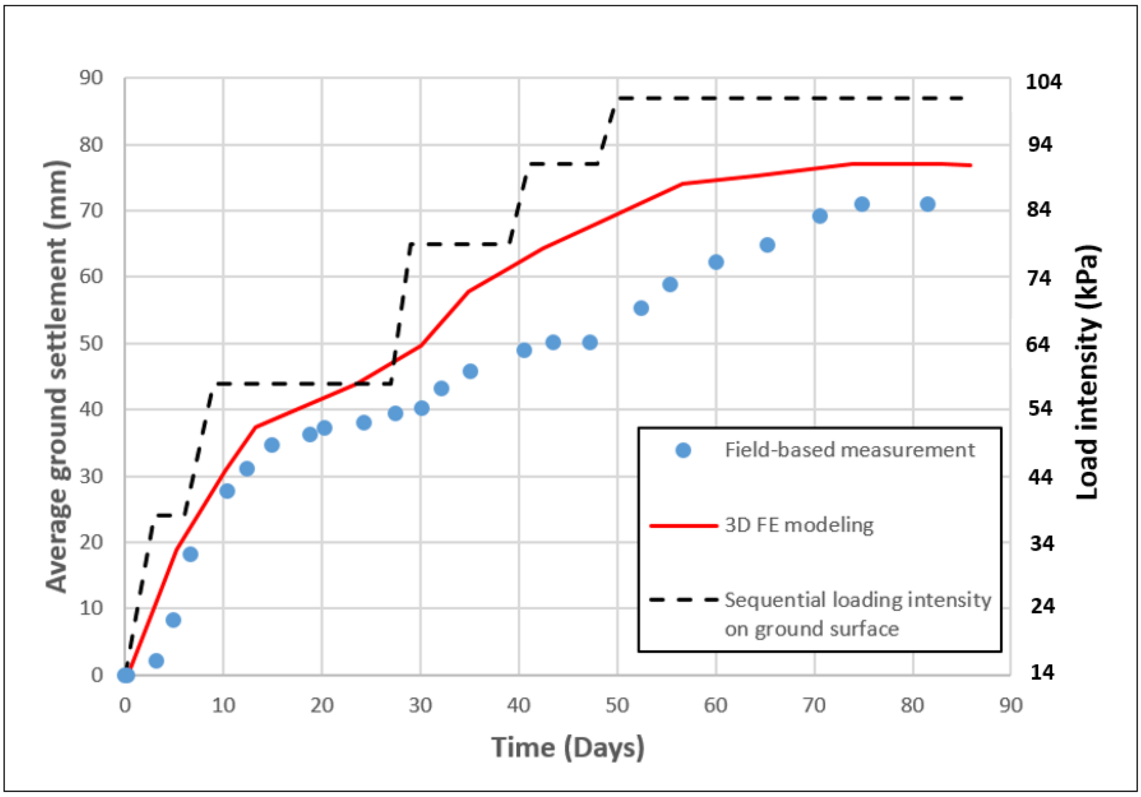


Figure 3.59: Comparison between FEM and field data

As evident from the graph displayed in Figure 3.59, the results predicted using the FE method are in good agreement with the field-based measurements. Therefore, the accuracy of the numerical modelling is validated, as the FE modelling line (presented by a red line) follows a similar path to the field-based measurements (indicated by blue circles). However, the results obtained from the numerical modelling are conservative, with a maximum consolidated settlement reading of 77 mm for FE modelling, while the field data measurements show a maximum value of just above 71 mm.

3.6 Discussion and Recommendations

According to the results of this numerical investigation, the following conclusions can be drawn:

- Vertical inclusions are extremely consequential with respect to increasing the bearing capacity of the shallow ground and reducing ground settlement.
- As anticipated, the CMC technique proves to be the most effective vertical inclusion for ground improvement and significant mitigation of settlement.

- Among floating and end-bearing vertical inclusions, the latter offers greater benefits in terms of reducing ground settlement. Nevertheless, the decision to opt for the end-bearing option depends on factors such as ground conditions and cost-effectiveness.
- Bi-modulus columns represent a relatively novel approach in ground improvement techniques. They offer significant advantages by addressing issues such as the mushroom effect resulting from the rigidity of CMC inclusions, while also effectively reducing settlement.
- The impact of dynamic loading on ground settlement is minimal, but it is concluded that an increase in speed decreases settlement regardless of whether ground improvement techniques are employed.
- The Load Transfer Platform (LTP) plays a crucial role in ground improvement projects utilizing vertical inclusions, and the thickness of the LTP can influence the overall settlement outcome.
- For the most conservative design, it is preferable to assume the water table is at ground level.
- As anticipated, vibro stone columns are the least effective vertical inclusions for reducing ground settlement.
- The spacing between vertical inclusions is the primary design factor determining the permissible settlement of the ground.
- The geotechnical properties of the soil particles are very consequential in the settlement analysis of reinforced ground with floating vertical inclusions.
- Additional research is needed regarding ground improvement in the area of embankment batter slopes.

For future research endeavours, it is advised that investigators conduct further studies on floating vertical inclusions under dynamic loading conditions to comprehensively understand the effects of speed in such scenarios. Additionally, enhancing vertical inclusions as cost-effective techniques for reinforcing weak ground and soft soil with low bearing capacity could yield substantial benefits for both urban and rural areas in the development and maintenance of transportation structures. Such improvements may lead to increased stability, reduced maintenance costs, and enhanced overall performance of infrastructure systems.

4

Interview with Experts

4.1 Introduction

This chapter highlights the insights from experts, drawing on their practical experiences with the application of vertical inclusion ground improvement techniques in real-world projects. The interviewees were chosen from diverse geographical regions and held various positions within their respective fields. Each interviewee brought unique expertise and experiences to the table, enriching the discussion with nuanced insights. Their responses were curated to reflect both the advantages and limitations of the vertical inclusions ground improvement technique within their specific regions. This approach has ensured a wide-ranging understanding of the applications of techniques and challenges across different global contexts. Table 4.1 serves as a concise introduction to the diverse array of interviewees, underlining their geographic locations and areas of expertise.

Table 4.1: List of interviewees

Number	Name of interviewees	Category	Affiliation	Country of practice
1	Dr Babak Hamidi	Industry	Menard, Oceania	Australia/Iran
2	Professor Sudip Basack	Academic	IIEST, Shibpur	India
3	Mr Jerome Racinais	Industry	Menard, France	France(Europe)
4	Dr Martin Larisch	Self-employed	Larisch Consulting	Germany/New Zealand
5	Dr Adnan Sahyouni	Industry	Menard, Oceania	Australia/France
6	Mr Philippe Vincent	Industry	Menard, Oceania	France/Australia
7	Mr Ondrej Synac	Industry	Tetra Tec Coffey	Czech/Australia
8	Dr Zaman	Industry	Transport for NSW	Australia/Bangladesh
9	Mr Mehdi Hajian	Self-employed	Geostructdesigns	Australia
10	Mr Michal Krzeminski	Industry	Keller, Australia	Poland/Australia

The author, currently pursuing his PhD, collaborated with his supervisor, to conduct many interviews with industry experts. These meetings were orchestrated with the specific goal of acquiring insights, expertise, and firsthand accounts related to the research topic. Through these interactions, a wealth of valuable perspectives crucial for the advancement of the research project were obtained. This exchange of ideas served to enrich the depth and breadth of understanding within the study. In essence, the interviews with industry experts were not just a means to an end but rather a vital component of the research journey, illuminating pathways to new discoveries and enriching the scholarly discourse surrounding the topic. Figure 4.1 presents the images of interviewers.

Figure 4.1: Interviewers, PhD candidate, Yashar Salehi, and his supervisor, Hadi Khabbaz

These interviews were conducted with the aim of clarification of the following major factors:

- Conducting detailed comparison between vibro stone columns (VSC) and controlled modulus columns (CMC) techniques in terms of design, application, settlement mitigation, sustainability, and limitations.
- Exploring various methods to enhance the aforementioned techniques.
- Employing bi-modulus columns as an innovative method to investigate their advantages and challenges.

This chapter also seeks to discover the interviewee's responses with respect to the cost effectiveness of these techniques and the reasoning behind it. This information is used in Chapter 5, which addresses the cost of these ground improvement practices.

Prior to presenting the research findings regarding the application of vertical inclusions based on insights from industry experts, concise biographies of the interviewees will be provided.

It should be noted that all the interviewees find the research topic very interesting and they considered it a significant investigation in order to optimise the utilisation of these ground improvement techniques.

In the following sections, the interviewees are briefly introduced, followed by the questions posed to them and their respective responses.

4.2 Interviewees' Responses to Key Questions

In this section the details of interviews questions and response are outlined.

4.2.1 Interviewee 1 (Dr Babak Hamidi)

Dr Hamidi is a distinguished technical and commercial geotechnical expert, boasting over two decades of prolific experience within the industry. His portfolio encompasses involvement in Australia's esteemed projects characterized by intricate deep foundations, challenging excavations, and ground improvement initiatives, alongside contributions to ground-breaking geotechnical endeavours worldwide. Dr Hamidi is renowned for his adeptness in navigating projects from inception to completion, showcasing not only technical prowess but also a keen understanding of commercial dynamics. Collaborating with eminent geotechnical engineers globally, he has cultivated a wealth of expertise, drawing from a spectrum of innovative and demanding projects. Currently serving as the lead geotechnical engineer at Menard Oceania, Dr Hamidi also holds the prestigious position of Chair for the ISSMGE TC211 (Ground Improvement Technical Committee), further solidifying his prominence in the field.

Dr Hamidi recommended to use the word CMC (rigid inclusions) instead of CIC to be internationally recognizable as CIC is a term that is used by TfNSW only, which would not be understood by others. He also mentioned that certain individuals are opting to avoid the term "CIC" and instead are referring to it as "rigid inclusions”. Figure 4.2 depicts the image of interviewee 1, Dr Babak Hamidi.

Figure 4.2: Interviewee 1, Dr Babak Hamidi

The following questions were asked and the answers of the interviewee are provided.

- **The range of length of the columns for both CMC and VSC?**

Dr Hamidi asserted that the variability in column lengths is contingent upon the capabilities of equipment, including the torque output of machinery employed, thereby enabling the installation of narrower diameter columns to greater depths.

For CMC:

The shallowest installation conducted by Dr Hamidi measured at 4 m, though depths can vary. Conversely, the deepest installations in Australia reached 34.5 m at Perth's Optus Stadium, while globally, depths have reached 42 m along the coast of the Mississippi River.

For VSC:

The greatest depth recorded stands at 76 m in Germany; however, stone columns typically range between 25 and 30 m in length. Installation of these columns usually involves a vibro-float suspended from a crane, which is propelled by its own weight, aided by water flushing and vibration. Beyond depths of 25 to 30 m, frictional resistance may present a constraint, necessitating the use of alternative, less conventional penetration techniques.

- **The range of diameter of the columns for both CMC and VSC?**

For CMC:

According to Dr Hamidi, the smaller the diameter, the more desirable for various reasons such as less spacing between the columns and narrower LTP. As such, the system would have more pseudo-redundancy and if one of them fails the whole system would not fail once diameter and spacing are small. In addition, the failure would become very much localised. This is of course different than if the design is problematic and the system, as a whole, fails to satisfy the criteria.
The minimum diameter found in Australia is 280 mm, while the maximum diameter, installed by the interviewee, reaches 600 mm.

For VSC:

The smallest diameter is in the order of 600 mm and the largest is in the order of 1.2 m. Dr Hamidi has undertaken projects in New Zealand involving diameters of 800 mm, indicating that these dimensions represent typical parameters rather than absolute limits. The crucial aspect is that the diameter of the vibroflot tube is approximately 400 mm, suggesting that creating a stone column of the same diameter does not require excessive compaction efforts. Conversely, there is a limit to how much a 400 mm cavity can be enlarged through pushing and vibrational action.

This limit is practical and contingent upon factors such as the power of the vibroflot and the type of soil. Additionally, Dr Hamidi has executed a project in Port Hedland (WA) where the columns measured approximately 1 m in diameter.

- **The range of spacing between the columns for both CMC and VSC?**

For CMC:

Dr Hamidi stated that it is a very crucial item for any project and needs to be checked before anything else.

He explained that when using the displacement CMC drilling tool (which is what most people understand by 'CMC'), the column spacing (S) must be greater than 4D, where D is the diameter of the column. In soft ground, if S is less than 4D, the soil will not have sufficient time to consolidate properly and will undergo plastic deformations that cause ground heave. When the spacing is too tight, installing a new column will exert forces on existing CMC. If the concrete in the previously installed column is still fluid, it can be squeezed out, creating a weakened section. If the concrete has set, this may lead to cracking and even separation of the CMC into two parts.

He further clarified that while theoretically, CMC spacing can be expanded to any desired extent, there exists a practical limit that dictates design considerations, ensuring the maintenance of column size, socket depth, Load Transfer Platform (LTP) thickness, ground slab bending moments, and other relevant factors.

For VSC:

According to Dr Hamidi the typical spacing would be 3D and D= diameter of the column.
24% replacement ratio was the highest done by Dr Hamidi. He noted that the old design method for stone columns is the Preibe method but increasingly, engineers are turning to numerical analysis as their preferred method.

- **What is your opinion with respect to cost effectiveness of any of these 2 techniques?**

Dr Hamidi suggested that there is not a straightforward answer to this question; it varies depending on the circumstances. Generally, stone aggregates tend to be more economical than concrete in terms of material costs. Moreover, employing recycled materials instead of aggregates can potentially lower the material expenses associated with the VSC technique even more. Nevertheless, the production rates of CMC usually range from 2 to 4 times greater than those of VSC. He further argued that in countries such as Australia where labour costs are notably high, CMC tends to be consistently more financially advantageous, unless there are unusual circumstances affecting the cost and availability of concrete. Additionally, Dr Hamidi underscored the importance of feasibility over financial considerations, highlighting that a cost-effective solution that proves ineffective holds no value. There exists a constraint on the extent to which ground settlement can be diminished by stone columns. For example, horizontal pressures within stone columns may surpass ground resistance, resulting in a phenomenon known as barrelling. Consequently, from a technical standpoint, the preferred method tends to be CMC when substantial improvements are necessary.

- **What is your experience about the effectiveness and role of LTP for both techniques?**

Dr Hamidi explained that LTP, formerly known as "Granular Blanket", holds significant importance in the CMC foundation system due to the extreme rigidity of CMC, necessitating precise design. In contrast, for the VSC technique, where columns are semi-rigid, there is not as much sensitivity, but LTP remains a necessary component. However, in both approaches, the LTP serves to distribute forces and mitigate differential settlement at the ground surface. A thin LTP may lead to a surface resembling an egg box, where the columns settle notably less than the areas in between. The thickness of the LTP can be decreased if a ground slab is present, as it aids in reducing differential settlement.

Dr Hamidi confirmed that the thickness of LTP is usually designed according to British standard, $t = 0.7\ (S\text{-}D)$ where S denotes the spacing and D is the equivalent diameter of the columns. However, more recently, it has been observed that the BS method has some deficiencies and does not always result in an acceptable thickness. He further stated that in one of his projects, where the ground was highly compressible, double the thickness recommended by the British Standard was used for the construction of the LTP, indicating that requirements can be site-specific.

- **What is your recommendation with respect to soil suitability for adopting these techniques?**

For CMC:

Dr Hamidi noted that CMC are applicable to a wide range of soil types, encompassing gravel, sand, silts, peat, organic chalk, and various fills, although they are predominantly utilized in soft compressible soils. Historically, they have not been employed for liquefaction mitigation.

However, ongoing research is underway to explore the use of CMC for treating liquefiable soils, suggesting their potential application in the near future.

For VSC:

Dr Hamidi asserted that stone columns remain the primary choice for addressing liquefiable soils. Moreover, he suggested that for ground improvement in offshore environments and onshore sites situated in close proximity to marine areas, they may be the sole viable solution.

- **What is your opinion about the bi-modulus columns?**

Dr Hamidi explained that the technique is relatively new, with limited research conducted in this area thus far. The combination of CMC for the bottom portion and VSC for the top portion of this vertical inclusion presents a promising solution. This hybrid approach has the potential to mitigate mushroom effects and reduce the thickness of the Load Transfer Platform (LTP), addressing common concerns associated with LTP implementation. However, the cost-effectiveness of this method varies depending on several project-specific factors, including the additional expense associated with mobilizing two different plants (one for CMC and one for VSC), which could be considered a drawback. On the other hand, there may be cost savings due to reduced concrete usage, which is a positive aspect to consider. In general, he believes that further research and project-specific analysis are essential for determining the overall feasibility and effectiveness of this technique in different scenarios.

Concluding his remarks, Dr Hamidi expressed appreciation for our research efforts and conveyed his belief in the potential of bi-modulus columns as a relatively novel and, in certain instances, highly advantageous technique. He emphasized his support for further exploration through numerical-based research in this domain, highlighting its importance in advancing understanding and application.

4.2.2 Interviewee 2 (Professor Sudip Basack)

Professor Sudip Basack is a civil engineering professional with significant experience and expertise in geotechnical and geoenvironmental engineering. He has held several responsible senior academic positions in India and abroad. He published more than 125 technical papers in reputed journals and conferences and is recipient of several research awards at national and international levels. He is an active reviewer of numerous top-class international journals. He has supervised more than 10 research students at postgraduate (Masters and PhD) levels and executed sponsored research projects in different Universities. He has undertaken several academic visits in many countries including USA, UK, Germany, Australia, New Zealand, Singapore, China, etc. Figure 4.3 illustrates the image of interviewee 2, Professor Sudip Basack.

Figure 4.3: Interviewee 2, Professor Sudip Basack

The following questions were asked and the answers of the interviewee are provided.

Comparing stone columns with rigid inclusions and bi-modulus columns:

- **In design of stone columns which parameters are more sensitive (Spacing, pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP, traffic load or soil properties)?**

Professor Basack emphasized the significance of various parameters in structural design, yet his research on piles and stone columns highlights the column-to-soil stiffness ratio, denoted as the stress concentration ratio (SCR) as paramount. This ratio, distinct from geometrical considerations, emerges as the principal determinant in stone column design. Upon installation, the column material undergoes consolidation within the ground, leading to inherent bulging effects and subsequent soil consolidation. Consequently, both soil and column stiffness escalate, resulting in an augmentation of the column-to-soil stress concentration ratio. His investigations reveal a progressive increase in this ratio over time, reaching a plateau at a certain juncture, thus establishing it as the predominant design parameter for stone columns.

- **What are the effects of rate of injection pressure and rate of installation for CMC and can these parameters be included in the design phase because sometimes the rigid inclusions are installed very fast and sometimes slow depending on the capability of equipment or based on decision of the person who is running the rig?**

Professor Basack asserted the critical importance of incorporating the parameters under discussion into the design phase. However, he noted a glaring gap in research pertaining to the significance of two specific parameters: injection pressure and installation rate. According to him, when employing a slower installation pace for both stone columns and CMC, the materials are afforded ample time to settle within the column, leading to an anticipated increase in capacity. Conversely, an acceleration in the installation rate, based on limited investigations, correlates with a gradual decline in column stiffness. While expedited installation enhances construction efficiency, it concurrently compromises bearing capacity to a certain extent. Professor Basack underscored the compelling need for in-depth exploration of these parameters' influence.

- **According to your experience in India, stone columns are more popular or rigid inclusions?**

Professor Basack highlighted the extensive coastal expanse of over 3000 km in India, spanning both Eastern and Western regions, characterized by soft marine soil deposits. Additionally, parts of India feature soft clayey soil within its alluvial plains, posing challenges for infrastructure construction with shallow foundations. Consequently, ground improvement measures become imperative, with stone columns emerging as a popular choice in India. While piling systems offer enhanced bearing capacity compared to soft soil, they lack consolidation benefits.

Conversely, stone columns not only augment soil stiffness and bearing capacity but also facilitate consolidation, offering dual benefits of reinforcement and soil consolidation. However, the incorporation of rigid inclusions in stone columns transforms their behaviour akin to piled foundations, impeding the consolidation of virgin soil and gradually reducing permeability. This issue warrants attention, particularly as the utilization of rigid inclusions is limited in India due to associated downsides. Primarily, rigid inclusions lack consolidation benefits, posing a significant drawback. Secondly, their utilization significantly escalates costs, chiefly due to the high expense of cement. Thirdly, the complex process of grout injection into the ground further complicates their implementation in India. Professor Basack and his colleagues at the Indian Institute of Technology (IIT) have conducted numerous studies aimed at comprehensively assessing the efficacy and benefits of rigid inclusions in the Indian context. However, despite these efforts, rigid inclusions remain relatively unpopular within ground improvement sector in India.

- **What do you think about reducing the amount of cement and replacing/mixing it with some marginal and by-product materials such as different kinds of ashes? Do you think this might be popular in India?**

Professor Basack fully agreed with the idea, particularly regarding its popularity as a cement replacement in India. When cement is injected into the ground, its binding forces effectively aggregate stone particles, consequently reducing the overall permeability of the column. However, <u>substituting cement with alternative materials such as ashes or stone dust yields less pronounced binding effects, even if still reducing permeability to a certain degree</u>. Despite this, the utilization of such alternatives remains prevalent, presenting an attractive option according to professor Basack.

- **Which technique is better for the following scenarios?**

Saturated versus unsaturated:

Professor Basack noted that in India, piled foundations are typically favoured for unsaturated soil conditions. This preference stems from the challenges encountered during the consolidation process when employing stone columns in such conditions, rendering their application notably arduous.

Offshore and onshore:

Professor Basack emphasized the heightened significance and utility of rigid inclusions, particularly in regions characterized by unsaturated soil conditions, predominantly observed in northern areas of India. Conversely, in coastal regions and other alluvial zones, stone columns emerge as the preferred choice, with particular prominence noted in offshore platforms and wind turbine installations, where their usage is widespread.

- **In Australia for bridge approaches, rigid inclusions are mostly used but for normal embankments there are 2 choices, either stone columns or rigid inclusions. What is your suggestion?**

Professor Basack emphasized the multitude of parameters necessitating consideration, yet underscored the paramount importance of cost and construction timeline from a designer's perspective. Additionally, from a technical standpoint, the utilization of rigid inclusions notably augments bearing capacity while concurrently impeding consolidation, resulting in a lessened stiffening effect on the virgin soil (an issue of concern). Consequently, rigid inclusions initially enhance bearing capacity substantially, but subsequent decreases pose significant research considerations. Ultimately, determining the optimal technique is contingent upon various factors and lacks a definitive conclusion.

Long columns versus shorter columns:

Professor Basack recounted his tenure as a geotechnical consultant in Ballina, situated on the border of New South Wales and Queensland, Australia, spanning three years. During this period, extensive field installations were conducted to ameliorate marine soil conditions, characterized by a soft compressive layer extending to depths of 10 to 15 m, transitioning into stiff clayey soil beneath. Stone columns were installed to depths of approximately 10m below the ground surface, employing partially penetrated shallow stone columns in the project. He noted that full penetration of stone columns significantly enhances bearing capacity, as the base firmly embeds into the rigid soil layer atop. However, this approach escalates costs and installation complexities, necessitating a pragmatic compromise. Conversely, installing stone columns to full depth augments bearing capacity while simultaneously increasing the column's area and interface, thereby accelerating overall consolidation rates, contingent upon the applied loading which is a critical consideration. Professor Basack underscored the need to reconcile construction costs, ease of installation, and technical considerations. In essence, he asserted that construction costs and technical feasibility are paramount factors warranting meticulous consideration.

- **What is your experience with respect to clogging effects of stone columns?**

Professor Basack presented a scenario involving ground improvement through stone column installation within a soft soil deposit, concurrent with the construction of an embankment. The loading effects exerted by the embankment on the ground surface, coupled with a hydraulic gradient, prompt significant considerations. When the water table lies close to the ground surface, a notable hydraulic gradient emerges, particularly pronounced at the interface. This heightened hydraulic gradient prompts the gradual migration of particles from the soft clayey soil into the pore spaces of the stone columns. As these particles traverse the depths of the stone column pores, they accumulate within, gradually reducing the effective drainage area. Consequently, the effective radius of the stone column responsible for drainage diminishes over time. Eventually, the stone column is anticipated to become fully clogged, thereby ceasing drainage altogether. In response to this problem, Professor Basack said that design engineers must meticulously calibrate the geometrical parameters of the columns, select appropriate column materials, and tailor embankment construction to forestall premature clogging. Essentially, the design life of the stone column-reinforced soft clay deposit should align with or exceed the anticipated duration of its intended service life, preventing premature clogging.

- **Is clogging a common occurrence in stone column reinforcement projects in India?**

Professor Basack affirmed the widespread occurrence of clogging, particularly prevalent in coastal regions of India characterized by abundant soft clayey and marine deposits, exhibiting undrained shear strengths as low as 10 to 20 kPa, indicative of their soft nature. In such instances, marine clayey particles migrate from the soil into pore spaces, posing a significant challenge. To address this issue, he stated that the incorporation of rigid inclusions proves effective in mitigating clogging; however, it concurrently diminishes consolidation.

- **What are the construction challenges for both stone columns and rigid inclusions in India?**

According to Professor Basack, the utilization of rigid inclusions in India remains primarily within the realm of research, awaiting widespread acceptance within the industry. However, stone columns, a prevalent alternative, employ two primary installation techniques: the dry method and the wet method. The dry method is typically favoured for off-shore constructions where marine soil deposits, particularly soft marine clay beneath the seabed, are present. Conversely, the wet method is employed for constructing stone columns in saturated soft clayey deposits found in alluvial areas of central and northern India.

- **What is your experience about long-term performance of stone columns and rigid inclusions?**

Professor Basack emphasized that the cost and consolidation factors are pivotal considerations in the implementation of rigid intrusions. These factors directly influence bearing capacity and consolidation, with a consequent increase in bearing capacity and reduction in consolidation. However, regardless of whether stone columns are installed with or without rigid intrusions, the consolidation of the undisturbed soil remains notably high. Therefore, a compromise is necessary in terms of performance optimization. Notably, the incorporation of rigid inclusions mitigates the clogging effect, prolonging the lifespan of stone columns. Conversely, without rigid intrusions, stone columns are prone to rapid clogging. Professor Basack clarified that when referring to the use of rigid intrusions with stone columns, it entails the installation of two separate vertical inclusions in the ground: one comprising stone and the other a rigid inclusion. Stone columns primarily serve as drainage pathways and contribute to consolidation efforts.

- **With respect to this new technique which we call it bi-modulus columns, is there any study or construction attempts performed in India so far or is it very new over there?**

Professor Basack noted that while some of his colleagues at IIT (Indian Institutes of Technology) are actively conducting research on this subject, the industry has not yet embraced this emerging methodology. He further explained that even though there have been publications, including conference papers, stemming from this research, satisfactory results are still pending, which are crucial for industry acceptance.

- **As an expert in this area, do you suggest this initiative, or this is not useful?**

Professor Basack strongly advocated for the significance of studying this area. He asserted that the incorporation of rigid inclusions is poised to improve both the overall bearing capacity and longevity of bi-modulus column-reinforced soft soil deposits. Simultaneously, the reduction in consolidation may impact the strength and stiffness of the original soft clayey deposit, necessitating a careful balance. Nevertheless, he underscored the intriguing nature of this research domain and personally encouraged its advancement through thorough investigations.

- **Mushroom effects - Since the rigidity of the rigid inclusions are several magnitudes higher than the surrounding soil, they sometimes stick out of the ground, and there is something called mushroom effects and there are some problems with respect to the LTP and the thickness of the LTP. What is your insight on that?**

Professor Basack highlighted the significance of this matter, noting that in India, it has not been extensively investigated, with limited experiences thus far. However, he accentuated the importance of conducting research in this area, as it remains relatively unexplored in the Indian context. He attributed the limited popularity of rigid inclusions in India to the associated costs, as well as the necessary equipment and technology requirements.

- **In support of high rise buildings, which technique is better? Stone columns or rigid inclusions? Not only in India, but anywhere else in the world?**

Professor Basack underlined findings from the literature indicating that the Taj Mahal in India, constructed over 500 years ago, stands as one of the earliest examples of a ground improvement project utilizing stone columns. Remarkably, despite the passage of time, the structure continues to perform exceptionally well, with occasional rehabilitation efforts. He emphasized that in India, the choice of ground improvement technique hinges on factors such as soil conditions, soil layering, and associated costs. He noted that the conventional stone column method is predominantly favoured, particularly in regions with soft soil deposits, although pile foundations are utilized in certain urban areas due to the simplicity of installation and the technology involved compared to stone column installation.

- **Floating and end bearing columns? End bearing columns obviously give the best result with respect to settlement mitigation but sometimes they are not possible and floating columns are used instead. What is your insight?**

Professor Basack explained that the construction of floating columns is simpler due to the shallower depth of the embankment, which consequently reduces costs. Additionally, when these columns perform adequately, they are often preferred because their lower sections aid in drainage as well. In India, floating columns are predominantly used in scenarios where stiffer soil is located at considerable depths, typically around 30 to 40 m below the ground surface. Conversely, in sandy soils or when stiffer soil is closer to the surface, typically around 15 to 20 m deep, Professor Basack suggested that fully penetrated stone columns are preferable. This choice aims to optimize consolidation and bearing capacity, resulting in better overall performance.

- **Do you think that the bi-modulus columns can be used as a replacement for other techniques in the future?**

Professor Basack expressed keen interest in the subject matter, deeming it both intriguing and valuable for research. He advocated for further investigation into the topic, emphasizing the critical importance of considering consolidation and bearing capacity enhancement within this new technique. Additionally, he underscored the necessity of evaluating factors such as construction speed, installation efficiency, and cost implications in research endeavours. According to him this comprehensive approach aims to provide a holistic understanding and facilitates beneficial industrial applications.

- **What is your suggestion in regards to optimal spacing between the columns for both techniques?**

Professor Basack explained that he typically bases his designs on the normalized spacing, calculated as the spacing divided by the radius of the column (S/r), which is a crucial parameter in the design process. Additionally, he considers the spacing in relation to the normalized depth of the embankment (the L/D ratio), where L represents the depth of the embankment and D denotes the column diameter. These two parameters play pivotal roles in the design process. Generally speaking, Professor Basack recommended a spacing range of 2 to 3 times the column diameter for stone columns and 3 to 5 times the column diameter for rigid inclusions.

What is the range of thickness for LTP in your design considerations?

Professor Basack suggested that allocating 20 to 25% of the spacing would be an optimal selection. However, given the nascent stage of this ground improvement technique within the Indian industry, he emphasized the necessity for further investigation and research.

In conclusion, Professor Basack expressed his belief in the intriguing nature of rigid inclusions and bi-modulus columns, commending our investigation efforts. He recommended finding a balance between cost, construction time, enhancement of bearing capacity, and consolidation effect, identifying these as the four critical parameters for study in this research project. He stated that he anticipates promising outcomes, particularly concerning bi-modulus columns.

4.2.3 Interviewee 3 (Mr Jerome Racinais)

Mr Jerome Racinais is a practicing geotechnical engineer, graduating in the multidisciplinary engineering institute ENSTA in Brest (France). He is member of the Technical Committee of the French Society of Soils Mechanics (CFMS) and immediate Past Vice-Chairman of the Technical Committee TC211 (Ground Improvement). Since graduating in 2001, he has worked in the field of geotechnical engineering for the ground improvement specialist company MENARD. As Engineering director and design department manager, he and his team provide technical support to the Menard agencies spread around the world. He is responsible of the development of new design approaches and internal software for ground improvement solutions. He also maintains close partnership with Universities and Software providers companies. He is a visiting professor in French engineering school (CHEC, Builders for Society). He is currently involved in the French ASIRI+ national program and actively participates to the development of design procedures for ground improvement by rigid inclusions.

Mr Jerome Racinais stands as a distinguished figure in the realm of geotechnical engineering, renowned for his contributions to industry advancement, academic collaboration, and the development of innovative solutions for ground improvement challenges. Figure 4.4 shows the image of interviewee 3, Mr Jerome Racinais.

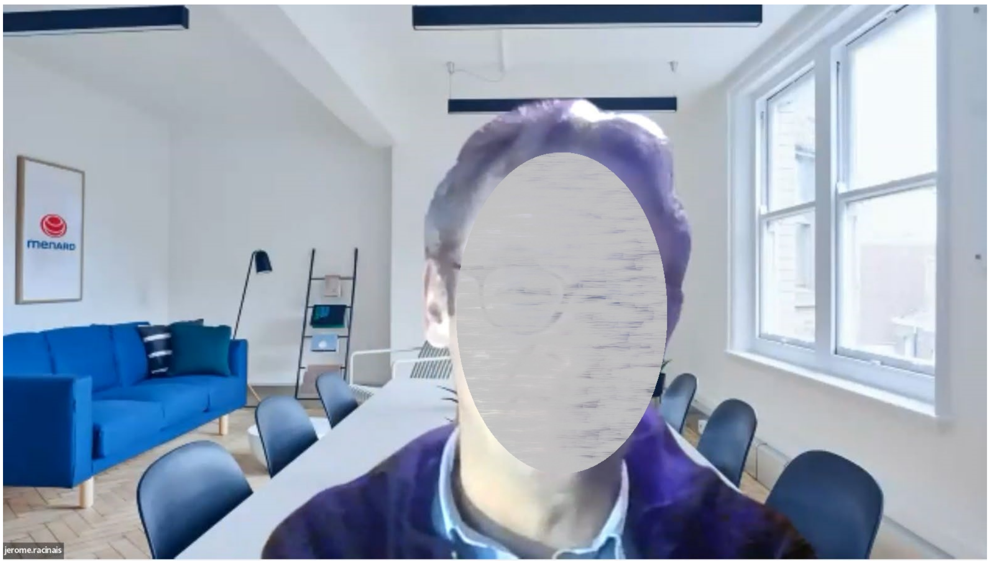


Figure 4.4: Interviewee 3, Mr Jerome Racinais

The following questions were asked and the answers of the interviewee are provided.

- **In France, are both CMC and Vibro Stone Columns (VSC) employed for compressible soil ground improvement? If so, which one is more dominant? Which method is more favourable by stakeholders in France?**

Mr Racinais highlighted the utilization of both CMC and Vibro Stone Columns (VSC) in France. He noted that during the 1990s, stone columns were the prevalent choice until Mr Jean-Marie Cognon from Menard introduced the Concrete Modulus Columns (CMC) in 1996, providing a competitive alternative. Since then, CMC rigid inclusions have become the dominant technique, constituting 65 to 70% of ground improvement projects in France, while VSC accounts for only 10 to 15%. This significant disparity in usage is attributed to the higher production rate and lower cost of CMC compared to stone columns. Mr Racinais explained that in France, two-thirds of ground improvement projects involve rigid inclusions, which may be CMC from Menard or other variants from companies like Keller, albeit under different names.

- **Which method do you suggest employing, taking into account the soil type (e.g., sandy clay, clay with high plasticity and clay with low plasticity)? What are the differences between settlement behaviour of stone columns and CMC?**

Mr Racinais asserted that CMC can be effectively deployed across a wide spectrum of soil types, ranging from very soft clay to sand, and even peat. In contrast, stone columns are unsuitable for use in extremely soft organic soils, thereby restricting their applicability. The domain of application for CMC is considerably broader than that of stone columns. Regarding settlement, the reduction factor achieved with stone columns typically ranges between 1.5 and 3, whereas with rigid inclusions, such as CMC, it ranges between 3 and 6. This variance is attributed to the greater stiffness of rigid inclusions, resulting in a higher settlement reduction factor. This factor represents the ratio between settlement observed without ground improvement and settlement observed with ground improvement. Mr Racinais emphasized the importance of assessing efficiency in terms of settlement rather than stress.

- **How about on-shore and off-shore conditions? Which method is preferred?**

Mr Racinais explained that Vibro Stone Columns (VSC) are primarily employed for offshore applications. Currently, they are engaged in a project at Porto di Vado in Italy, utilizing VSC for offshore conditions. Previously, for a land reclamation project, they utilized Vibro Concrete Columns (VCC) offshore, employing the same equipment as for stone columns along with the insertion of a tube to facilitate concrete injection into the ground, thereby enabling offshore CMC implementation. Additionally, in a recent project in Monaco, they successfully employed offshore VSC. Therefore, according to Mr Racinais, while VSC is generally more straightforward to implement than VCC in offshore settings, both approaches are feasible.

- **Is it accurate to state that stone columns represent a preferable choice for mitigating liquefaction in soils?**

Mr Racinais concurred and elaborated that with stone columns, soil densification occurs around the columns, accompanied by a reduction in shear stress on the soil due to the presence of reinforcing elements. Moreover, the stone columns serve as drainage elements, enhancing the coefficient of earth pressure at rest (K0) value around them. Consequently, there are numerous positive aspects associated with using stone columns. Mr Racinais added that CMC can also be utilized for liquefaction mitigation, particularly in situations where seismic activity is limited. For instance, if the factor of safety against liquefaction is approximately 0.9 or 1, CMC may effectively mitigate liquefaction risks. However, in severely liquefied conditions, stone columns are predominantly employed. He further explained that as an alternative solution suitable for high seismic regions, Deep Soil Mixing cells or caissons are considered.

- **Which technique is better for the support of bridge approaches? CMC or VSC?**

Mr Racinais explained that the choice between CMC and VSC depends on the sequence of construction activities. He highlighted CMC as the preferable option due to its higher settlement reduction factor, resulting in significantly reduced settlement. He supplemented this by mentioning that bridges are typically constructed atop piles to ensure minimal settlement, making it advisable to reinforce access embankments with CMC rather than VSC to minimize differential settlement. Mr Racinais further noted an alternative sequence where stone columns and access embankments are installed first, allowing the embankment to settle before subsequently installing piles and the bridge. However, he emphasized that this approach is less common due to the extended time required, which clients often find impractical.

- **What are the limitations or drawbacks of CMC (rigid inclusions)? What are the limitations or drawbacks of VSC semi-rigid inclusions?**

Mr Racinais pointed out that CMC exhibit brittleness, making them potentially unsuitable for applications subjected to significant horizontal loads or shear forces. However, this limitation can be mitigated by reinforcing CMC with steel cages. Another constraint for CMC rigid inclusions arises in liquefiable soils, a topic previously discussed. Additionally, Mr Racinais expressed reservations regarding floating „ particularly if their base is not situated on a firm soil or rigid stratum, as this could pose challenges. Regarding Vibro Stone Columns, their efficacy is contingent upon lateral confinement, rendering them unsuitable for use in very soft organic soils. He elaborated on Mr Cognon's development of CMC in the 1990s as a response to the limitations of stone columns. Mr Cognon sought a solution akin to stone columns but using cohesive materials independent of lateral confinement. This led to the creation of the first mortar CMC in France, boasting a UCS of only 4 MPa. Mr Racinais disclosed his tenure with Menard since 2001, during which he has been involved in designing CMC with UCS ranging from 6 to 8 MPa. However, nowadays, under the pressure of consultants and checkers and because they compare the CMC with piles, mortar of concrete typically from C12/15 to C20/25 is utilised even though it is not always needed, and money could be saved, and carbon dioxide could be reduced by using materials with lower UCS.

- **What is your experience about long-term performance of stone columns and rigid inclusions? What do you think about long-term issues of stone columns such as bulging or clogging? Is there a maximum recommended length for stone columns to prevent bulging?**

Mr Racinais acknowledged encountering challenges with both ground improvement techniques, typically manifesting at the onset of the project. Instances have occurred where immediate settlement and column failures were observed following ground improvement works. Regarding long-term issues, concerns arise particularly in the presence of organic soils or peat layers, where the possibility of secondary settlement must be carefully considered. Mr Racinais cited insights from French insurance companies, indicating that organic soils and peat layers are commonly associated with ground improvement issues, primarily due to the complexities involved in installing CMC in such conditions, thus increasing the likelihood of long-term settlements. Therefore, he underscored the importance of attending to organic soils to mitigate potential issues such as bulging, clogging, and prolonged settlement. Addressing concerns about column length to prevent bulging, Mr Racinais explained that the determination is based not on length but on the capacity of the surrounding soil, which is assessed using the Pressure Meter Test (PMT) predominantly employed in France for column design.

- **In rigid inclusions (CMC), it is possible to consider that some columns may crack or break in the long-term due to shear stresses? What would be the importance of LTP to tackle this issue? In numerical investigations, broken CMC with very thin LTP show a large settlement, but with a proper LTP thickness, not much difference is observed between intact CMC and CMC system with some imperfect ones.**

Mr Racinais concurred that CMC are susceptible to cracking or fracturing under shear stresses, necessitating caution, particularly in seismic conditions. With increasing instances of CMC installations beneath residential structures, the potential for significant shear stresses during seismic events is a critical concern. To mitigate these risks, an adequate Load Transfer Platform (LTP) is typically positioned directly below the footings in such projects to minimize shear stresses. Furthermore, ensuring accurate estimation of bending moments and shear stresses during the design phase is imperative. To address this issue, two potential solutions are available. One approach is to adjust the thickness of the LTP to sufficiently reduce shear stresses, eliminating the need for reinforcing the CMC. Alternatively, if shear stresses exceed acceptable limits, steel reinforcement is necessary within the CMC. Mr Racinais emphasized that their calculations never assume or depend on fractured CMC. Initially, they compute shear stresses and bending moments, and based on this data, if the calculated values fall within acceptable ranges, no reinforcements are needed for the CMC. However, if shear forces or bending moments exceed acceptable thresholds, the CMC require reinforcement with steel cages. On the other hand, underneath embankments, significant shear forces may also act upon the CMC. To address this, one option is to reinforce the LTP with steel meshes or robust geogrids to mitigate lateral forces, thus obviating the need to reinforce the CMC. Alternatively, steel cages can be positioned around the CMC at the embankment toe. While it is acknowledged that some CMC may still incur cracking or breakage, the design endeavours to prevent such occurrences. In summary, according to Mr Racinais, strategies to limit lateral displacement beneath embankments include increasing LTP thickness, reinforcing the CMC, and reinforcing the LTP itself.

- **What are your thoughts on employing a ground improvement technique that utilizes both CMC and VSC in one project, such as having one row of CMC and one row of VSC?**

Mr Racinais asserted that such a practice is typically reserved for scenarios involving liquefiable soil. He cited an instance where CMC were initially employed for settlement mitigation, but subsequent geotechnical assessments uncovered liquefaction susceptibility. As a remedy, stone columns were integrated to address liquefaction, alongside CMC to enhance soil bearing capacity and substantially diminish settlement. Mr Racinais posited that this dual approach is applicable in situations characterized by liquefiable soil, wherein stone columns mitigate liquefaction risks while CMC concurrently bolster soil bearing capacity and diminish settlement effects.

- **Some companies have proposed a new technique called bi-modulus columns. This involves combining stone column material at the top and rigid inclusions at the bottom within a single element. What is your insight about this technique? Can bi-modulus columns resolve some issues related to CMC such as mushroom effects? Since the rigidity of the rigid inclusions (CMC) are several magnitudes higher than the surrounding soil, they sometimes stick out of the ground, and there is something called mushroom effects. Can a thick LTP resolve the problem?**

Mr Racinais delineated that the development of this technique is motivated by two primary considerations. Firstly, it aims to mitigate the occurrence of mushroom effects, typically observed in situations where thin embankments are utilized. Bi-modulus columns are deployed to counteract the differential settlement phenomenon in such cases. Secondly, in seismic regions, where numerous CMC installations are present beneath footings, establishing a Load Transfer Platform (LTP) between the footings and CMC proves challenging, particularly in shallow water table conditions. This necessitates excavation, laying, and compacting of the Load Transfer Platform, presenting significant logistical hurdles. Consequently, the utilization of bi-modulus columns obviates the need for constructing Load Transfer Platforms. This entails installing the CMC segment of the bi-modulus column first, followed by direct excavation within the stone column section, bypassing the requirement for an LTP. In summary, according to Mr Racinais, bi-modulus columns serve as an effective solution beneath thin embankments to mitigate mushroom effects and in seismic zones beneath buildings to avoid the necessity for a thick LTP. The stone column component atop the bi-modulus column serves the same function as constructing an LTP, namely reducing shear stresses acting on the CMC. The installation sequence involves initially installing the CMC, followed several hours later by the stone column on the upper part.

Mr Racinais shared insights into a project undertaken in Germany over a decade ago, wherein CMC were employed to support a notably thin embankment. Manifestations of mushroom effects, evidenced by discernible distortions on the asphalt road, were directly associated with each CMC rigid inclusion. To address this challenge, Mr Racinais advocated for the adoption of bi-modulus columns, positing their potential to effectively mitigate such issues. The aforementioned project involved the installation of CMC within a notably soft soil stratum, comprising a 4-meter-thick peat layer overlaying a compacted sand layer. A slender embankment, measuring 1.25m in height, was subsequently erected atop the shallow ground treated with CMC. Within a short span of several months post-construction, the imprint of each rigid inclusion became evident on the asphalt road surface, underscoring the inadequacy of the CMC approach for such conditions. Mr Racinais asserted that bi-modulus columns offer a superior alternative in such scenarios. Regarding the construction of bi-modulus columns, he noted that the process necessitates the use of two distinct equipment types. Efforts are underway to develop a single rig capable of executing both techniques synergistically. However, until such advancements materialize, the concurrent deployment of two rigs on-site remains a requisite, albeit not prohibitively costly.

- **Can bi-modulus columns be a great replacement for other vertical inclusions?**

Mr Racinais suggested that bi-modulus columns offer considerable advantages under certain specific conditions, notably in instances of exceptionally thin embankments or as an alternative to Load Transfer Platforms in seismic regions, contingent upon the prevailing geological and structural factors. Nevertheless, the viability of bi-modulus column implementation hinges upon achieving competitive pricing and streamlining construction processes to require only a single rig. If these criteria are met, bi-modulus columns could emerge as a highly favourable substitute solution, Mr Racinais confirmed.

He further highlighted a limitation associated with CMC rigid inclusions, particularly concerning the challenge of controlling their depth during installation. Specifically, beneath footings, it is challenging to halt the CMC at the desired level. Consequently, upon surfacing, the top portion of the CMC element necessitates removal, a task that must be executed while the concrete remains in its fresh state. This process can present difficulties in achieving precise levelling. Conversely, bi-modulus columns offer an advantageous solution, as excavating the top portion of the element is considerably more manageable. Mr Racinais elaborated on the specifications concerning the diameters of the CMC and VSC components within bi-modulus columns. While Menard provides specific guidelines, a common ratio observed is typically 2, wherein the diameter of the VSC is twice that of the CMC diameter. For instance, a configuration might entail a 300 mm CMC accompanied by a 600 mm VSC. Regarding length, there exists a stringent limitation on the VSC segment, which should ideally not exceed 1 to 1.5 m. Furthermore, Mr Racinais underscored the necessity of a transition zone between the two components. Reflecting on experiences with excavated bi-modulus columns from Menard, it has been observed that such a transition zone indeed exists, typically comprising a combination of stone and concrete materials.

- **What is your experience with respect to the thickness of the LTP for both techniques and what is the range of thickness for LTP in your design considerations?**

Mr Racinais explained that in the context of the CMC technique, the recommended thickness of the Load Transfer Platform (LTP) typically ranges between 400 and 500 mm when situated beneath slabs, whereas it measures approximately 300 mm beneath footings and rafts. Conversely, in the case of stone columns, the use of an LTP is not obligatory and may even be entirely omitted. This is attributable to the flexible nature of stone columns, which permits them to be positioned directly beneath slabs without necessitating an intermediary Load Transfer Platform.

- **For CMC socketed into rigid base or sitting on bedrock, the numerical analysis indicates that the settlement is close to zero. Is this correct in the real world?**

Mr Racinais affirmed this notion, elucidating that settlement can manifest either at the base of the CMC or at the top, where the CMC interfaces with the Load Transfer Platform (LTP). If the lower section of the CMC is embedded within a highly resilient layer, settlement at its base is effectively mitigated. Moreover, with the presence of an adequate Load Transfer Platform, settlement at the top, where the CMC interfaces with the LTP, should remain within moderate bounds. Drawing from extensive experience conducting static load tests atop CMC within Menard projects, he noted that under certain conditions, loads ranging from 50 to 100 tons have been applied onto a rigid CMC element. Through these tests, it has been observed that when the base is sufficiently robust, settlement is nearly negligible.

Mr Racinais also disclosed that in his design considerations he limits the vertical load on top of a CMC element to 5 MPa SLS (Serviceability Limit State which means in service/operation) and that's his safety rule to make sure there is no punching in to the rigid base and anything above that value might cause problems in terms of anchorage of the CMC in to the base.

- **What is your experience regarding rigid inclusions used for the batter of embankments? Do you suggest using the same spacing and length, or reducing them?**

Mr Racinais discussed a previous project undertaken in Australia, specifically at the port of Brisbane, which exemplifies a scenario where the length of CMC was abbreviated within the embankment batters. Along the slopes of these embankments, known as batters, active lateral earth pressures exert significant bending moments on the CMC. Despite this, the axial load imposed on the CMC remains relatively limited. Consequently, there exists leeway to reduce the length of the CMC to a certain extent. By doing so, the bending moments experienced by the CMC are correspondingly diminished, owing to the absence of anchorage within a rigid structure.

Mr Racinais further explained that, for embankment batters, the typical approach involves increasing the spacing between CMC as the primary solution. Additionally, when deemed appropriate, they may opt to shorten the length of the CMC as a supplementary measure.

- **Which technique (CMC or VSC) is more cost effective where you are? Which method (CMC or VSC) is more economical with respect to the thickness of LTP?**

Mr Racinais underscored the dispensability of Load Transfer Platforms (LTP) for stone columns a notable advantage. He elucidated the cost dynamics, delineating that in France, the pricing of techniques is contingent upon linear meterage. According to him for CMC, the cost varies with diameter, ranging between 20 and 40 Euros per linear meter. Similarly, stone columns incur expenses ranging from 30 to 40 Euros per linear meter. However, the expeditiousness of CMC deployment is emphasized, with installation rates reaching 600 to 800 linear meters per day, a feat unattainable with VSC. Consequently, according to Mr Racinais, the accelerated production rate of CMC translates to considerable time savings, constituting a noteworthy advantage, exemplified by the predominance of CMC utilization in two-thirds of ground improvement endeavours in France.

- **In terms of sustainability of CMC, is it recommended to mix cement with other materials such as different kind of ashes (fly ash, bagasse ash, etc.) or lime in Europe?**

Mr Racinais acknowledged his non-specialist status in concrete matters but confirmed the affirmative. The objective is to mitigate the carbon footprint, prompting research into optimal mixtures for CMC projects. Regarding pumpability, he explained that the substitution of Portland cement with fly ash and other ash varieties in Menard's endeavours yielded no issues, indicating feasibility.

- **What do you think about the usage of construction wastes and debris for vibro stone columns in Europe?**

Mr Racinais indicated efforts to revise French recommendations and regulations to accommodate the utilization of such materials. Drawing from his experience, he noted the underutilization of construction wastes in the construction of stone columns, advocating for an innovative shift in this direction. Additionally, he highlighted Keller's exploration of construction waste application in VSC as a potential avenue for future investigation, albeit urging caution and referencing WEHR and WECKE (2017), vibro replacement with sand and recycled aggregates.

- **What is the acceptable settlement range for CMC and VSC?**

Mr Racinais explained that VSC possess a flexible nature, enabling them to withstand considerable displacement. They are occasionally employed as drainage elements, such as beneath embankments, where substantial settling is permissible without adverse consequences. Conversely, CMC present a distinct scenario, where minimal settlement is desirable to prevent the development of shear forces and bending moments, which could be deleterious. Generally, substantial settlement during the construction of stone columns can be advantageous for consolidation and total settlement, although this reliance on settlement is not feasible for CMC. He noted that despite CMC not primarily serving as drainage elements, empirical observations indicate that soil reinforced by CMC settles at a quicker rate compared to untreated soil. Mr Racinais suggested that determining a precise threshold for permissible settlement is challenging. However, when utilizing CMC for embankments, it is customary to anticipate settlement within the range of 100 to 150 mm, with exceeding this range being discouraged. Furthermore, it is imperative to consider not only settlement but also the forces acting within the CMC.

- **In design of Stone Columns and CMC, which design parameters are more sensitive (spacing, pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP, traffic load or soil properties)? What is your suggestion regarding optimal spacing between the columns for both techniques and what is the range of diameter for VSC and CMC?**

Mr Racinais emphasized the paramount significance of the replacement ratio, comprising the interplay between diameter and spacing, as the critical parameter. Regarding depth, they have successfully implemented CMC to depths exceeding 45m. Remarkably, when ground improvement projects entail considerable depths, the utilization of CMC is notably advantageous over VSC. In contrast, ensuring the installation of stone columns exceeding 30m in depth presents considerable difficulty. He recommended an effective pre-design strategy for CMC, suggesting an assumption that 100% of the load is borne by the CMC while limiting the load intensity to a maximum of 5 MPa. Spacing calculations are then derived based on this criterion. Concerning CMC diameter, design standards typically prescribe a range between 300 to 400 mm. Conversely, stone column diameter varies depending on the installation method; for dry bottom-feed techniques, diameters typically range between 600 to 800 mm, whereas wet-top feed methods necessitate larger diameters ranging from 800 to 1200 mm.

- **What are the effects of rate of injection pressure and rate of installation for CMC and can these parameters be included in the design phase because sometimes the rigid inclusions are installed very fast and sometimes slow depending on the capability of equipment or based on the decision of rig operator?**

Mr Racinais highlighted Menard's development of rigs capable of achieving high production rates, typically ranging between 600 and 800 linear meters per day. The injection pressure typically hovers around 4 to 5 bars. However, he underscored that, in the design of CMC, he does not consider the installation or injection rates as significant factors. Rather, the emphasis lies on expediency, with faster rates being inherently preferable. Mr Racinais further explained that in highly specialized projects aimed at addressing liquefaction risks and enhancing ground stability, CMC are occasionally employed to perform compaction grouting within liquefiable strata. In such cases, the diameter of the CMC is enlarged, and the installation speed is deliberately slowed to facilitate densification of the surrounding soil. These unique applications, which straddle the realms of compaction grouting and rigid inclusion, may warrant consideration of installation rates, albeit such instances are infrequent.

- **What are the construction challenges for both stone columns and rigid inclusions in Europe?**

Mr Racinais reported the completion of over 9000 ground improvement ventures worldwide utilizing CMC, with depths exceeding 45 m. According to him, in France, geotechnical consultants commonly regard the rigid inclusion technique as the foundational solution for projects, with a well-established market presence. Conversely, in other regions where this approach is less familiar and concerns regarding cost or equipment availability persist, alternative methods like piles or stone columns may enjoy greater popularity. Therefore, Mr Racinais clarified that with respect to CMC, there are no construction challenges and identified the primary hurdle as the necessity to engage with geotechnical consultants globally and enlighten them about the advantages of the CMC rigid inclusion technique. This aims to prompt a shift away from entrenched practices in those areas and mitigate their challenges.

- **What is the effect of speed on settlement behaviour of an embankment built on CMC or VSC? What is the effect of groundwater?**

Mr Racinais stated that if both the embankment and the Load Transfer Platform (LTP) exhibit sufficient thickness, there should be minimal impact. Presently, they are examining this phenomenon within the ASIRI+ national project in France. He underscored the necessity for further investigation, advocating for both numerical simulations and experimental approaches to thoroughly explore this aspect.

Towards the conclusion, Mr Racinais exhibited enthusiastic interest in our research, highlighting the vast terrain yet to be traversed and explored regarding these methodologies. He asserted that there are notable prospects for expanding and enhancing advancements within this domain.

4.2.4 Interviewee 4 (Dr Martin Larisch)

Dr Larisch finished his university education in Germany approximately 25 years ago. Throughout the majority of his professional journey, he dedicated his efforts to ground improvement and piling, contributing his expertise to specialized piling firms in Germany (a joint venture (JV) between Franki Grundbau GmbH (home of the ‘Franki Pile’ and Menard) which was formed in 2005 and they installed CMC for the very first time in Germany. Subsequently, Dr Larisch relocated to Sydney, Australia, where he was employed from 2005 to 2007. During this period, his involvement in ground improvement projects was limited, except for a minor project in Wollongong that did not pertain to rigid inclusions.

Dr Larisch then moved to Brisbane in 2007 and joined ‘Piling Contractors Pty Ltd’ which was the leading Australian piling/ ground improvement contractor during this period and was also a part of the international Keller group. He stayed with Piling Contractors more than 7 years as a Project Manager, where he did lots of Design & Construction (D&C) jobs involving ground improvement and was later promoted to become the National Technical Manager since early 2013. Dr Larisch was privileged to join Keller’s global technology committee for about 3 years, and he represented Australia within the Keller group together with a representative from Keller Ground Engineering. Subsequently, after a brief period of working with Professor David Williams at the University of Queensland on a part-time basis, Dr Larisch moved to New Zealand in 2016. He then took on the role of Geotechnical Engineering Manager at Fletcher Construction, the largest contractor in the country. With numerous ground improvement projects in progress, he spearheaded the geotechnical team, overseeing their involvement in a variety of infrastructure, marine, and building projects where extensive ground improvement was necessary. Notably, stone columns remained highly favoured in New Zealand, particularly for liquefaction mitigation, providing Dr Larisch with valuable learning experiences. Three years later, he transitioned to consultancy and spent two years at Golder Associates in Brisbane. Despite his location, he continued to engage in numerous projects in New Zealand during this period as well. Returning to New Zealand, Dr Larisch joined Jacob's and began exploring prospects involving conventional concrete displacing systems for ground improvement. He departed from Jacobs in 2023 and established his own independent consultancy, operating primarily in New Zealand but also extending services to Australia. Presently, he is actively engaged in a ground improvement project in the Wellington Region, where they have substituted precast concrete piles with drilled displacement columns for a substantial project.

Figure 4.5 shows the image of interviewee 4, Dr Martin Larisch.

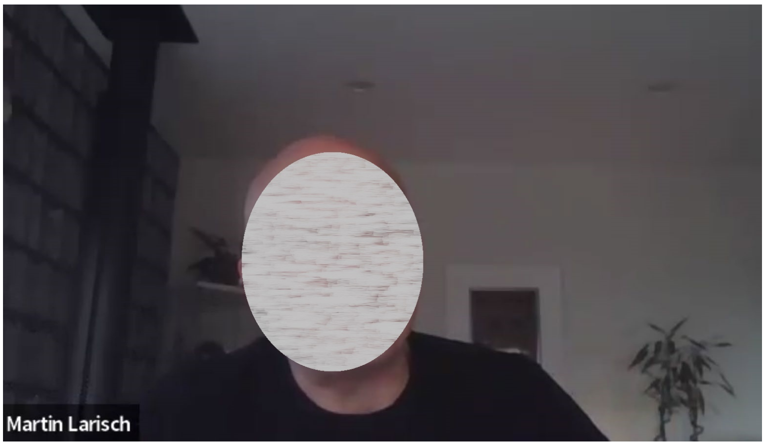


Figure 4.5: Interviewee 4, Dr Martin Larisch

The following questions were asked, and the answers of the interviewee are provided.

- **What are the disadvantages of CMC?**

According to Dr Larisch, a significant drawback of employing the CMC technique is the potential for inducing ground heave because of soil displacement effects. This could pose a considerable challenge, especially when utilizing this method for constructing structures. However, using CMC for an earth embankment likely does not cause a huge problem. Nevertheless, by incorporating these rigid inclusions and displace the ground in some stages during the installation process, there is a possibility of lifting the entire ground. For example, in specific soil conditions, when the CMC are installed consecutively, there is a risk of the concrete being forced out. This occurs due to the densification effect caused by the installation of the adjacent column as it descends, resulting in the extrusion of concrete from the freshly installed column. Under these circumstances, one likely encounters challenges related to integrity, necking and possibly some other issues as well. To mitigate these problems, contractors traditionally employ a "hit and miss" approach. However, the drawback is that it necessitates a return to fill the gaps later and there are two factors to consider. Firstly, these unreinforced elements are subjected to lateral loads using the piling rig, and if they are only 24 to 48 hours old, cracks may develop, which might not be posed as an issue with solely vertical loads. However, for lateral forces like those during an earthquake, cracks in the rigid inclusions become a significant concern. The second consideration is that when the gaps are filled, the ground is disturbed once more, and some ground heave is induced. This poses a risk that the ground heave resulting from filling the spaces between the columns may elevate the entire ground, including the already installed rigid inclusions.

If the rigid inclusion head is observed moving upward by, for example, 100 mm in certain scenarios, the question arises: did the entire 20-meter-long inclusion shift upward, or was it only the upper 1 or 2m above a crack that moved or did the inclusion just cracked? In such cases, conducting on-site low strain integrity testing (utilizing PIT or comparable methods) becomes crucial. If, for instance, a crack is detected at a depth of 2m, it may not be ideal, but it provides awareness that there is an issue that needs to be addressed. To tackle this issue, some designers attempt to insert a reinforcing bar into the inclusions. However, from a construction standpoint, this approach undermines the cost-effectiveness, nearly doubling the overall expenses.

- **What is your experience with clogging effects of stone columns?**

Dr Larisch stated that he has actively participated in numerous ground improvement projects across New Zealand, with a particular emphasis on the widespread use of stone columns for mitigating liquefaction. He has taken the lead in managing geotechnical teams for various companies, overseeing their involvement in a multitude of infrastructure, marine, and building projects that extensively relied on vibro stone columns for ground improvement.
With respect to clogging effects, Dr Larisch expressed his belief that it is likely influenced by the material of the stone column. He admitted to not having delved deeply into the specifics of clogging effects and mentioned uncertainty about available publications on the subject. However, Dr Larisch acknowledged the inherent risk of clogging and suggested that using a stone column material with lower fine content might potentially mitigate this effect to some degree. Nevertheless, he emphasized that the effectiveness of such an approach would depend on the intended purpose of the stone column.

For instance, the application of a stone column as a drainage element differs significantly from a situation where the goal is to enhance the stiffness of a reinforced soil block and minimize settlement. Furthermore, Dr Larisch believes that in soft cohesive soils, particularly, the risk of clogging is evident and undisputed. In a broader sense, he noted that smaller aggregates generally tend to result in more pronounced clogging effects.

- **What are your thoughts regarding bi-modulus columns?**

Dr Larisch finds the concept of bi-modulus columns intriguing, although he has not personally utilized them. He was aware of their installation by Menard but has not encountered them in any of the projects he has observed. Overall, he viewed the idea as excellent because it merges the strength of rigid inclusions with displacement effects, offering distinctive rigid elements. Based on his experience, the most challenging segment of rigid inclusions lies in the upper two to three meters. During this range, various construction-related issues emerge, including the tracking of construction plant, the application of lateral loads, column cracking, ground heave, and similar factors. Therefore, utilizing a bi-modulus column, where the upper section is comprised of stone columns, would be advantageous. In such a case, ground heave becomes less critical, as it becomes manageable by simply using a scraper (earthmoving equipment) to traverse the area, offering a more straightforward approach. According to Dr Larisch, the only potential hindrance could be the construction process of bi-modulus columns and if it be practicable to use a single rig, it would simplify the procedure. However, introducing a second machine for the process could pose a challenge.

- **Is it conceivable for two machines to work sequentially, with one handling the rigid inclusion and the other completing the top part with the semi-rigid inclusion (stone column)?**

Dr Larisch expressed that, in his opinion, such an arrangement is feasible, and he appreciates the concept as it allows for a focus on pure ground improvement. When it comes to rigid inclusions, Dr Larisch frequently observes confusion where people mistake them for piles and inquire about their nature as either piles or columns. He stated that if these bi-modulus columns can be efficiently constructed, a highly potent ground improvement system would be created. Furthermore, when examining the transfer of loads from the structure to the ground, there is a more pliant and flexible response at the surface. The transfer of loads into the rigid elements also occurs, provided that the effectiveness of this load transfer can be ensured. When implementing concrete inclusions, Dr Larisch occasionally encounters a significant construction risk. This risk arises when pouring of the concrete stops, typically about three meters below the surface, leaving a gap in soft soil conditions without backfilling. Removing the surcharge, especially in soft soil conditions, can lead to necking in the shafts of the rigid inclusions as the ground exerts pressure against the fluid concrete.

Dr Larisch admitted that he may not have given the bi-modulus columns a thorough consideration, acknowledging that companies like Menard and Keller, who offer such solutions, likely have addressed and thought through these aspects. He holds the belief that individuals employed in above mentioned prominent geotechnical companies are very capable and innovative, and if they provide such solutions, it implies they have successfully resolved any potential issues. He is enthusiastic about the concept, although he is unsure if it can be executed similarly to the construction of large stone columns, which are, for instance, grouted at the bottom. Nevertheless, he genuinely considers the bi-modulus columns as a commendable idea.

- **What are the long-term performances of VSC and CMC?**

Dr Larisch mentioned that he lacks extensive data on the long-term performance of CMC and VSC. The rationale behind this is that if these vertical inclusions are installed and function adequately without any noticeable issues, it should be deemed acceptable. Typically, any shortcomings in their performance would be evident, and any unexpected settlement issues would be clearly observable. Dr Larisch is of the opinion that if these columns are constructed soundly, there should not be any issues. He emphasized that the long-term performance is significantly impacted by the presence of cracks in the columns. Drawing from his experiences, he has encountered instances where columns did not perform optimally. During his PhD research on the installation effects of drilled displacement columns in clay, they observed that in clayey soils, an inconsistent installation rate can lead to a remoulding effect in the clay. This effect has the potential to decrease the initial shear strength of the soil by up to 50%. For instance, instead of assuming an undrained shear strength of 40 kPa, a remoulded strength ranging from 20 to 25 kPa might be present. This observation was made through testing columns in Keller's yard in Brisbane as part of Dr Larisch's research.

He discovered that if the piling rig possesses sufficient power and can sustain a consistent penetration rate that aligns with the displacement tool, soil remoulding can be avoided. In such cases, there is an improvement effect in situ. Additionally, their research revealed that, in comparison to theoretical capacity, results could be enhanced by up to 40%. This was intriguing at the time, as it suggested that by utilizing appropriate equipment and adhering to specified guidelines regarding diameter, depth, and a complete displacement system, along with employing a powerful rig to ensure a consistent penetration rate, the installation of columns could be trouble-free. However, if a less powerful and struggling small rig is utilized, there is a risk of disturbing or remoulding of the soil surrounding the column, which weakens the soil in the column's vicinity, leading to a settlement response higher than anticipated. Dr Larisch encountered this issue in some previous jobs where for example, columns had to penetrate 20 m through marine clay before reaching a stiffer clay layer. In that job site it proved to be quite frustrating since the initial design specified a 4 m penetration into stiff clay. However, the rig completed the drilling through 20 m of soft clay in just two minutes, and the subsequent penetration into stiff clay exhibited varying rates: 30 seconds for the first meter, one minute for the second meter, two minutes for the third meter, and five minutes for the final meter.

Dr Larisch stated that he conducted numerous tests, including PDA tests, on columns with varying embedment depths in stiff clay. He found it particularly intriguing that the column with a 1 m embedment displayed 30% more capacity than the column with a 4 m embedment. He emphasized that the installation effects, especially in the case of columns installed in stiff cohesive soil, play a significant role in assessing long-term performance based on his understanding and experiences.

Yet, when it comes to installing columns in sand, Dr Larisch has not observed any adverse effects if the installation is done correctly. This is because that displacement effects are not as pronounced in sand. Additionally, he mentioned that Dr Jim Slatter's Ph.D. thesis, conducted at Monash University, provides valuable and thorough research on the installation effects of displacement augers in granular soils.

- **Which methods do you suggest being used according to the soil (such as sand, clay with high plasticity or low plasticity?)**

Dr Larisch believes that both methods could be effective, and their suitability depends significantly on the specific purpose and design intent. For instance, whether the goal is settlement reduction, enhancing soil bearing capacity, mitigating liquefaction and utilizing elements for drainage purposes, stone columns emerge as the preferred choice in the latter case. When it comes to liquefaction mitigation, Dr Larisch expresses reservations about employing rigid inclusions, especially in the upper sections. He is concerned that during earthquake shaking, cracking may occur at interfaces between softer and stiffer layers. In contrast, bi-modulus columns could be a suitable alternative in such scenarios, but further investigation is required before drawing conclusive findings. In terms of suitability, he stated that both systems generally function across various ground conditions; however, the choice depends on the specific goals. A recognized problem with stone columns in soft cohesive soil is bulging. In such conditions, continually pushing the stone into the ground may result in a significantly larger diameter at the top than the intended 800 mm column for example. Therefore, stone columns are not ideally suited for cohesive soils, and in certain cases, grouting may be necessary. Nevertheless, rigid inclusions can be considered as an alternative in such circumstances. Moreover, a similar issue may arise when using rigid inclusions, particularly if the concrete is highly fluid or if the concrete pumping pressure is excessive. Dr Larisch described a situation from his early engineering career in northern Germany, where he encountered challenges during a project involving full displacement piles in very soft soil with an undrained shear strength of approximately 15 to 20 kPa. They faced difficulties bringing the concrete to the ground surface because the lateral resistance of the soil could not withstand the lateral pressure of the fresh concrete.

While considering pumping more concrete to overcome this issue and to bring up the concrete to the surface when it was stopped 1 to 2 m below the ground level, it unexpectedly led to a mushroom effect and the creation of a substantially larger top section. In such ground conditions, stone columns might have been a more suitable choice, but Dr Larisch emphasized that there is no definitive right or wrong in handling such situations.

- **Is it possible to employ both techniques in both offshore and onshore projects?**

Dr Larisch stated that he is not familiar with any offshore projects incorporating rigid inclusions. He believes that vibro compaction, specifically using vibro floats to compact the soil, is the sole viable option. Additionally, he expressed uncertainty about the feasibility of the replacement method in offshore areas, leaving stone columns and vibro compaction as the only available methods for offshore projects. Conversely, under onshore conditions, both techniques are viable. However, <u>certain regions, like Sydney, face a scarcity of granular materials required for constructing stone columns</u>. <u>Despite this challenge, there is potential to utilize recycled concrete as an alternative, albeit with the necessity of treating the recycled concrete to make it suitable for stone column construction.</u> Nevertheless, there remains a considerable opportunity.

- **What about the cost and construction timelines associated with these two methods?**

While working in Brisbane in 2019, Dr Larisch shared an experience of a project where the client required stone columns. Upon contacting a Menard representative, he was informed that there were no available stone column rigs in the country at that time; the rigs could be found in Asia, and stone columns were no longer being done in Australia. This led Dr Larisch to ponder why rigid inclusions were not being considered as an alternative. Subsequently, Dr Larisch reached out to Keller, and once again, he received the same response. They suggested exploring the option of using rigid inclusions instead.

Therefore, Dr Larisch believes that rigid inclusions come with a lower cost. However, when evaluating the overall system and factoring in the Load Transfer Platform (LTP), the cost dynamics change. This is contingent on the column configuration, where smaller diameter columns with larger spacing might require a larger LTP which is more costly. On the contrary, stone columns, typically having larger diameters, could potentially result in cost savings in terms of LTP. Additionally, surplus material from the stone columns could be repurposed for constructing the Load Transfer Platform which is not possible in the case of rigid inclusions and there is a risk of contamination. Nonetheless, according to Dr Larisch, overall, the installation of rigid inclusions is generally more cost-effective and less time consuming.

- **Regarding bridge approaches, a consensus among many experts is in favour of rigid inclusions, firmly asserting that stone columns should be avoided. What is your recommendation in this regard?**

Dr Larisch emphasized the importance of considering varying stiffness requirements. For instance, in close proximity to bridge piers where a high level of stiffness is necessary, rigid inclusions are deemed suitable to offer a more rigid foundation response. However, as the distance from the bridge increases, it becomes advisable to reduce the stiffness response. This precaution is taken to prevent potential differential settlement issues between the relatively stiff ground improvement work and the original ground.
Understandably, in these cases, the area replacement ratio has been modified by using rigid inclusions.

For example, to provide some numerical values, closer to the piles, let's say a 10% area replacement ratio is obtained. Moving 10 to 20 m further up, the area replacement ratio reduces to 7%, and then, probably in the furthest area, a 3% area replacement ratio will be achieved. Therefore, the further away from the bridge, the number of rigid inclusions is reduced. Nevertheless, Dr Larisch emphasizes that it is essential to highlight the critical nature of constructing an appropriate Load Transfer Platform (LTP) in these instances as well.

- **Regarding both techniques, which one proves more effective: end bearing or floating columns? While end bearing columns can significantly decrease settlement, there are instances where utilizing them may not be feasible due to ground conditions, associated costs, and other considerations. What has been your experience in this regard?**

According to Dr Larisch, the utilization of floating columns could be advantageous if full displacement effects are possible. The feasibility of this approach is mainly influenced by the soil strength, as it allows for the creation of a block of enhanced soil that has the potential to float. However, the applicability of this technique is closely tied to the specific objectives of the project.

For instance, in projects involving liquefaction mitigation, Dr Larisch has experienced the successful implementation of both end bearing and floating columns. The effectiveness of floating columns is also highly contingent upon the characteristics of the soil layer being targeted. Specifically, when dealing with a very soft soil such as a peat layer near the surface for example, the recommendation is not to halt the improvement process on top of that layer. Instead, it is advisable to penetrate through the peat layer to reach a stiffer underlying stratum. Furthermore, caution is advised when depending solely on end-bearing columns, as there is a risk of the rigid inclusions transforming into piles. For instance, if terminated on rocks, these columns may bear excessive loads and may not effectively contribute to ground improvement. Instead, the outcome could resemble unreinforced piles that, being considerably stiffer than the surrounding soil and might be prone to cracking as they are not specifically designed for such conditions.

- **What is your opinion on employing industrial and agricultural waste materials for both stone columns and CMC as potential substitutes for cement?**

Dr Larisch mentioned that numerous substitutions of this kind are currently taking place. He has been involved in projects where fly ashes were extensively utilized in concrete mixing, primarily for enhancing workability and for decreasing concrete strength. This practice is widespread in Australia, where mixes incorporating slag and fly ash are commonly employed. According to Dr Larisch, workability is a crucial factor for the successful pumping of concrete. Therefore, a specific quantity of fines in the fresh concrete is necessary. He suggested having approximately 25 to 30% of fine content passing through a 600-micrometer sieve, which is essential for effective concrete pumping. Additionally, he highlighted a significant risk for contractors, which is the "blocking" of concrete supply lines. If concrete cannot be pumped and becomes stuck, it can block the line and the drilling head, incurring substantial removal costs amounting to thousands of dollars.

- **How about reducing the cement and adding other pozzolanic material such as sand or gravel?**

Dr Larisch expressed reservations about this approach, as he believes it might alter the percentage of fine materials. The conventional cement tends to be much finer, and depending on the material used, it has the potential to impact the pumpability of fresh concrete. Considering the installation process and the challenge of introducing these materials into the ground, he emphasized that pumpability is a critically important factor.

In addition, Dr Larisch was fully aware of ongoing research into this matter, noting that a contact in New Zealand, employed by a prominent concrete supplier, has shared videos showcasing a pure slag cement with a strength of 15 MPa. This sticky mix serves as evidence that individuals within the industry are actively exploring alternative options for cement replacements.

In summary, historical practices have involved significant use of slag and fly ash as substitutes for cement. However, complete elimination of cement has not been achieved; instead, the cement content has been reduced to some degree. The extent of reduction depends on project specifications, and certain clients, such as road and traffic authorities, impose minimum cement content requirements in their specifications. This limitation poses constraints on designers and contractors. Nevertheless, there exists an opportunity to explore this aspect further.

- **What are your thoughts on utilizing construction waste for the creation of vibro stone columns or compacted stone columns?**

According to Dr Larisch, this presents a highly positive prospect, suggesting significant potential for vibro stone columns, aggregate piers, or standard stone columns. He stated that if construction rubble is appropriately sieved and integrated into the columns, starting with around 20 to 30%, could be a promising initial approach. He was also aware that certain countries, like Germany, have regulations permitting the inclusion of up to 20% recycled aggregates in concrete, and this percentage could potentially increase with further research.

Moreover, delving deeper into the utilization of construction rubble is worth exploring. After the Christchurch earthquake, this became a significant consideration due to the abundance of construction rubble. It was employed in constructing certain stone columns, but issues arose as a substantial amount of fines, including cement dust, were introduced. This could potentially obstruct the drainage path and is detrimental to liquefaction mitigation efforts as well. On the other hand, if the drainage function of the stone columns is not depended upon, the situation changes, opening significant avenues for further research. Dr Larisch acknowledged that he lacks extensive experience in this aspect because, in most cases, specifications did not permit such approaches.

- **Australia possesses abundant sources and stockpiles of railway ballast, which are not highly angular in shape. Could these railway ballasts be effectively employed in the construction of stone columns?**

Dr Larisch affirmed the potential usefulness of using railway ballast and suggested that incorporating 20 to 30% of it as a starting point could be a beneficial idea to assess its performance. However, he expressed concern about potential contamination and soil pollution with rail ballast. Yet, if the ballast is clean, washed, and sieved, it presents an excellent opportunity. The viability also hinges on the size of the ballast; if it ranges from 100 to 150 mm, it may be somewhat large, but there is certainly an opportunity, particularly for deep dynamic compaction.

- **Is there a particular geometry or form recommended for both stone columns and CMC?**

Dr Larisch recommended maintaining a minimum centre-to-centre spacing of 3D to avoid over-densifying the ground, making it challenging to install the next column. Specifically for concrete rigid inclusions, he suggested that a spacing of 4 to 5D is a prudent choice. He also pointed out that the displacement effects associated with rigid inclusions can pose issues for adjacent columns and these effects can be quite substantial. Considering his expertise, he suggested that, for CMC columns, a spacing of 5D might be optimal, though 4D is feasible as well, with 5D potentially being the ideal balance.

Concerning stone columns, the key factor is the area replacement ratio. Dr Larisch recounted a recent conversation with a colleague about a ground improvement project in New Zealand involving 25 m deep stone columns. They concluded that a 22% area replacement ratio is impractical because it prevents the installation of adjacent columns, due to significant ground densification. Therefore, for stone columns, Dr Larisch recommended not exceeding a 20% area replacement ratio. Ideally, for stone columns, their findings suggest a target of around 15% for liquefaction mitigation, while the approach for settlement control may vary.

In projects involving rigid inclusions, Dr Larisch has experienced ratios ranging from 3 to 5%, showcasing a significant cost advantage for CMC due to the ability to space them at larger intervals. In summary, for rigid inclusions, the recommended spacing is not less than 3D and ideally 5D. For stone columns, the area replacement ratio should ideally range from 10% to a maximum of 20%, depending on ground conditions and the intended purpose of ground improvement.

- **What was the range of thickness for the LTP in projects?**

Dr Larisch suggested that relying on the British standard for piled embankments might result in overly conservative platform thickness, which may be unnecessary for all projects. He cited a paper written by Dr Luis King and Dr Daniel King, who completed their PhD research at Monash University in Melbourne, as a significant resource in this context. Their investigation into Load Transfer Platform (LTP) led to the development of a more efficient method than the British standard. The research demonstrated a significant reduction in LTP thickness and Dr Larisch shared this information to address the query.

- **Is it required to include a geosynthetic layer, or is it preferable to omit it?**

Dr Larisch believes that incorporating a geosynthetic layer can be highly beneficial, and he would choose to do so, if possible, as it aids in reducing the thickness of LTP.

- **With respect to bulging mode of stone columns, is there any specific length not to exceed?**

Dr Larisch mentioned that it depends on the methodology and soil strength. For instance, in cohesive soils with an undrained shear strength of less than 20kPa, bulging is prone to happen. Therefore, employing an effective technique to establish a very stiff vertical inclusion may mitigate bulging concerns, as the primary compaction forces are directed downward. In contrast, traditional stone columns, constructed with horizontal vibrations, may push gravel material into the soft layer, resulting in bulging. Hence, it is essential to consider various materials, ground conditions, and installation methods.

- **In saturated conditions which technique is better? VCS, CMC or bi-modulus columns?**

Dr Larisch explained that the effectiveness depends on the intended design, and he suggested that bi-modulus columns could be beneficial. This is because they offer an opportunity to alleviate pore water pressure efficiently through effective drainage. Based on his observations with full displacement columns, there is a tendency for increased stresses with greater depth. In such cases, the columns may reach a point where further penetration is not possible and this often leads to disagreements between the contractor and designer. For example, when the design specifies a depth of 10 m, but the contractor faces practical refusal after reaching 8 m. For instance, in a specific project that Dr Larisch was involved, a contractor specializing in ground improvement faced challenges in reaching the specified depth due to the accumulation of pore pressure. They suspected that the ground might be stiffer than initially assumed, posing a risk to the entire design. Dr Larisch suggested a pause and advised them to revisit the project after a week, selecting an area with fewer installed CMC. Following this recommendation, they were able to achieve the desired depth successfully.

Dr Larisch further clarified that in the case of the CMC technique, particularly in cohesive soils, there is a tendency to elevate the pore water pressure across the entire site. This occurs when employing full displacement systems, hindering the contractor from penetrating the densified soil further for subsequent columns due to limitations in the strength of the piling equipment. Interestingly, he highlighted that such an issue is not often observed with stone columns. This is attributed to the rapid dissipation of pore water pressure through the stone columns, presenting an additional advantage for them and, conversely, posing a construction risk for rigid inclusions.

- **What is your suggestion in terms of sustainability of these techniques?**

Dr Larisch explained that the sustainability relies on material accessibility and location. For instance, transporting stone column material from Newcastle to Sydney may not be advantageous. Similarly, the same constraint could apply when bringing sand for the concrete of CMC columns from Sydney to Newcastle.

So, in this scenario in terms of sustainability none of the options are ideal, but compacting the existing ground thoroughly would be the most favourable choice. Additionally, a crucial factor is minimizing the use of cementitious material. However, this needs to be assessed on a case-by-case basis, irrespective of the method employed. For instance, if a settlement of 50 mm more than the optimal amount can be tolerated, could a potential 30% reduction in construction costs be achieved? Dr Larisch emphasized that it is important to note that such adjustments are only feasible for structures with a degree of flexibility and not for highly critical structures such as bridges and tall buildings; thus, the applicability depends on the specific use case. Once more he suggested that bi-modulus columns might present the most effective solution, given the combination of a highly rigid base from the improved block and slightly more flexible upper sections.

- **What is the acceptable settlement for these techniques?**

The significance varies based on the application, and according to Dr Larisch, in the case of stone columns, it seems inconsequential. This is because the existing soil block undergoes improvement, becoming relatively flexible and ductile. Therefore, if it settles, say by 100 mm or more, it is not catastrophic, as it does not induce negative shaft friction on any columns.
In the case of CMC, Dr Larisch suggested restricting the settlement to 10% of the diameter of the rigid inclusion. For instance, if a 450 mm column is being installed, the recommended design settlement limit would be only 45 mm.

He continued that following the conventional load transfer mechanism of rigid inclusions, soft soil exerts pressure through the inclusions, resulting in negative shaft friction at the top. Below the neutral plane, there is resistance, and an effective design should account for these factors.

- **What is your suggestion in terms of cost of these techniques?**

Dr Larisch clarified that, in broad terms, rigid inclusions are likely the most economically efficient option, surpassing stone columns. This is because the production rates are higher, and with the installation of stiffer elements, the need for area replacement ratios may also decrease. Conversely, there is a greater risk of installation-related issues. Therefore, whilst cost savings are achieved, there's a trade-off with increased risks. However, effective risk management can mitigate these concerns, which would be highly beneficial.

In addition, the construction process involving stone columns is considerably slower. However, a notable advantage is the absence of issues related to saturated conditions, pore water pressure build-up, and cracks. This is why bi-modulus columns present an attractive option, as they blend the benefits of both traditional stone columns and rigid inclusions. He included that while they may fall somewhere in terms of cost between stone columns and CMC, significant reduction of potential risks associated with construction occurs, and by investing slightly more, numerous risks and challenges are eliminated. Dr Larisch considered this factor as a prime opportunity to advance the use of bi-modulus columns. Furthermore, if mechanical engineers can devise a rig or equipment capable of simultaneously implementing both techniques in the future, it would present a remarkable opportunity.

- **Is the combination of PVD vertical drains with CMC recommended?**

Dr Larisch acknowledged that it is an intriguing idea but emphasized the need to consider potential consequences. Introducing more settlement between the CMC is a concern, as it generates negative skin friction. Therefore, depending on the accuracy of the design, there's a risk of causing more harm than benefit.
For instance, if the soil settles 300 mm between the CMC while the CMC themselves experience minimal settlement, the CMC could be eventually dragged down by the settling soil. Additionally, insufficient thickness of the LTP could lead to problems, with the rigid inclusion heads potentially penetrating through the LTP if it is not thick enough. Dr Larisch indicated he would likely opt for a different combination, such as pairing CMCs with stone columns, rather than pursuing this approach.

At the conclusion, Dr Larisch conveyed a strong interest in our research, emphasizing that there remained ample room for exploration and investigation concerning these techniques. He asserted that there were noteworthy opportunities for further development and advancement in this field.

4.2.5 Interviewee 5 (Dr Adnan Sahyouni)

Dr Sahyouni is a seasoned geotechnical engineer whose expertise is underscored by his doctoral thesis focusing on "Rigid Inclusions under Wind Turbine Foundations: Experimental & Numerical Studies." His career trajectory led him to join Menard Oceania, where he plays a pivotal role in both design and business development for the company. Over the years, Dr Sahyouni has demonstrated a keen interest and aptitude for tackling complex geotechnical challenges, particularly in the context of ground improvement using vertical inclusions. His innovative approaches and commitment to advancing the field have earned him recognition among peers and colleagues. Dr Sahyouni's dedication to pushing the boundaries of geotechnical engineering continues to drive his contributions to the industry, positioning him as a valuable asset in the pursuit of sustainable and resilient infrastructure solutions.
Figure 4.6 shows the image of interviewee 5, Dr Adnan Sahyouni.

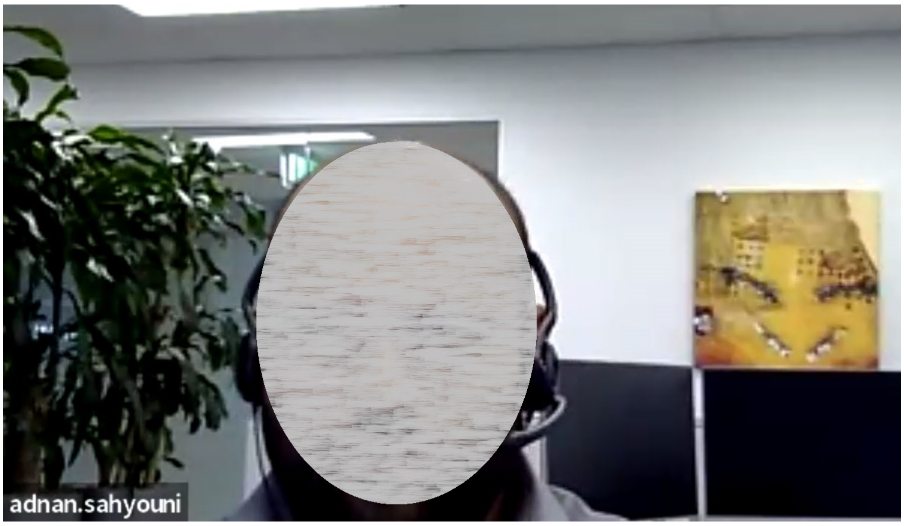


Figure 4.6: Interviewee 5, Dr Adnan Sahyouni

The following questions were asked and the answers of the interviewee are provided.

- **Comparison between CMC and VSC and if stone columns are still used where you are?**

Dr Sahyouni provided insights for comparing these techniques based on their similarities and differences. According to him, Controlled Modulus Columns (CMC) and Vibro Stone Columns (VSC) are both ground improvement techniques used in geotechnical engineering to enhance soil characteristics and support structures.

Similarities:

- Geotechnical Goal: Both CMC and VSC are designed to increase the bearing capacity of the ground, reduce settlement, and improve the overall stability of soil to support various types of structures, including buildings, roads, bridges, wind turbines, etc.
- Methodology: Both methods involve the insertion or creation of columns in the ground. CMC involve the installation of a concrete or mortar mix to form columns, whereas VSC involve the insertion and vibration of aggregate into the soil to form stone columns.
- Load Distribution: By forming stiffer columns in the ground, both techniques redistribute loads from the foundation/structure above to more competent soil layers. It is important to note that there are also differences in how loads are distributed from the structure to the CMC or VSC.

- Environmental Considerations: Each method can be adapted to minimize environmental impact, such as using non-displacement techniques in contaminated soils to avoid spreading contaminants.

Differences:

- Material: CMC are typically made from a mix of concrete or mortar. VSC consist of compacted aggregates (stones).
- Installation Method: CMC can be installed using displacement or non-displacement methods. Displacement methods involve driving a mandrel into the ground and filling the void created with concrete or mortar, whereas non-displacement methods are similar to CFA method. VSC are installed using a vibro-flotation technique where a vibrating probe compacts the surrounding soil and creates a cavity for stone or aggregate to be filled in, compacting it in layers to form a column.
- Suitability for Soil Types: CMC are generally suitable for a wider range of soil types, including cohesive soils, because their installation does not rely on soil granular characteristics for densification. VSC are most effective in non-cohesive, granular soils where the vibration can help in densification of the soil around the columns.
- Load Bearing Capacity: CMC, typically offer a higher load-bearing capacity due to the strength of the material itself. VSC improve load-bearing capacity by densifying the surrounding soil and creating a composite ground that shares the load, but the overall capacity is influenced by the characteristics of the native soil and the compacted stone.
- Cost: The cost and efficiency of CMC versus VSC can vary depending on the project scale, soil conditions, and specific project requirements. CMC might be less expensive in smaller projects due to the high productivity that reflects in costs. However, the cost shall be studied in a case by case basis.
- **What do you think about the combination of techniques, for example, CMC and VSC together?**

According to Dr Sahyouni, the beauty of ground improvement techniques lies in their flexibility; indeed, it is possible to combine both techniques. However, the project's needs, soil investigation results, challenges, and the criteria governing the design need to be considered.

- **Which methods do you suggest to be used according to the soil (sand, clay with high plasticity and low plasticity, etc.)?**

Dr Sahyouni stated that the choice between CMC and VSC largely depends on the specific soil conditions at a project site and the decision should be informed by a comprehensive geotechnical investigation. Additionally, factors such as cost, time, and environmental impact of each method need to be considered.

VSC are particularly effective in sandy soils. The vibration during installation compacts the surrounding sand, reducing the potential for liquefaction and enhancing both bearing capacity and settlement characteristics. Furthermore, VSC can also be effective in low plasticity clays, especially where the soil can be adequately compacted or where drainage improvement is beneficial.
On the other hand, CMC, can be used in a variety of soil conditions, including sandy soils, high plasticity clays, low plasticity clays, and almost all other types of soils.

- **Keller has suggested a new methodology called bi-modulus columns where there is stone column material at the top and rigid inclusions at the bottom in one element. What do you think of that?**

Dr Sahyouni argued that he is not certain whether the terminology and technique of bi-modulus columns originate from Keller; this needs further clarification. Regarding this technique, he explained that the columns integrate the benefits of both approaches and are suitable for very soft soils where a stone column solution might fail due to insufficient lateral confinement and the risk of bulging. Bi-modulus columns enhance bearing capacity, reduce total and differential settlements, and improve stress distribution from the structure to the inclusions. This improvement optimizes the thickness of the Load Transfer Platform between the structure and the inclusions. Furthermore, bi-modulus columns are especially effective in mitigating the mushroom effects and also in situations requiring a deep cut-off to prevent unwanted moments in backfilled slabs or in seismic zones. The effectiveness of this solution has led to its exponential adoption since its development.

- **What are the disadvantages of CMC rigid inclusions? And how bi-modulus columns can resolve those issues?**

According to Dr Sahyouni, bi-modulus columns can compensate for the designed thickness of LTP necessary for rigid inclusions in situations where there is not enough height to install a thick LTP. Bi-modulus columns can reduce the need for such high thickness. For example, this is applicable in flexible pavements.

- **How about the onshore and offshore conditions and which method is preferred?**

Dr Sahyouni clarified that he has never designed or been involved in offshore CMC projects. However, using VSC offshore is beneficial, and at Menard, they have extensive experience with this application.

- **How about long-term performance such as bulging or clogging?**

Dr Sahyouni mentioned that phenomena such as bulging and clogging are not typically associated with CMC due to the material high rigidity and low permeability. In the case of VSC, however, bulging can occur under limited lateral soil pressure, which can often be predicted through detailed soil investigation. As a preliminary solution (subject to further investigation), increasing the column diameter or incorporating geosynthetics may help. Additionally, to prevent clogging, selecting well-graded aggregates could be beneficial. Dr Sahyouni disclosed that at Menard, their extensive database from sites where they have installed stone columns provides valuable insights, aiding in risk understanding and prevention.

- **How about broken rigid inclusions?**

Dr Sahyouni stated that fracturing of rigid inclusions can occur due to various factors. If the loading experienced on-site is primarily axial (as is often the case), the issue may not be significant. However, design verification is necessary to ensure that the project's criteria can still be met. Conversely, in the presence of substantial lateral loading and overturning moments, a detailed investigation should be undertaken, especially for sensitive structures. He emphasized that it is important to remember that rigid inclusions are typically capped with a Load Transfer Platform. Additionally, it is worth noting that expertise in installing rigid inclusions and a strong design background can help prevent such occurrences.

- **The importance of LTP? In numerical investigations, broken CMC with no LTP show a very large settlement but with LTP not much difference is observed. What is your experience in this regard?**

Dr Sahyouni suggested that the Load Transfer Platform (LTP) is crucial in the case of CMC. The designer needs to be careful when defining its thickness and parameters to ensure effective load transfer from the superstructure to the columns. Furthermore, according to his experience regarding the comments about the numerical investigations of a broken CMC without an LTP leading to increased settlement, he found it correct and understandable. However, he assumed this is part of a sensitivity analysis and he emphasised that the LTP should be always installed on top of the CMC unless certain exceptions can be justified.

- **What is your experience with respect to the thickness of the LTP for both techniques and what is the range of thickness for LTP in your design considerations?**

Dr Sahyouni confirmed that the thickness of the LTP is crucial in the design of CMC and according to him it is advisable to refer to the ASIRI guidelines for detailed recommendations. As a quick guide, for wind turbine foundations, the average thickness of the LTP is around 0.8 m. In the case of a concrete slab, even though the average thickness of LTP beneath the slab is typically 0.4 m, attention must also be paid to the spacing between CMC and the additional bending moment in the slab. Thus, the thickness of the LTP could be an important parameter to consider. In other scenarios, such as when CMC support flexible pavements or embankments, Dr Sahyouni clarified that the LTP thickness tends to be greater. In addition, care should also be taken to prevent any “mushroom effect” in these situations. For calculating the thickness of the LTP in such case, referencing standards such as the Eurocodes and British Standards is recommended.

- **For end-bearing CMC, the numerical analysis calculates the settlement close to zero. Is this correct in the real world?**

It was confirmed by Dr Sahyouni that if end-bearing CMC are defined as columns firmly anchored in bedrock, significant settlement within these columns should not be anticipated. However, there may still be some settlement in the soil located between the columns. It was emphasized by him that in the design phase for CMC, the aim to reach bedrock is typically not pursued, marking a key difference between CMC and Piles. The use of the CMC technique, for instance, under a structure, is intended to increase the soil's bearing capacity (if needed) and reduce excessive soil settlement. In such cases, with the geotechnical parameters of the soil identified, the goal would be to terminate the CMC in a competent layer, ensuring that the settlement criteria are met. For example, a post-construction settlement criterion of 30 mm, which can vary from one project to another, is commonly applied to industrial buildings.

- **What is your experience in regard to rigid inclusions used for the batter of embankments?**

Dr Sahyouni explained that rigid inclusions are widely used in cases of embankments. He mentioned the significance of the literature review for further clarification, specifically referring to the ASIRI guidelines and the state-of-the-art report.

- **Which technique (CMC or VSC) are more cost effective where you are?**

Dr Sahyouni believes that evaluating costs requires considering the overall aspects of a project, including time, sequences, materials, mobilization, labours, etc... He explained that while CMC can sometimes be more cost-effective, this is not universally true. It is advisable to assess costs on a project-by-project basis through detailed case studies.

- **Which method (CMC or VSC) is more economical with respect to the thickness of LTP?**

Dr Sahyouni stated that the thickness of the LTP varies depending on the type of structure, as previously highlighted. The LTP is typically more critical in the case of CMC versus VSC. However, ongoing studies examining the behaviour of LTPs and the use of different materials may provide more definitive answers in the future. Nevertheless, when discussing cost-effectiveness, it is essential to consider all aspects of the project before addressing potential savings.

- **In design of vibro stone columns (VSC) and concrete injected columns (CMC) which parameters are more sensitive (Spacing, pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP, traffic load or soil properties)?**

Regarding CMC, Dr Sahyouni explained that their application is specific to each project, requiring a case-by-case approach. For instance, when the objective is to reduce settlement, the focus should be on identifying the layer causing settlement and exploring how to mitigate it. This could involve decreasing the spacing between CMC rather than opting for columns with larger diameters. According to him, increasing diameter primarily enhances the axial strength within the CMC, a factor that must be verified during the design phase. It is crucial to determine which parameter predominantly influences the design and project. A sensitivity analysis of these parameters can then be conducted. However, based on his experience, the key elements of each project must be understood first and prioritized for addressing these critical issues before considering other factors.

- **Floating and end bearing columns? End bearing columns obviously give the best result with respect to settlement mitigation but sometimes they are not possible and floating columns are used instead. What is your insight?**

According to Dr Sahyouni, in the context of CMC, the term "end-bearing" does not strictly imply extending the columns to the bedrock, as this is not an absolute requirement. End-bearing can also apply when CMC are anchored in a sufficiently stiff layer, providing the necessary support. In the design process of CMC, base resistance (qb) and friction (qs) emerge as crucial design parameters. When the qb/qs ratio is significantly high, indicating substantial base resistance compared to friction, the columns can be considered to have end-bearing capacity, even without reaching the bedrock. Therefore, it would be inaccurate to describe such columns as "floating". He clarified that the bearing capacity of CMC is closely linked to these parameters, highlighting the importance of their accurate identification during the design phase.

- **What is the acceptable settlement for these techniques (VSC and CMC)?**

Dr Sahyouni stated that settlement needs to be considered as part of the project criteria; no settlement can be deemed acceptable or unacceptable without context. However, with the potential punching of the columns into the LTP, the axial strength of the columns, and negative skin friction, these parameters must be carefully verified in cases where excessive settlement may occur.

- **Is there any specific geometry or shape for both stone columns and CMC?**

Dr Sahyouni confirmed that columns are generally solid cylinders. For CMC, a threaded variant is also available. The distance between CMC commonly varies from 1.2 to 3.0 m, with diameters spanning from 280 to 450 mm.

- **When the CMC are installed, the soil around the auger is smeared, but in the numerical model, the properties of the soil are inputted into PLAXIS without differentiating the soil adjacent to the CMC columns. How this situation operates in the real world is to be considered.**

Dr Sahyouni found this topic interesting and mentioned that once the displacement technique is employed to install CMC, the soil at the edges of the CMC typically becomes densified, potentially increasing friction at the column-soil interface. However, when numerically modelling it with PLAXIS, for example, if this effect is not accounted for (as it is not straightforward to model), the capacity of the CMC could be underestimated. Conducting an instrumented static load test helps to thoroughly understand this phenomenon by providing direct measurements of friction, which can then be used to refine PLAXIS simulations. Furthermore, analytical formulations such as Frank and Zhao (1982) offer insights into the friction along the CMC column based on soil type, often yielding higher results compared to those from PLAXIS software.

In conclusion, Dr Sahyouni demonstrated a strong enthusiasm for this research, emphasizing the vast avenues for exploration and investigation that remain within these techniques. He was highly optimistic about the substantial potential for further growth and progress in this particular field.

4.2.6 Interviewee 6 (Mr Philippe Vincent)

Philippe Vincent has dedicated two decades of his professional career to the Soletanche Freyssinet Group. A French national, he made the significant move to Australia in January 2002, immersing himself in various facets of Menard's enterprises, including Freyssinet, Menard Oceania, and REMEA. Currently serving as the Managing Director of Menard Oceania/REMEA, he holds the esteemed position of President within the French Australian Chamber of Commerce, specifically leading the NSW chapter and is also a Director of the Australian Federation of Piling Contractors. Educationally, Philippe laid the foundation for his career in France, culminating in a Master's degree in science from a prestigious French School of Mines. Upon relocating to Australia, he further enriched his academic profile by attaining a second master's degree in civil engineering from the University of New South Wales (UNSW) in 2002. His commitment to academia persists, marked by ongoing collaborations with universities and active involvement in numerous ARC projects over the years focusing on innovative geotechnical technologies. Recognized as a Chartered Engineer in Australia and New Zealand, as well as with the Asia Pacific Economic Cooperation (APEC), Philippe achieved the distinguished status of Fellow and Engineering Executive of Engineers Australia in 2018. Throughout his career, Philippe has played pivotal roles in several noteworthy projects, contributing to the design and construction of some of

Australasia's largest geotechnical endeavours. Figure 4.7 shows the image of interviewee 6, Mr Philippe Vincent

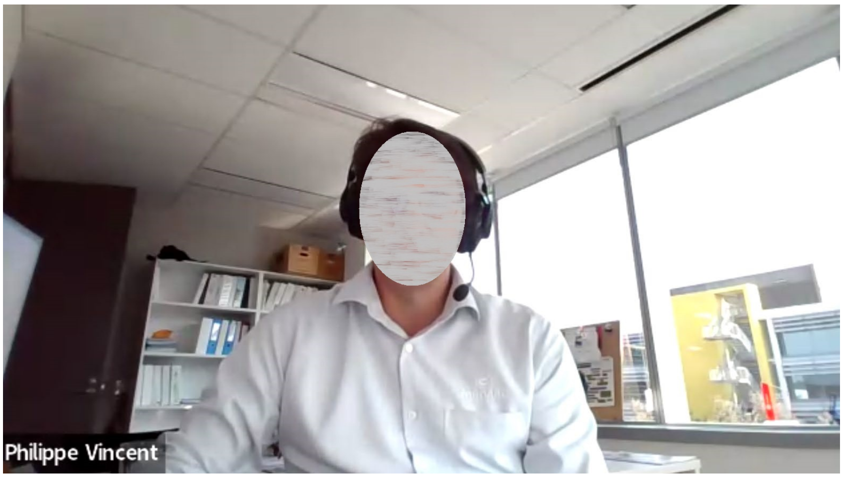


Figure 4.7: Interviewee 6, Mr Philippe Vincent

The following questions were asked and the answers of the interviewee are provided.

- **We acknowledge Menard's substantial engagement with CMC rigid inclusions. Are stone columns also a method integrated into your firm's projects, or is this approach not part of your project methodologies?**

Mr Vincent stated that they have completed numerous projects involving stone columns in Australia and New Zealand. These projects aimed to mitigate seismic liquefaction, enhance stability for existing structures, and address slope stability concerns.

- **What are the critical factors in the design and construction of stone columns? From a contractor's perspective, we're interested in understanding which parameters are the most sensitive and crucial? (Parameters such as spacing, the pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP and soil properties.)**

Mr Vincent mentioned that the primary limitation regarding the installation of stone columns is the maximum replacement ratio. This ratio, determined by the combination of column diameter and spacing, must stay within a specific range. Depending on the ground conditions, exceeding 25 to 30% can pose significant challenges, leading to excessive heave and making proper installation difficult. It is crucial to prevent deformation of existing columns or excessive heave and deformation of adjacent properties. That's the initial concern to address. With respect to the depth of installation, it really depends on the equipment that's available. For wet-bottom feed, it is possible to go down as far as 40 plus meters and usually using equipment that is attached to cranes. Regarding the dry-top feed method, there's a specific range of applications to adhere to. This technique is highly adaptable, typically limited to around 25 m depth. It is generally applicable across a broad spectrum of ground conditions and suitable for various terrains, including onshore and offshore lands, clayey and sandy materials, and stiff ground requiring predrilling.

- **For CMC installations, the rate of installation varies; some contractors work at a rapid pace, while others opt for a slower approach. Overall, what is the general effect of the installation rate, or can they be installed quickly without issue, depending on equipment limitations?**

Mr Vincent explained that the speed of installation does not notably affect existing columns, as long as there's adequate spacing between them. Whether installing 200 m a day or a thousand meters a day, the difference is minimal. In most cases, the ground will not be able to dissipate excess pore water pressure within the given timeframes. Therefore, the key focus is to consistently uphold quality control measures to ensure that the columns are constructed efficiently and align with the designated design parameters.

- **Regarding the installation of stone columns and CMC, do you typically install them in a single row, one after the other, or in a staggered pattern such as “hit and miss”? Could you elaborate on the methods used and indicate any preference for a particular method?**

Mr Vincent disclosed that their typical preference is to install columns continuously, proceeding one row at a time. However, there are certain circumstances that might prompt them to consider employing a "hit one, miss one" pattern, although this approach can introduce additional complications. Specifically, there's a heightened risk of damaging previously installed CMC columns during subsequent passes, requiring careful attention from the installer. Therefore, for CMC columns, they lean towards continuous installation, and the same preference extends to stone columns as well.

- **In ground improvement projects involving embankments, are the edge columns and middle columns typically uniform, or are there variations based on design and construction factors? For instance, are some columns shorter or wider? What recommendations would you offer in this regard?**

According to Mr Vincent, the approach varies depending on the design. Along the shoulders of embankments where the load is lighter, columns can either be spaced further apart or installed at shorter lengths. However, if lateral stability needs to be addressed, spacing must be adjusted to meet design specifications. Ultimately, the decision hinges on various parameters, particularly the ground conditions.

- **In CMC, a significant quantity of cement is utilized. Some individuals propose incorporating marginal materials as a partial substitute for cement. For instance, alternatives like fly ash, bagasse ash, and rice husk ash are being considered. Various materials and by-products are accessible. Do you endorse conducting research on the feasibility of using such materials, considering factors such as pumpability, slump, and other relevant considerations, or do you not support this approach?**

Mr Vincent affirmed and emphasized this point fully. Initially, it is crucial to note that ground improvement solutions generate substantially lower CO2 emissions in contrast to conventional piled foundations. He noted that wherever feasible, they have already incorporated considerable amounts of fly ash into their CMC mixes, typically ranging from 20 to 40%. It is evident that fly ash is readily accessible in Australia, which may not be the situation in other regions. Mr Vincent also mentioned that they are currently exploring various alternatives to substitute some of the other by-products, which could include recycled materials. Additionally, they are considering a new method for installing stone columns utilizing CMC technology, where the binder is eliminated. This approach would naturally limit the range of applications due to significantly reduced compression characteristics. Furthermore, he explained that ground improvement naturally restricts the quantity of material utilized, as it depends partly on the existing mechanical properties of the ground. Therefore, the initial approach involves removing reinforcement whenever feasible and opting for lower mortar strength (such as 15 to 20 MPa mortar instead of 40 MPa concrete). Additionally, as they progress and scrutinize site-specific limitations more closely, they can optimize further by incorporating recycled materials and reducing the binder content even more.

- **The objective of this research study is "finite", aiming to offer recommendations regarding the optimal methods based on various factors such as cost, speed, durability, sustainability, and more. We have a few distinct scenarios and would like to seek your recommendation on the preferred method.**

In scenario one, considering both saturated and unsaturated soil conditions, which method do you suggest is more suitable: stone columns or CMC rigid inclusions?

According to Mr Vincent, both methods have distinct advantages. CMC enables the support of heavier loads and offers better control over deformation, making it preferable in scenarios where limiting deformation to 25 to 50 mm is crucial, such as in warehouse projects with concerns about differential settlement. On the other hand, for tasks like stabilizing a quay for example, where a target post-construction settlement of 100 to 200 mm is necessary, stone columns might be the more suitable choice. In summary, stone columns and CMC each have unique strengths and weaknesses, making them suitable for different applications.

The next scenario pertains to both onshore and offshore projects. Which method would be preferable for offshore construction, and which method for onshore projects?

Mr Vincent reiterated that the choice depends on the structure being built atop. For embankments and reclaimed land, stone columns prove highly effective, offering good control over deformation and lateral deflection. However, if heavy loads are anticipated, other techniques such as CMC or deep foundations may be necessary. In cases like having a large diameter oil tank on an earth embankment, a combination of both methods could be employed. Stone columns could be utilized around the periphery to control lateral deflection, while CMC could be applied within the central area of the tank.

Regarding the use of CMC underwater, Mr Vincent noted that it is not commonly practiced to his knowledge. While he does not rule out its possibility, he acknowledged that it would likely be a complex undertaking.

The next scenario is related to very long columns and also short columns (L/D greater than 40 to 50 and also shorter). Which method would be better for the long columns?

Mr Vincent disclosed that for both CMC and stone columns they install columns up to 40m deep and there is no big difference in that regard. In ground conditions that are extremely soft, it is necessary to check the risk of buckling and the impact of vertical loading on the design tolerance and structural capacity of the CMC columns. But that's a very rare type of scenario.

With respect to cost and construction rate which method do you suggest? Stone columns or CMC?

According to Mr Vincent, in consideration of environmental impact and greenhouse gas emissions, stone columns present an efficient solution. This is because they rely solely on raw materials without the use of cement, thereby avoiding the release of CO_2 into the atmosphere.

Given the current focus on environmental concerns, this aspect holds significant importance. Mr Vincent suggested that the engineering community should reassess the criteria for various structures to enable more projects to be constructed atop stone columns. CMC also boasts strong advantages and is often employed as an excellent substitute for traditional piling methods. Furthermore, compared to piles, it stands out as a superior technique from an environmental standpoint, aside from the evident cost and time savings. Therefore, it is essential to adopt an approach that prioritizes resource conservation whenever feasible.

- **In terms of construction challenges for installation of both techniques (stone columns and CMC) what are your experiences that you can share with us?**

Mr Vincent stated that for CMC, the main challenge lies in the installation process, where the risk of damaging existing columns must be taken into consideration. It is crucial to ensure that the design and methodology account for installation effects. Careful consideration is required for adjacent structures as well. For example, if there are underground structures or roads and embankments which could be impacted by the deformation during the installation of CMC. Moreover, it is essential to conduct quality control during the installation of the columns to guarantee a satisfactory rate of extraction and effective concrete pumping. This ensures that there are no instances of necking or deformation of the inclusion throughout the installation process. Finally, accuracy testing is conducted once the computer is configured to verify that the design assumptions are fulfilled. In the realm of geotechnical engineering, it is prudent to anticipate the worst-case scenario and acknowledge that our hypotheses may not always be entirely accurate. So that's from the CMC perspective.

On the stone column front, usually the challenges could be similar as there is also a displacement methodology which can induce lateral deformation and damage adjacent properties. However, the concern in terms of damage to existing columns is not as prevalent as they are made of deformable material. Mr Vincent explained that he has experience installing stone columns using a vibrator, which is lowered into the ground. However, this method is more prone to encountering obstructions. In landfill areas, on the other hand, CMC can be utilized. He cited a recent project completed in Tempe, Sydney, where CMC columns were successfully installed to a depth of 25 m through landfill. This achievement would not have been feasible with stone columns due to their limited effectiveness in overcoming obstructions. Furthermore, another advantage of CMC is its ability to be installed in incremental steps, making it more convenient to work under overhead obstructions.

- **In our numerical analysis, we simulated a scenario where 10 to 15% of the CMC columns fail. Despite having a robust Load Transfer Platform (LTP), we observed minimal changes in settlement differences. However, upon removing the LTP, we noticed a significant increase in settlement, highlighting the crucial role of LTP in these techniques. What are your thoughts on the importance of having an effective LTP in both of these methods?**

Mr Vincent argued that he would not expect to see as many as 10 to 15% of the rigid inclusions to fail and generally speaking most inclusions are able to withstand the design load that they have been designed for. This ensures that target safety factors (in the range of 2 to 3) are met. Nevertheless, he confirmed that LTP is crucially useful to redistribute loads and can to an extent overcome the issues associated with isolated non-performing CMC elements that could have not been identified during the installation. As a result the CMC plus LTP offers a great level of resilience.

- **When we refer to "failure," we mean instances where the CMC rigid inclusions are fractured or no longer intact. What is your perspective on this matter?**

Mr Vincent holds the belief that even if CMC are cracked or broken, they can still support vertical loads. However, as a hypothesis and to confirm the significance of the Load Transfer Platform (LTP), it is a valuable initiative to investigate further. He emphasized that the LTP stands as a pivotal component in the philosophy of ground improvement using rigid inclusions. Typically, inclusions are not directly employed to underpin a structure. However, in cases where they are, reinforcement may be added, or greater care may be taken during construction to ensure they are delivered within stricter tolerances.

- **What was the thickness of the Load Transfer Platform (LTP) in the projects you've worked on? Can you provide a range?**

Mr Vincent mentioned that the thickness varied, ranging from 0.4 to 1.5 m.

- **What are the differences, advantages, and drawbacks between floating and end-bearing columns? As you're aware, for both rigid inclusions and stone columns, we have the option of using either floating or end-bearing configurations. In your opinion, which of these two approaches offers better cost savings and yields the most favourable outcomes simultaneously?**

Mr Vincent explained that in designing end-bearing CMC columns, the emphasis lies more on the principles of tip reaction. Conversely, for floating CMC columns, friction plays a more crucial role than tip reaction. However, in reality, there's usually a combination of both end-bearing and floating configurations. This is because CMC installation is typically halted upon reaching a firm or stiff layer, with rare extensions to reach bedrock. Such an extension might occur in scenarios where, for instance, there's a highly elastic material, and connecting it to hard rock would direct the entire load to the tip of the inclusion.

Now, revisiting the concept of floating CMC, he clarified that this typically occurs when the CMC columns terminate within soft to firm clayey layers. They are commonly utilized for managing the transitional zone between CMC anchored in stiffer materials. In such cases, there may be an expected deformation of, for example, 50 mm over the next 10 to 20 years. Accordingly, the design involves addressing the transition zone, which could span from the abutment of a bridge to an area experiencing more substantial deformation. This latter area may be improved by conventional consolidation techniques, with or without wig drains, and could extend over several hundred meters. Within this transition zone, adjustments in the depth of the CMC can be made to a level where they can effectively function as floating elements.

- **If you have the option to choose between floating or end-bearing configurations, which one would you suggest?**

Mr Vincent clarified that each option serves a distinct purpose. For instance, in the case of a bridge abutment, end-bearing CMC, which manage settlement to around 25 to 50 mm, would typically be employed within the structural zone (approximately 20 to 30 m away from the bridge piles).

Beyond this area, underneath the embankment, floating CMC would be utilized to create a transition with areas that have not undergone ground improvement.

- **Have you encountered any cases in a project where you utilized both floating and end-bearing columns simultaneously? If so, did this approach result in any instances of inducing differential settlement?**

Indeed, Mr Vincent affirmed that such situations have occurred. In these cases, it is necessary to carefully calculate and adjust the depth of floating CMC gradually to effectively manage and control any potential instances of differential settlement.

- **So essentially, you're suggesting that the design should be primarily based on the floating columns, correct?**

Mr Vincent explained that, in general, the design process focuses on areas where settlement criteria are more stringent and then progresses to design transition zones. During this process, the depth of CMC is gradually reduced, and spacing is increased accordingly.

- **What is your opinion on the efficacy of bi-modulus columns, which we are exploring in this numerical investigation? Do you consider this to be a promising alternative to other techniques in the future, given that it offers the combined benefits of both methods simultaneously?**

Mr Vincent acknowledged and confirmed that bi-modulus columns are indeed utilized by Menard. This technique, developed some time ago, is typically employed when there are restrictions regarding the thickness of the Load Transfer Platform (LTP). In order to accomplish this, they perform post-drilling at the top of the column and substitute it with a comparatively large stone section. This facilitates the transfer of load from the drilled-out head of the inclusion back onto the underside of the pavement or structure slab that requires support, all while reducing the thickness of the LTP.

He pointed out that the installation of bi-modulus columns is more expensive compared to installing regular CMC because additional steps like post-cutting are involved in the construction process. Consequently, it typically incurs higher costs than simply opting for a thicker LTP layer. Therefore, if there is ample space available to accommodate a thicker LTP, it usually proves more economical to choose that option.

- **If you're aware, one of the drawbacks of the CMC technique is the occurrence of mushroom effects. Perhaps the primary concept behind introducing bi-modulus columns to the industry is to address this issue. Have you been involved in any projects where you encountered mushroom effects?**

Mr Vincent acknowledged that he had seen pictures of such problems around 20 plus years ago, but in recent years, they have not encountered this issue as it has been effectively managed. However, to mitigate problems caused by punching effects, it is crucial to ensure that there's a sufficient Load Transfer Platform (LTP), or alternatively, consider using bi-modulus columns.

- **As a practical inquiry, we're curious if you've been involved in any projects or are aware of scenarios where both CMC and VSC techniques were employed simultaneously. Specifically, where stone columns were primarily utilized for drainage paths, while CMC were employed for settlement control purposes.**

Mr Vincent explained that they have had projects where they used both. For example, stone columns could be utilized at the embankment's edges to manage lateral spread, especially where settlement control is not highly critical. Additionally, CMC might be applied beneath structures. However, he noted that he is not aware of any projects where stone columns are specifically employed for drainage purposes. He argued that if drainage were the sole concern, they would opt for wig drains instead. Another concern regarding the use of stone columns solely for drainage is the potential for contamination of the columns by silty or clayey materials during installation, particularly when employing the top-feed wet method or over time. Additionally, stone columns are typically spaced too widely apart to significantly enhance ground drainage within an appropriate timeframe.

- **In terms of design considerations, understanding spacing and diameter is crucial for both stone columns and CMC. What would you recommend as the optimal spacing relative to diameter for these techniques?**

Mr Vincent suggested that for stone columns, they aim to limit the replacement ratio to 25 to 30%, rather than basing it on diameter. For instance, based on his experience, for 800 mm columns, one could have a spacing of approximately 1.8 m.

- **Would a ratio of 3D for stone columns and 4D for CMC be considered acceptable?**

Mr Vincent disclosed that for CMC, they typically adhere to a replacement ratio of no more than 5 to 7%, making a spacing of 4D acceptable. However, for stone columns, achieving a replacement ratio of 20 to 30% is often necessary, necessitating a much closer spacing than 3D.

- **In your experience and insight, how do these two methods compare in terms of sustainability and durability? Which one demonstrates greater reliability in terms of sustainability?**

Mr Vincent explained that both designs have a durability of around 100 years, making them suitable for long-term use. However, when considering durability comprehensively, stone columns without binder are deemed more durable, although this criterion is typically not prioritized. Regarding sustainability, reducing the amount of binder and minimizing the use of cement can significantly enhance sustainability by conserving resources. Nevertheless, other factors should also be taken into account, and the most suitable approach depends on the specific problem being addressed.

Mr Vincent also mentioned that Menard conducts analyses on a project-specific basis, considering the merits of different approaches. Factors such as the availability of fill material can influence the chosen solution. For instance, in the case of the LTP, selecting from a variety of thicknesses can affect the extent of remedial work required in the long-term. Hence, it is crucial to carefully consider all design and construction parameters and reflect on the consequences of design choices over the project lifespan.

In conclusion, Mr Vincent expressed encouragement for our research, thanked us for our questions, and found the discussion very interesting. He kindly offered to remain available for any further inquiries and assistance, welcoming us to reach out to him as needed.

4.2.7 Interviewee 7 (Mr Ondrej Synac)

Mr Synac has served as a chief engineer and designer for several prominent geotechnical companies worldwide. He possesses extensive expertise and hands-on experience in various ground improvement techniques, gained through his involvement in numerous projects across Europe, Australia, and other regions.

Mr Synac prefers to refer to CMC (Controlled Modulus Columns) or CICs (Concrete Injected Columns) as rigid inclusions (RIs), and he believes that investigating this topic is an excellent subject. Figure 4.8 shows the image of interviewee 7, Mr Ondrej Synac.

Figure 4.8: Interviewee 7, Mr Ondrej Synac

The following questions were asked and the answers of the interviewee are provided.

- **Provide information on the comparison between CMC and VSC, and whether stone columns are still utilized.**

Mr Synac stated that currently he is involved in designing a very large CMC project for an exceptionally tall building, and he has noticed that this technique is becoming increasingly popular. In addition, he noted that there is an increase in technical papers with a topic of “disconnected raft," which he regards as rigid inclusions with LTP.
With respect to stone columns, Mr Synac explained that he spent a decade designing stone columns in the UK and believes that the technique is comparable to soil mixing. According to him, while stone columns are a popular practice in British culture, unfortunately, they are not widely known in Australia.

However, they enjoy significant popularity in New Zealand. <u>Currently, there are only a handful of companies worldwide that still specialise in stone columns.</u> Nevertheless, Mr Synac believes that they are an incredibly sustainable option, with carbon calculators indicating that they comprise only 15% of rigid inclusions. Additionally, exploring the potential for recycling aggregates is an important consideration. He clarified that there are 2 design approaches in stone columns. One is following Priebe (1995) and similar methods (such as Baalam & Booker - 1985). The other approach is considering stone columns as rammed columns such as Geo-piers. Both approaches have different design assumptions. While Geo-piers are gaining popularity in New Zealand, they are still relatively unknown in Australia due to the fact that compared to rigid inclusions, stone columns require more experience from the driver and are slower. On top of that they reduce the settlement less than rigid inclusions. According to his experiences, stone columns reduce settlement by 2 to 3 times, while rigid inclusions reduce settlements by 5 to 10 times, especially if the inclusions are embedded in very stiff or dense materials.

He argued that stone columns have to bulge to start acting, but this is not needed with rigid inclusions. Additionally, rigid inclusions penetrate the LTP, and therefore, the stiffness of the platform is crucial for mobilizing the arching effect. However, for stone columns, the realization of the arching effect takes much longer. Mr Synac expressed pessimism about rigid inclusions in one critical aspect, which is their liquefaction and earthquake dynamic behaviour, and according to him, in such situations, stone columns are undoubtedly the superior solution.

- **What are your thoughts on a proposed innovative approach by a prominent specialist contractor, known as bi-modulus columns, which integrate stone column material at the upper part and rigid inclusions at the lower part within a single element?**

Mr Synac is in favour of bi-modulus columns, and he stated that the idea of these types of columns was introduced by him in Australia when he was the Chief Engineer of a prominent subcontractor where he designed them. He asserted that bi-modulus columns can offer superior performance in ground improvement but also acknowledged their higher cost, which might explain why they are often overlooked by the industry.

- **What are the disadvantages of CMC rigid inclusions? And how bi-modulus columns can resolve those issues?**

Mr Synac believes that there are a few issues with CMC such as the installation effects. He argued that installation effects are extremely important because of the possibility of tensile stresses due to the heave, which creates difficulty for the CMC rigid inclusions and may cause them to crack at the head.

He noted that implementing bi-modulus columns would be a viable solution to address this issue. In his previous role at a prominent contracting firm, he oversaw the development of a small rig capable of constructing these type of columns, which proved to be an attractive technique at the time. By replacing the head of the CMC rigid inclusions with gravel and re-compacting a portion of the Load Transfer Platform, bi-modulus columns could effectively mitigate installation challenges.

According to his assessment, he holds the view that the initial rigid inclusions used in Australia encountered a notable difficulty with LTP movement. However, with the introduction of bi-modulus columns, as the head of the column engages and connects with the rigid inclusions, this characteristic allows for the interaction of the CMC into the platform, effectively addressing that challenge.

As per Mr Synac's perspective, studying bi-modulus columns is a great subject, but many companies are hesitant to use them due to the added cost and logistical challenges they present. Currently, up to 1200 linear meters of rigid inclusions can be installed per day, making it a highly effective method. Although bi-modulus columns are still technically more efficient, their installation requires two separate crews, which makes them less attractive to contractors. Despite this, Mr Synac recommended investigating the use of bi-modulus columns in a PhD program. He remains optimistic that as installation techniques become more advanced, bi-modulus columns may become the most efficient technique in the future.

- **What are your thoughts on utilizing a blend of methodologies, such as combining CMC with VSC?**

Mr Synac shared that he utilised a particular combination of techniques in an LPG plant located in Western Australia, where they conducted dynamic replacement of sand and installed wig drains in between. However, the downside of these methods is that they can be time consuming. For soils that can liquefy, using more drains and fewer stone columns may work better. However, Mr Synac's experience with drains and stone columns is not very positive due to the additional smearing that occurs around the drains. He further explained that installing stone columns is quite challenging in soft conditions, where it must rely on the capability of the driver and installer to use a bottom-feed system.

This is perhaps the reason why the installation of stone columns is often perceived as risky due to many examples of companies improperly installing them. By contrast, the installation of rigid inclusions is nearly automatic.

On the other hand, with rigid inclusions since they can be designed quite accurately and precisely with finite element numerical techniques such as PLAXIS 3D and their installations are not challenging as stone columns, an acceptable prediction of their behaviour can be expected. Conversely, the installation process of stone columns, which includes compaction and vibration, etc., is extremely important in determining the overall behaviour of the stone columns and it is virtually impossible to model these installation effects unless a highly sophisticated model is generated. This is the reason why the predictions of the behaviour of stone columns using numerical modelling cannot be as reliable as rigid inclusions. Therefore, he can foresee that in the near future (5 to 10 years), there will not be any stone columns anymore.

- **What are your views on both onshore and offshore conditions, and which approach is favoured?**

Mr Synac stated that rigid inclusions are not suitable for offshore conditions, and only stone columns can be used in these situations. However, installing stone columns in marine environments poses quality assurance challenges, as seen in his experience on a tunnel project in Greece. Some of the questions that need to be answered before using stone columns are:

how much settlement will be generated, how much sand blanket is required, and how much compaction can be achieved? Leading contractors have also experienced compaction difficulties with calcareous sediments in a project in Dubai. While stone columns remain an option for marine environments, contracting companies are moving away from this technique due to declining confidence. Nonetheless, according to Mr Synac, vibro-floatation is still the more widely accepted method for marine environments, compared to stone columns.

- **What are your thoughts on the long-term performance of stone columns and issues such as bulging or clogging?**

Mr Synac explained that he worked as a site engineer in the UK where they excavated a site that had stone columns installed for a decade, as stone columns continue to be a popular choice for marginal housing sites in the UK. Interestingly, the 10-year-old stone columns they dug up were not clogged. While he is not sure if certain materials are more prone to clogging than others, he remains sceptical about the phenomenon of clogging in stone columns. He noted that it has been observed that stone columns do bulge, but this phenomenon is usually short-term, and consolidation takes place as the columns undergo bulging, along with pore water pressure dissipation. Although there are no studies to confirm it, according to his opinion, long-term deterioration and bulging are not major concerns when it comes to stone columns, and they are an excellent solution in the long run. Mr Synac cited an example of a project involving a warehouse for a wine company. The original design was based on three levels of pallets, and the client thought that the stone columns designed for the warehouse were inadequate when the slab began to crack. His company was then called in to rectify the problem, and it was discovered that instead of three pallets, nine pallets (three times more) were placed on the slab. When the ground was excavated to see what was happening, it was found that the long-term loading, much more than designed and expected, did not cause the long-term deterioration and excessive bulging of those columns. Therefore, Mr Synac concluded that long-term problems with stone columns are not a major concern. Perhaps in 50 to 100 years, there could be a concern, but for a typical structure with a lifespan of 12 to 15 years, there should not be any problem.

- **What are your considerations regarding fractured rigid inclusions?**

Mr Synac believes that 10 to 15 percent of rigid inclusions are possibly broken in any project, regardless of efforts to prevent it. He explained that if there are no significant changes in loading above the LTP, there should not be any issues. However, if there are different spacing between rigid inclusions, caused by varying loading, it can result in detrimental problems. This issue is more serious in residential projects than infrastructure projects. Additionally, there is a high risk of post-installation damage to rigid inclusions due to excavation between them for services, which is often overlooked by designers. If the number of broken rigid inclusions exceeds 15 percent, it can lead to significant problems.

- **The significance of (LTP) is evident. In numerical simulations, broken CMC lacking LTP exhibit considerable settlement, whereas with LTP, the settlement is minimal. What are your insights on this observation?**

Mr Synac clarified that in terms of the numerical discussion, this is true, noting that modelling does not consider the practical aspect of it. He also stated that he finds it difficult to accept the geotextile behaviour used between CMC and LTP when it is predicted by numerical means such as PLAXIS 3D. Even if the model is getting re-meshed to be more precise, he still has reservations about its accuracy.

Mr Synac shared his experience with a project in Poland, where very high rigid inclusions were used for a high bridge embankment. Strain gauges were installed above the rigid inclusions to obtain measurements. However, the PLAXIS experts employed by the client for the numerical investigation of the project were not able to model the stresses that were observed and measured. He commented that according to his recollection, strains in geotextiles were greatly underestimated using PLAXIS, estimating 3 to 5 times less strain than the actual values. He further mentioned that some Australian major companies have conducted very comprehensive and well-executed numerical modelling, measurement, and monitoring in projects where rigid inclusions are used. He suggested that they can be contacted for further information. In summary, he held the belief that the mechanism of creeping and settlement is not very well understood in numerical modelling.

- **What is your experience with respect to the thickness of the LTP?**

Mr Synac elaborated that there are two approaches in the design of LTP. One is to ignore the LTP and go as close as possible to the foundation, which is usually used for pad foundations and warehouses, or a very large raft foundation where designers must rely on the arching above. He mentioned a French National specification ASIRI, which is the only design standard worldwide for rigid inclusions and can be used here in Australia too. According to him, French and German investigators have conducted very extensive research on CMC and monitored the behaviour of these columns for various thicknesses of the LTP. Based on their research, to calculate the thickness of LTP, they recommended 0.7 × S, where S is the spacing between edge to edge of the rigid inclusions. He further disclosed that there is an alternative approach to designing the Load Transfer Platform (LTP) often used by German designers.

In this approach, the thickness of the LTP is made approximately equal to the spacing between the edges of the rigid inclusions. Mr Synac commented that he has designed LTPs with a thickness of less than 0.5 m for some projects. However, very specific design and a very stiff geogrid were selected to assist with arching effects. Mr Synac emphasized that he does not recommend using rigid inclusions without geotextile as it can be dangerous, in his opinion. The long-term performance of arching is not well understood, particularly in relation to changes of the groundwater level and excavation between rigid inclusions can also impact the overall performance of the ground improvement. In short, he said that he has designed the thickness of LTPs from 0.5 to 1.5 m depending on each specific project and its requirements. Furthermore, he confirmed that the results obtained from the numerical analysis that the more the thickness of LTP, the more total settlement, are close to reality. He believes the settlement can be minimised substantially once the rigid inclusions are as close as possible to the foundation to be able to rely on the stiffness of the foundation rather than arching effects and in such conditions maybe there is no reason to use piles.

- **For end bearing CMC, the numerical analysis calculates the settlement close to zero. Is this correct in the real world?**

Mr Synac expressed his scepticism and lack of trust in numerical analysis in terms of limited CMC settlement. He noted that contractual companies prefer using simpler soil models, like Mohr Coulomb or Soft Soil Creep, instead of advanced models such as Cam-Clay or modified Cam-Clay, to demonstrate and achieve more believable settlement predictions. Additionally, he holds the belief that end-bearing CMC, as modelled in PLAXIS 3D, is no longer a rigid inclusion and behaves differently. In his opinion, a single rigid inclusion should be in ULS condition, very close to a factor of safety of 1.1 to 1.2 to engage the arching and ground improvement behaviour. Furthermore, Mr Synac argued the fact that since PLAXIS is not very efficient in terms of modelling the skin friction and the end-bearing effects of the element, it is therefore, may be better to use some piling settlement programs as an initial sensitivity check. According to his experience settlement load curves obtained by PLAXIS for single rigid inclusions are sometimes not realistic in comparison to what is known about the rigid inclusions and their behaviour in practice. Mr Synac also discussed that for the design of vertical inclusions (VSC, CMC, or bi-modulus) in PLAXIS, he prefers the volumetric design approach over the embedded beams option. The reason for this is that embedded elements are outside the mesh and not connected to the mesh, therefore, behaving like a pile. He was then informed that the results obtained from the numerical analysis prove that embedded beams and volumetric elements both yield similar results with respect to ground settlement. According to Bentley engineers, once many vertical inclusions are used in a model (more than 80 elements), the only way to design that ground improvement project in PLAXIS is through embedded beams.

- **What are the differences between settlement behaviour of stone columns and CMC?**

Mr Synac stated that, according to his experience, typically, stone columns have 80% of their settlement realized during construction, with only 20% of the settlement occurring in the long-term. With respect to rigid inclusions, his experience is in infrastructure only, and he has not even seen creep because with good arching development on top of the rigid inclusions, the soil around the rigid inclusions is unloaded.

- **Which technique is the best for the support of bridge approaches? CMC or VSC?**

According to Mr Synac, the soil mixing approach is the best solution for such situations. However, he would never recommend stone columns for bridge abutments. He stated that he is aware of a leading specialist contractor having an enormous problem because of using stone columns in bridge abutments in a project in Malaysia. He clarified that reason for these issues is that settlement and creep is dependent on long-term consolidation and drainage after construction of the bridge. Therefore, the settlement can still occur and stone columns are not always suitable for such situations as bridge might deform or develop cracks. Rigid inclusions, on the other hand, can be a reliable technique for bridge approaches. However, Mr Synac strongly recommended using a steel mesh instead of geogrid, as its behaviour is much stiffer and does not move as much.

- **How bi-modulus columns can be a great replacement for other vertical inclusions?**

Mr Synac expressed that, from a geotechnical perspective, the technique is commendable. However, its appeal is diminished by the expenses associated with involving two separate crews and the slower pace of production. He envisioned a future where advanced technology and industrial engineering could potentially merge both techniques into a single, rapid, and efficient process. This advancement could unlock the potential for widespread adoption of the technique, addressing numerous challenges related to poor ground conditions across various projects.

- **What is your experience in regards to rigid inclusions used for the batter of embankments?**

Mr Synac noted that the design of embankments relies heavily on the bending moments at their edges. He mentioned that he effectively addressed issues related to batter slopes in the past by employing L-shaped soil mixing techniques at the edges. This method facilitated the distribution of forces, thereby reducing the need for significant reinforcement. He explained that he is very fond of soil mixing technique, and he thinks it is the right environmental solution for Australia as stone columns are not very suitable due to the lack of materials in this region. He strongly believes that the stiffness of soil mixing increases over time, and due to the larger replacement ratio (15 to 25% compared to stone columns), there is an added safety factor and minimal engineering risk involved when using this technique. However, the only drawback of soil mixing is its tendency to soften under certain pressures, causing the soil-mixed columns to yield. Therefore, designers must ensure that the yielding stress is not reached. Overall, Mr Synac believes that rigid inclusions will eventually surpass the soil mixing technique.

- **Which of the two methods, CMC or VSC, is more economically efficient, and which one do stakeholders in Australia prefer?**

Mr Synac mentioned that while the materials for stone columns are less expensive, the significantly shorter installation time of CMC compared to VSC makes CMC a more cost-effective technique. He also emphasised that not only in Australia but the whole world prefers the CMC technique.

- **In terms of sustainability of CMC technique, is it recommended to mix cement with other materials such as different kind of ashes or lime?**

Mr Synac stated the he does not recommend lime admixtures due to bad experiences but believes that ashes and fly ashes are okay. However, achieving high plasticity and flow in concrete mix is difficult. Nevertheless he believes that admixtures are possible and could lead to a more sustainable low-strength concrete.

- **What is the acceptable settlement for CMC and VSC?**

Mr Synac disclosed that for a client's point of view, CMC is much more acceptable and understandable. He also holds the belief that designing stone columns to limit settlement to 25 mm is challenging. However, he is confident that, based on the CMC technique, settlement can generally be reduced to 25 mm in most instances.

- **Which method (CMC or VSC) is more economical with respect to the thickness of LTP?**

Mr Synac clarified that the installation of stone columns does not require such a large platform. One reason for this is that when stone columns bulge, the upper portion of the columns (usually the first third) and the surrounding soil contribute to the bulging. Consequently, the thickness of the Load Transfer Platform (LTP) can be decreased. Furthermore, Mr Synac expressed his major concern about the forces acting on the geotextile in long-term (e.g., 50 years) after the installation of rigid inclusions. He pointed out that rigid inclusions are commonly used in various infrastructure projects, but their performance after 50 to 100 years is still uncertain. This is because there may be significant settlement between the rigid inclusions and the geotextile, which will impose increased load over time on CMC, which in turn, may eventually lead to a loss of their capacity.

In his concluding remarks, Mr Synac conveyed his support for the research, expressed gratitude for the questions, and found the discussion highly engaging. His availability for any additional inquiries or assistance was graciously extended, encouraging contact whenever necessary.

4.2.8 Interviewee 8 (Dr Ahm Kamaruzzaman "Zaman")

Dr Zaman, a civil engineer with a Ph.D. in geotechnical engineering, holds fellow and chartered status in Australia, boasting over 30 years of experience across consulting, construction, public, and research sectors. His expertise lies in providing specialized geotechnical advice and managing technical risks for numerous multi-million/billion-dollar infrastructure and tunnelling projects in Australia and Southeast Asia. Notable projects include the Rozelle Interchange, WestConnex, Sydney Metro City, Sydney Gateway, and various highway projects. Dr Zaman's contributions encompass geotechnical design, investigations, ground improvement, instrumentation, and construction issues, ensuring the highest standards of technical proficiency and risk management. His extensive experience extends to developing specifications, technical directions, and geotechnical documents for long-term risk management and quality control of transport assets. Additionally, he has authored numerous technical papers and served as a keynote/invited speaker at national and international conferences. Dr. Zaman's affiliations include adjunct faculty positions at the University of Technology Sydney and the University of Wollongong, along with serving as an editorial board member for the Journal of Ground Improvement, ICE, and London. Figure 4.9 depicts photo of interviewee 8, Dr Zaman.

Figure 4.9: Interviewee 8, Dr Zaman

The following questions were asked and the answers of the interviewee are provided.

- **What are your thoughts on bi-modulus columns?**

Dr Zaman mentioned that this topic is quite novel, as recently proposed by Keller, and he has not encountered this method before. In practical terms, Dr Zaman has not encountered bi-modulus columns yet, and he believes the primary issue lies in the bulging of the VSC segment due to the constraints posed by the soft soil's strength. In soils with a shear strength of less than 20 kPa, stone columns tend to underperform due to the likelihood of encountering soil remoulding during construction. Hence, the stone column alone faces numerous constraints stemming from bulging effects and long-term creep. He noted, therefore, that it might be prudent to initially conduct a field test to ascertain the feasibility of the bi-modulus approach. Additionally, in ground conditions where soil shear strength is below 20 kPa, it is imperative to avoid employing the VSC component, even within a hybrid system like bi-modulus, as it would prove ineffective. Dr Zaman explained that the primary motivation for adopting the bi-modulus solution is to mitigate the mushrooming effects resulting from the construction of CMC, along with other associated issues at the upper section of CMC. To avoid these challenges, it is advisable to utilize a non-displacement type of column, such as a stone column.

In theory, it appears feasible, but meticulous attention must be paid to the geotechnical modelling of the upper section of the bi-modulus column. In practical application however, it is essential to ensure the absence of bulging effects in the VSC segment. Additionally, employing a highly efficient LTP is crucial. Dr Zaman admired the thorough research conducted by Ghosh in 2020 on LTP and again emphasized the significance of determining the depth of the VSC segment of the bi-modulus columns in geotechnical modelling, as bulging effects may not be evident in simulated scenarios and typically manifest only in field conditions. He mentioned that bi-modulus columns, in general, represent a novel and promising area of research, but they come with various challenges and complexities. Consequently, he underscored the importance of conducting a field trial before providing any practical assessment or commentary on their viability.

- **The length of bi-modulus columns are taken to be 11m in this research which consists of 9.5 m CMC at the bottom, 0.5 m transition zone and 1 m VSC at the top. Will there still be bulging effects in a 1 m depth of VSC, given that the underlying structure is rigid?**

Dr Zaman explained that whether its 0.5 m or 1 m, it depends on the geotechnical model, shear strength, and OCR (Over Consolidation Ratio) of the soil. Typically, in NSW, the upper 0.5 to 1 m comprises a desiccated layer with a high OCR. However, once this layer is disturbed, the OCR decreases, reverting to normally consolidated soil. Subsequently, due to rainfall and wet conditions, this top layer becomes considered as normally consolidated soil again. Therefore, whether its 0.5 m or 1 m, or any other depth of VSC chosen for constructing bi-modulus columns, it is contingent upon the ground conditions. If we have stiff to medium stiff materials, it might work. However, if, for instance, the shear strength diminishes due to rain or flooding, the suitability of 0.5 m or 1 m of VSC may become problematic. It is imperative to meticulously analyse the actual geotechnical profile before determining the depth of the VSC section of the bi-modulus column. In addition, it is very critical depending on which location, the bi-modulus columns are going to be utilised as it is a function of post construction settlement. For instance, one should inquire whether vertical inclusions are utilized to meet design requirements for post-construction settlement, which can vary from 25 to 50 mm over 40 years or 100 to 200 mm over the same duration. He emphasized that in the critical area of the bridge approach which is a very risky area, the bi-modulus solution may not be suitable. However, at a distance from the transition zone where a post-construction settlement of 100 to 200 mm is deemed acceptable and the risk is comparatively lower, this novel technique could prove beneficial.

Dr Zaman further stated that he believes that in less crucial zones, like 20 to 30 m away from the bridge approaches, where wider-spaced CMC are employed, and greater settlements are permissible, bi-modulus columns can be implemented. Once again he argued that the determination of the depth of the VSC section relies on the geotechnical strength and OCR of the top layer. Undoubtedly, load transfer platform plays a pivotal role in load distribution, necessitating an effective LTP on top of the columns.

- **The attractiveness of bi-modulus columns is significantly influenced by the mitigation of mushroom effects caused by CMC. What are your thoughts on this aspect?**

Dr Zaman contends that nowadays, mushroom effects are effectively minimized. He emphasizes that adherence to the Specifications DC R225 Concrete Injected Columns: Transport for NSW, which he authored and published in 2021, incorporating numerous lessons learned, can significantly reduce the likelihood of mushroom effects through meticulous implementation of a well-executed construction sequence termed "hit and miss". It is acknowledged that mushroom effects typically arise in shallow depth stabilization when the prescribed construction sequence outlined in R225 is not followed. Clearly, the inclusion of an adequate Load Transfer Platform (LTP) is essential and is deemed obligatory according to R225; vertical inclusions would not be effective without the presence of an LTP. Dr Zaman foresees great potential value in this research for exploring the reduction in thickness of LTP. He believes that the findings from this numerical investigation could offer notable benefits to the industry as well.

- **What is your opinion regarding how the type of soil determines the selection of suitable vertical inclusions?**

Dr Zaman suggested that both techniques are applicable for various types of soft soil deposits. However, stone column technology, despite being historically utilized in regions like Malaysia and Southeast Asia, is often avoided due to concerns about bulging effects, especially at the top part, which can lead to long-term creep. Moreover, in locations such as Australia, importing stone for this purpose is not economically viable. Based on Dr Zaman's price analysis, the costs associated with implementing VSC and CMC can be quite comparable, while deep soil mixing emerged as the most cost-effective solution. Moreover, there are certain ground conditions where the use of stone columns is not straightforward. For instance, in some situations where VSC with larger diameters are required, pre-drilling becomes necessary, which adds complexity. Hence, conducting field trials and thorough geotechnical investigations are crucial to determine the most suitable solution.

- **Is VSC the optimal choice for soils prone to liquefaction?**

Dr Zaman explained that VSC may not be the preferred option, primarily because liquefaction is not a significant concern in Australia. In certain regions of the United States, liquefaction poses a challenge. However, traditional stone columns alone may not effectively address liquefaction, as the stone particles might disperse. Yet, with the use of geosynthetic encasement, this issue can be mitigated. He clarified that in stone column ground improvement, typically 80% of the load is borne by the stone column, while the remaining 20% is supported by the surrounding soil. However, in liquefiable soils, the entire load must be supported by the column, as the surrounding soil loses its strength. CMC appears to be a more cost-effective choice, as the combined cost of geosynthetic encasement and stone column is higher than the CMC option. Additionally, CMC tends to maintain its stability better due to its increased rigidity.

- **What are the diameter ranges for stone columns and CMC?**

Dr Zaman disclosed that the typical diameter range for stone columns is between 600 and 800 mm. He emphasized that larger diameters present more challenges in construction and quality control. Unlike numerical modelling where diameters can be easily chosen, in practical applications, there are limitations. He noted that Raju, V. R. (1997), has published insightful paper on stone columns with the name "The Behaviour of Very Soft Cohesive Soils Improved by Vibro Replacement," further elaborating on these challenges. In regard to CMC, he suggested a diameter range of 400 to 500 mm, cautioning that CMC with very small diameters, such as 240 mm, may encounter numerous issues unless they are intended for very short columns. Dr Zaman believes that CMC are employed for depths of 10 m and beyond, rather than shallower depths ranging from 4 to 5 m. With respect to bi-modulus columns, Dr Zaman admitted to lacking experience with their design and geometry. However, he sees potential benefits and innovation in terms of reducing the thickness of the LTP, as the top section (VSC part) would also serve as part of the LTP. He mentioned that according to standards, the thickness of the LTP typically ranges from 600 to 800 mm, with a maximum of 1 m. However, certain techniques have proven effective with an LTP thickness as low as 300 to 400 mm. He was optimistic that introducing bi-modulus columns could potentially further reduce the thickness of the LTP.

- **According to your experience what is the practical spacing for stone columns and CMC?**

Dr Zaman explained that the necessary spacing varies depending on the intended design settlement. For instance, a 50 mm settlement would require different spacing compared to a 100 mm settlement. With wider spacing, there's a risk of bulging effects, but this can be prevented by covering the columns with a suitable LTP. At the initial part of the bridge approach, a spacing ranging from 1.5 to 2 m is considered acceptable, contingent upon the acceptable design settlement. Dr Zaman suggested that for a 50 mm design settlement, maintaining an s/d ratio between 2 to 2.5 typically results in a highly controlled settlement. However, for a 100 mm design settlement, an s/d ratio of 3 to 3.5 could be deemed appropriate. He holds the view that in most instances, a spacing of 1.4 m between CMC with a diameter of 450 mm can be estimated as satisfactory.

- **What is the thickness of the LTP for both VSC and CMC techniques?**

Dr Zaman disclosed that the required thickness can vary depending on the amount of pressure exerted from above and the depth of the soft clay, ranging approximately between 300 to 600 mm.

- **What is the effect of speed in settlement behaviour?**

Dr Zaman suggested that if the ground improvement technique is executed precisely with a robust and sufficient Load Transfer Platform (LTP), the impact of speed can be minimal. He mentioned that typically, dynamic live loads ranging from 10 to 20 kPa are considered appropriate, with 10 kPa for slower local roads and 20 kPa for main highways.

- **What is the effect of groundwater?**

Dr Zaman emphasized that groundwater consistently poses a significant challenge for geotechnical endeavours and greatly influences the development of a geotechnical model. From a cautious standpoint, after establishing a geotechnical model and determining undrained shear strength and OCR (Over Consolidation Ratio), the groundwater level should be accounted for at the surface level. He further argued that although the actual groundwater level may sometimes lie below the surface, considering concerns related to global warming and the prevalence of flood-prone regions, it is prudent to account for the groundwater level at the surface.

- **If there is a choice between utilizing either stone columns or CMC, which option might be more advantageous?**

Dr Zaman suggested that it is advisable to conduct a trial to identify the best option for the projects but emphasized that the decision relies on several factors. He also recommended steering clear of the transition zone in typical soft soil areas and unequivocally avoiding trial near bridge approaches or critical structures where settlement requirements are extremely stringent.

In conclusion, Dr Zaman expressed his appreciation for our research, noting its high level of interest and its potential benefits for the industry. He also clarified that the information shared is solely based on his personal experiences and represents his individual viewpoint, unrelated to Transport for NSW. He mentioned that he views this interview as a professional obligation to assist researchers from UTS and expresses his readiness to offer support to students whenever needed.

4.2.9 Interviewee 9 (Mr Mehdi Hajian)

Mr Mehdi Hajian is a distinguished geotechnical engineer serving as the director at Geostruct Designs Australia. With a wealth of experience spanning numerous years, he specializes in a wide array of geotechnical engineering facets including but not limited to numerical modelling, tendering, bidding, and business development. His expertise extends to the design and estimation of various structures such as retaining walls, diaphragm walls, sheet piles, deep foundations (including bored piles, CFA, and driven piles), among others. Additionally, he possesses comprehensive knowledge in slope stability analysis, pile dynamic testing, grouting, jet grouting, and stone columns. Mr. Hajian has overseen numerous geotechnical investigations and laboratory testing endeavours across Australia and the Middle East, showcasing his profound expertise in the field. Figure 4.10 shows the image of interviewee 9, Mr Mehdi Hajian.

Figure 4.10: Interviewee 9, Mr Mehdi Hajian

The following questions were asked and the answers of the interviewee are provided.

- **In Australia, both CMC and Vibro Stone Columns (VSC) are options for enhancing compressible soil conditions. However, there is a query regarding their prevalence. Which method holds greater dominance? Moreover, which approach garners more favour among stakeholders in Australia?**

According to Mr Hajian, the preference leans towards CMC primarily because of its material availability and cost-effectiveness. This suggests that stakeholders in Australia may find CMC to be a more attractive option for ground improvement projects, considering both practicality and financial factors.

- **Which method do you suggest, when considering the soil type (e.g., sandy clay, clay with high plasticity and clay with low plasticity)?**

Mr Hajian explained that when considering feasibility, CMC stands out for its adaptability across various ground conditions except for rocky terrain. On the other hand, VSC is typically favoured for sandy ground conditions. This highlights the versatility of CMC and the specialized suitability of VSC, providing stakeholders with options tailored to specific soil types.

- **What about conditions both on-shore and off-shore? Which method is preferred in these situations? Can we assert that stone columns are a preferred option for addressing liquefaction in soils?**

Mr Hajian mentioned that off-shore projects are not his area of expertise. However, based on his experience, he does not recommend using CMC for offshore applications and concurs with the previous statement regarding this matter. He further clarified that despite not specializing in offshore work, his practical understanding aligns with the utilization of stone columns as a sole approach for liquefiable soils.

- **Which technique is better for the support of bridge approaches? CMC or VSC?**

Mr Hajian indicated that, drawing from his experience, he prefers the CMC option. He explained that the main reason for choosing CMC over stone columns lies in the fact that with stone columns, settlement and creep rely on prolonged consolidation and drainage post-bridge construction. Consequently, settlement remains a possibility, rendering stone columns unsuitable in certain scenarios where bridges could deform or develop cracks. Conversely, rigid inclusions emerge as a dependable alternative for bridge approaches.

- **What are the limitations or drawbacks of CMC (rigid inclusions)? What are the limitations or drawbacks of VSC semi-rigid inclusions?**

Mr Hajian pointed out that for CMC option, the drawbacks include restricted diameter, reliance on heavy machinery and limited depth capability. Additionally, he noted that material availability poses a limitation for VSC option. He argued that such factors need to be carefully considered when evaluating the feasibility and effectiveness of each ground improvement method.

- **Is it accurate to assert that in rigid inclusions (CMC), certain columns might experience cracking or fracturing over time as a result of shear stresses? What significance does the LTP hold in addressing this concern? Numerical studies indicate that broken CMC columns with very thin LTP exhibit considerable settlement, but when an appropriate thickness of LTP is utilized, the difference in settlement between intact CMC and those with imperfect columns is minimal.**

Mr Hajian emphasized the substantial impact of LTP on the design of CMC and its ability to manage differential settlement. He also highlighted the incorporation of reinforcement steel within CMC columns as a strategy to mitigate cracking, underscoring the importance of careful planning and reinforcement measures in CMC projects to ensure stability and longevity while controlling settlement differentials.

- **What is your opinion on employing a ground improvement approach that combines both CMC and VSC within a single project, such as utilizing alternating rows of CMC and VSC columns or employing a different pattern?**

Mr Hajian advised against this approach, expressing that he does not recommend it. According to him, even if the design allows for the avoidance of differential settlement, he suggested that it is economically unwise to utilize two techniques simultaneously, unless the project site can be divided into two sections with sufficient space for each technique and their respective machinery.

- **What is your opinion with respect to the thickness of the LTP for both techniques and what is the range of thickness for LTP in your design considerations?**

Mr Hajian mentioned that typically, the thickness of LTP (Load Transfer Platform) in CMC projects ranges from 500 to 1000 mm. However, in the VSC technique, which utilizes semi-rigid columns, there is less susceptibility, but the presence of LTP remains essential.

- **For CMC socketed into rigid base or sitting on bedrock, the numerical analysis indicates that the settlement is close to zero. Is this correct in the real world?**

Mr Hajian disagreed, stating that the assertion is incorrect, and emphasized that it ultimately depends on the loading conditions. He pointed out that even in the design of piles, which are generally more rigid than CMC, settlement is still encountered. He believes that it is essential to consider not only the bearing capacity of the material at the toe, especially in rocky terrain, but also the elastic settlement of the CMC column itself.

- **What are your thoughts on the use of rigid inclusions for embankment batter stabilization? Would you recommend maintaining consistent spacing and length, or is there merit in reducing the column length?**

Mr Hajian made a valid point that the suitability of using rigid inclusions for embankment batters depends on the loading conditions. If the loading is primarily horizontal, he suggested considering alternative techniques like piling, especially because the horizontal capacity of CMC might not be sufficient in such situations.

- **Which technique (CMC or VSC) is more cost effective in Australia? Which method (CMC or VSC) is more economical with respect to the thickness of LTP?**

Mr Hajian argued that, generally, CMC offer a more cost-effective solution in Australia due to factors such as lower material costs, reduced construction time, and improved long-term performance, making them a favourable choice in many situations. He suggested that, when compared to alternative techniques such as stone columns, CMC tend to offer better value for the investment.

- **In terms of sustainability of CMC, is it recommended to mix cement with other materials such as different kind of marginal materials or ashes (fly ash, rice husk ash, or bagasse ash) or lime?**

Mr Hajian emphasized that currently, cost is the primary factor influencing decisions in every project. However, when it comes to additives, it is crucial to prioritize ensuring the pumpability of cement mix or concrete when it comes to real projects.

- **What do you think about the usage of construction wastes and debris for vibro stone columns?**

Mr Hajian suggested that while there might be promising prospects, further research is required to fully capitalize on these opportunities.

- **What is the acceptable settlement range for CMC and VSC?**

Mr Hajian confirmed that different ground improvement techniques have varying thresholds for settlement tolerances, with VSC allowing for slightly more settlement compared to CMC. Concerning CMC, he stated that it is generally acceptable to tolerate settlements ranging between 200 to 300 mm. However, for VSC, higher settlement values might be permissible.

- **In design of Stone Columns and CMC, which design parameters are more sensitive (spacing, pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP, traffic load or soil properties)? What is your suggestion regarding optimal spacing between the columns for both techniques and what is the range of diameter for VSC and CMC?**

Mr Hajian regarded diameter and spacing as the most significant parameters in the design of vertical inclusion ground improvements. He explained that typically, the diameter of CMC ranges from 280 to 450 mm, although it can sometimes extend up to 600-plus mm. Additionally, the spacing between CMC typically falls within the range of 2 to 3 m for smaller diameters. On the contrary, stone columns typically have a diameter ranging from 600 to 1000 mm, with a spacing of 3D considered adequate. However, according to Mr Hajian, when it comes to design parameters, precise specifications are challenging to generalize, as they vary significantly for each specific project and must be tailored accordingly through individual assessment and planning. In practice, factors such as load requirements, environmental conditions, and structural considerations play crucial roles in determining the optimal design parameters for vertical inclusion installations. Therefore, a detailed analysis and customization are necessary to ensure the effectiveness and safety of the overall structure.

- **What are the effects of rate of injection pressure and rate of installation for CMC? Can these parameters be included in the design phase (because sometimes the rigid inclusions are installed very fast and sometimes slow depending on the capability of equipment or based on the decision of rig operator)?**

Mr Hajian emphasized the complexity of the question, stating that it is indeed a pertinent inquiry but one that is challenging to respond to definitively. He clarified that the answer hinges on various factors such as soil conditions, geographical location, efficiency of concrete/grout delivery, skill of the operator, diameter of the CMC, and the size of the platform being constructed, among others. These elements collectively influence the timeline and feasibility of the project. Moreover, each project presents its unique set of circumstances, making it difficult to provide a one-size-fits-all answer. In essence, according to him, a comprehensive understanding of these variables is essential for accurately estimating the time required for completion.

- **What are the construction challenges for both stone columns and rigid inclusions in Australia?**

Mr Hajian suggested that there is a need for increased promotion and marketing efforts for the implementation of CMC, as it is still considered a relatively new technique. Additionally, he pointed out that for VSC, the availability and cost of materials pose significant challenges compared to CMC. According to his experience, acquiring the necessary materials for VSC is both difficult and expensive when compared to CMC. In simpler terms, while CMC requires more promotion to gain traction, VSC faces greater hurdles in terms of material procurement and cost-effectiveness.

- **What is the effect of groundwater to select CMC or VSC for ground improvement?**

Mr Hajian indicated that groundwater does not impact CMC unless there is movement or a current within the groundwater. He explained that stagnant groundwater typically does not pose a problem for CMC structures. However, if there is any movement or flow in the groundwater, it could potentially affect the stability or integrity of the CMC. Therefore, the presence of groundwater alone is not a significant concern for CMC, but rather it is the dynamics of groundwater movement that may have an impact.

- **What are your thoughts in regards to bi-modulus columns? This involves combining stone column material at the top (1.5 m to 2.5 m) and rigid inclusions at the bottom within a single element.**

Mr Hajian acknowledged that he lacks familiarity with this innovative approach. At the end, Mr Hajian congratulated us for this investigation, and he believes there are lots of opportunities to enhance the ground improvement techniques using vertical inclusions.

4.2.10 Interviewee 10 (Mr Michal Krzeminski)

Mr Michal Krzeminski boasts a wealth of expertise as a design manager, showcasing a robust track record within the construction sector. Proficient in a spectrum of disciplines including tunnels, earthworks, foundation design, construction, and geotechnical engineering, he brings a comprehensive skill set to his role.

His academic background is anchored by a Master of Science degree in bridges and underground structures from Warsaw University of Technology, further solidifying his prowess in the field. Mr Krzeminski's dedication to excellence in arts and design, coupled with his professional acumen, underscores his capacity to deliver innovative and impactful solutions in complex engineering projects. Figure 4.11 presents the image of interviewee 10, Mr Michal Krzeminski.

Figure 4.11: Interviewee 10, Mr Michal Krzeminski

The following questions were asked and the answers of the interviewee are provided.

- **In Australia, both Rigid Inclusions (CMC/CSC/CIC) and Vibro Stone Columns (VSC) are utilized for ground improvement in compressible soil. Among these techniques, which one holds greater prominence? Moreover, which method do stakeholders in Australia tend to prefer?**

Mr Krzeminski asserted that rigid inclusions are unequivocally preferred. He emphasized that the efficiency and cost-effectiveness of their installation significantly surpass the comparatively slower process of installing vibro stone columns. Furthermore, he noted that the application of stone columns in Australia is constrained primarily to seismic remediation projects, thus limiting their overall usage.

- **Which method do you suggest, when considering the soil type (e.g., sandy clay, clay with high plasticity and clay with low plasticity)?**

According to Mr Krzeminski, both methods are suitable for the described soil types. The key determinant in selecting between them is the consistency and stiffness of the soil. Both methods are primarily effective when dealing with soils that exhibit a stiff consistency. This means that soils with a higher degree of firmness and resistance to deformation are better suited for applications of either method. Essentially, the choice between rigid inclusions and vibro stone columns depends on the specific characteristics and properties of the soil being treated, with soil stiffness being a crucial factor in the decision-making process.

- **How about on-shore and off-shore conditions? Which method is preferred? Is it accurate to state that stone columns represent a preferable choice for mitigating liquefaction in soils?**

Mr Krzeminski highlighted that vibro stone columns are suitable for both on-shore and off-shore projects, offering versatility in their application. In contrast, rigid inclusions are currently restricted to on-shore projects exclusively. He affirmed that vibro stone columns are the preferred option for addressing liquefaction issues. However, he also noted that rigid inclusions can be engineered to withstand seismic forces, making them a viable choice for projects in seismically active regions. Essentially, in seismic environments, whilst vibro stone columns offer broader applicability, rigid inclusions also provide specific advantages.

- **Which technique is better for the support of bridge approaches? CMC/CSC or VSC?**

Mr Krzeminski stated that both methods, rigid inclusions and vibro stone columns, see utilization; however, rigid inclusions are deemed more economically viable.

- **What are the limitations or drawbacks of CMC (rigid inclusions) and what are the limitations or drawbacks of VSC (semi-rigid inclusions)?**

Mr Krzeminski explained that the primary constraint for both methods lies in the stiffness of the existing soils on-site. Both techniques are unable to effectively penetrate soils categorized as stiff to very stiff, including stiff clays and dense sands. In simpler terms, <u>if the natural soil at the location is particularly firm or compacted, neither rigid inclusions nor vibro stone columns will be able to achieve their intended results efficiently and cost effectively.</u> Mr Krzeminski underscored the importance of assessing soil conditions thoroughly before selecting the appropriate ground improvement method for a project.

- **What is your experience about long-term performance of stone columns and rigid inclusions? What do you think about long-term issues of stone columns such as bulging or clogging? Is there a maximum recommended length for stone columns to prevent bulging?**

Mr Krzeminski confirmed that rigid inclusions outperform stone columns in terms of long-term settlement, showing 2-5 times less settlement over time. He mentioned that bulging, a concern with stone columns, does not affect long-term performance of rigid inclusions. In addition, according to him, bulging is not related to the length of the columns but rather to the presence of very weak ground. To prevent bulging, stone columns are designed to bear maximum loads efficiently.

- **Is it correct to say that in rigid inclusions (CMC/CSC), some columns may crack or break in long-term due to shear stresses? What would be the importance of LTP to tackle this issue? In numerical investigations, broken CMC with very thin LTP show a large settlement but with a proper LTP thickness not much difference is observed between intact CMC and CMC system with some imperfect ones.**

Mr Krzeminski clarified that if rigid inclusions are not adequately designed, they may indeed develop cracks. He explained that the likelihood of column cracking is not tied to the thickness of the Load Transfer Platform (LTP), but rather to external factors such as boundary conditions that can exert shear forces on the columns. These boundary conditions could include areas like the edges of embankment slopes or adjacent to excavations.

- **What do you think about a ground improvement technique using both CMC and VSC in one project, for example, one row of CMC and one row of VSC (or another pattern)?**

Mr Krzeminski asserted that this would necessitate highly specific requirements, and combining two techniques would not be cost-effective.

- **What is your opinion with respect to the thickness of the LTP for both techniques and what is the range of thickness for LTP in your design considerations?**

Mr Krzeminski emphasized the significance of the Load Transfer Platform (LTP) in both ground improvement methods. He underscored that the thickness of the LTP is determined by various factors, including the spacing of the columns, specific performance requirements, and other pertinent considerations. In essence, the design and dimension of the LTP play a crucial role in ensuring the effectiveness and stability of the overall ground improvement system.

He stated that as a minimum, the "HLTP > (0.7 to 1.4) × (s – 0.9d)" must be satisfied, where HLTP is the LTP thickness, s is the CMC spacing, and d is the CMC diameter.

- **For CMC socketed into stiff substratum or sitting on bedrock, the numerical analysis indicates that the settlement is close to zero. Is this correct in the real world?**

Mr Krzeminski suggested that there might be minimal settlement anticipated, although it hinges on the modelling approach utilized. If one employs a model assuming a completely rigid base with an infinitely stiff modulus, then settlement would indeed be non-existent. However, in practical terms, all materials possess their own stiffness, implying that some degree of settlement is unavoidable.

- **What is your opinion in regard to rigid inclusions used for the batter of embankments? Do you suggest using the same spacing and length or reducing the length of columns?**

Mr Krzeminski indicated that columns positioned under batter slopes are expected to be shorter in length. Additionally, they may require reinforcement, possibly through the use of a single reinforcing bar. This strategy aims to ensure the stability and effectiveness of the columns in supporting the ground under batter slopes. The shorter length and reinforcement help optimize the performance of the columns in challenging terrain conditions, such as sloping surfaces.

- **Which technique (CMC/CSC or VSC) is more cost effective in Australia? Which method (CMC or VSC) is more economical with respect to the thickness of LTP?**

Mr Krzeminski emphasized that CMC/CSCs is by far more economical.

- **In terms of sustainability of CMC, is it recommended to mix cement with other materials such as different kind of marginal materials or ashes (fly ash, rice husk ash, or bagasse ash) or lime?**

Mr Krzeminski approved of the concept and elaborated on the benefits of using ready-mix concrete. However, he mentioned that other materials and cement blends are also being taken into consideration.

- **What do you think about the usage of construction wastes and debris for vibro stone columns?**

Mr Krzeminski views the concept as innovative and acknowledged that, depending on the diameter of the vibro stone columns (VSC), there can be a waste material ratio ranging from 20% to 40%.

- **What are the differences between settlement behaviour of stone columns and CMC? What is the acceptable settlement range for CMC and VSC?**

Mr Krzeminski stated that CMC/CSCs will experience significantly less settlement, with a reduction factor ranging from 2 to 5.

- **In design of stone columns and CMC, which design parameters are more sensitive (spacing, pattern of installation, diameter, stone materials, depth of installation, ground water level, thickness of LTP, traffic load or soil properties)? What is your suggestion regarding optimal spacing between the columns for both techniques and what is the range of diameter for VSC and CMC?**

Mr Krzeminski asserted that the optimal spacing for both CMC/CSCs and VSC is contingent upon the specific structure and its intended application. He emphasized that all parameters mentioned are critical and require careful consideration to achieve the desired design output. He explained that generally speaking, CMC/CSCs are recommended to have a spacing of approximately 2 to 3 m, which is also applicable to VSC.

- **What are the effects of rate of injection pressure and rate of installation for CMC? Can these parameters be included in the design phase (because sometimes the rigid inclusions are installed very fast and sometimes slow depending on the capability of equipment or based on the decision of rig operator)?**

Mr Krzeminski indicated that the outcome relies on the soil conditions rather than the skill of the operator. He clarified that these specific parameters constitute proprietary knowledge belonging to the contractors.

- **What are the construction challenges for both stone columns and rigid inclusions in Australia?**

Mr Krzeminski highlighted potential challenges during the installation phase, including squeezing, heave, material loss, and damages caused by subsequent trades. In essence, he pointed out that during the installation process, there are risks such as soil squeezing, upward movement (heave), loss of materials, and damages that may occur due to activities carried out by other trades after the ground improvement work has been completed. According to him, these challenges underscore the importance of careful planning and coordination to mitigate risks and ensure the success of the project.

- **What is the effect of groundwater to select CMC or VSC for ground improvement?**

Mr Krzeminski stated that the presence of groundwater does not affect the installation process of both techniques.

- **Some companies (e.g. Keller and Menard) have proposed a new technique called bi-modulus columns. This involves combining stone column material at the top (1.5 m to 2.5 m) and rigid inclusions at the bottom within a single element. What is your insight about this technique? Can bi-modulus columns resolve some issues related to CMC such as mushroom effects? Since the rigidity of the rigid inclusions (CMC) are several magnitudes higher than the surrounding soil, they sometimes stick out of the ground, and there is something called mushroom effects. Can bi-modulus columns be a great replacement for other vertical inclusions in future?**

Mr Krzeminski noted that bi-modulus columns are implemented to prevent mushroom effects, particularly in situations where there is not adequate thickness in the Load Transfer Platform (LTP).

According to him when the Load Transfer Platform is not thick enough to fully support the columns, bi-modulus columns are used to distribute the load more effectively and prevent the formation of a mushroom shape at the top of the columns. He further explained that the term 'bi-modulus' indicates that these columns have varying stiffness levels, enabling them to better adapt to different ground conditions and load requirements. Consequently, there is significant potential for future progress and innovation.

As the discussion neared its end, Mr Krzeminski demonstrated a keen curiosity about this research, emphasizing the extensive uncharted territory that remained to be explored in these methodologies.

4.3 Discussion and Take Away Points

Upon conducting interviews with a diverse array of industry experts globally, valuable insights regarding ground improvement techniques utilizing vertical inclusions (specifically rigid, semi-rigid, and bi-modulus columns) have been gathered. These discussions shed light on various perspectives and experiences, offering a comprehensive understanding of the practicalities and nuances associated with each approach.

Regarding rigid columns (CMC), experts emphasized their efficacy in providing robust vertical support and accommodating substantial loads, making them particularly suitable for projects with stringent stability and durability requirements, such as heavy industrial infrastructure and transportation networks. Another distinguished benefit of this method is its exceptionally rapid production rate, achieving approximately 1000 linear meters per day, significantly outpacing the speed of semi-rigid column installation. However, complexities in installation procedures in some ground conditions and potential challenges in accommodating liquefiable soils and off-shore situations emerged as notable considerations. Table 4.2 highlights the responses acquired from interviewees to some common questions regarding Controlled Modulus Columns.

Table 4.2: Responses acquired from interviewees to some common questions regarding CMC

Interviewees	Cost Effectiveness over Stone Columns	Drawbacks	Suitability Based on Soil Type
1	Yes	Off-shore conditions	All except liquefiable soils
2	No	Very expensive	All except liquefiable soils
3	Similar/Maybe	Horizontal loads	All except liquefiable soils
4	Yes	Ground heave	All except liquefiable soils
5	It is contingent upon various factors.	Issues related to LTP	All except liquefiable soils
6	Yes	Installation process	All except liquefiable soils
7	Yes	Installation effects/Heave	All except liquefiable soils
8	Similar/Maybe	None	All
9	Yes	Installation process	Rocky & Liquefiable soils
10	Yes	Unsuitable for stiff ground	All except liquefiable soils

Conversely, semi-rigid columns (VSC) were recognized for their versatility and cost-effectiveness in developing countries. These columns, often comprised of materials like crushed stones or aggregates, strike a balance between strength and flexibility, offering an effective solution for improving soil stiffness and mitigating settlement issues across a range of soil conditions. Nonetheless, maintaining uniform performance across the site and ensuring adequate quality control during installation were highlighted as critical factors for success. Table 4.3 highlights the responses acquired from interviewees to some common questions regarding stone columns.

Table 4.3: Responses acquired from interviewees to some common questions regarding stone columns

Interviewees	Major Limitations	Preferred Method for Off-shore Projects	Usage Near the Bridge Abutment
1	Cost, Insufficient improvement	Yes	Not recommended
2	Clogging	Yes	Not recommended
3	Unsuitable for soft organic soils	Yes	Maybe
4	Cost, Slow construction time	Yes	Not recommended
5	Bulging, Clogging, Limited soils	Yes	Not recommended
6	Maximum replacement ratio, Cost	Yes	Not recommended
7	Cost, Insufficient improvement	Yes	Not recommended
8	Bulging, Cost	Not sure	Not recommended
9	Cost, Limited soils	Yes	Not recommended
10	Cost, Insufficient improvement	Yes	Maybe

During interviews, it was explained that the significance of load transfer platforms (LTP) is paramount. Experts emphasized that within the context of CMC inclusions, LTP plays a crucial role owing to the inherent rigidity of CMC materials, demanding meticulous design considerations. Conversely, in the case of the VSC technique, wherein columns exhibit semi-rigidity, there exists comparatively lesser sensitivity, although the inclusion of LTP remains crucial. Nevertheless, in both methodologies, the function of LTP is indispensable for the equitable distribution of forces and the mitigation of disparate settlement phenomena at the ground level.

The innovative approach called bi-modulus columns was also discussed, presenting a promising fusion of characteristics from both rigid and semi-rigid techniques. By employing varying materials and mixing ratios within the same column, engineers can tailor the stiffness profile to suit specific project requirements and address the LTP-related issues such as mushroom effects more effectively. Although offering potential advantages, the design and execution of bi-modulus columns may entail greater expenses compared to conventional methods and necessitate a deeper comprehension of soil mechanics and material behaviour. Moreover, the development of an advanced rig capable of simultaneous installation of CMC and VSC segments, further accentuates the need for extensive research and thorough investigation into this innovative technique. Table 4.4 highlights the responses acquired from interviewees to some common questions regarding bi-modulus columns.

Table 4.4: Responses acquired from interviewees to some common questions regarding bi-modulus columns

Interviewees	Major Disadvantage	Addressing the Issues Related to LTP Thickness	Mitigation of Mushroom Effects
1	Cost, Time	Yes	Yes
2	Not sure	Not sure	Not sure
3	Cost, Time	Yes	Yes
4	Cost, Availability of equipment	Yes	Yes
5	Cost, Time, Availability of equipment	Yes	Yes
6	Cost, Time	Yes	Yes
7	Cost, Availability of equipment	Yes	Yes
8	Bulging of VSC segment, Availability of equipment	Yes	Maybe
9	Not sure	Not sure	Not sure
10	Not sure	Yes	Yes

Among the key takeaways from these interviews is the recognition of the importance of site-specific solutions tailored to the unique challenges and objectives of each project. The findings suggest that the VSC technique is deemed more cost-effective for developing countries, primarily attributable to the lower costs of stone and labour in such regions. Conversely, CMC inclusions remain the predominant choice in developed areas, where access to advanced technologies is readily available. Moreover, the role of engineering expertise, encompassing rigorous geotechnical analysis, meticulous design considerations, and thorough quality assurance protocols, emerged as fundamental to achieving successful outcomes. Continuous monitoring of ground response and column performance post-construction was also emphasized as essential for validating design assumptions and ensuring long-term stability. Furthermore, the interviews underscored the ongoing need for innovation and research in the field of ground improvement techniques using vertical inclusions. Advancements in material science, construction methodologies, and design approaches are crucial for advancing the effectiveness, efficiency, and sustainability of vertical inclusion techniques in ground improvement applications.

In summary, the insights gleaned from these interviews provide valuable guidance for practitioners, researchers, and stakeholders involved in ground improvement projects, emphasizing the importance of informed decision-making, collaboration, and a commitment to excellence in geotechnical engineering practice.

5

Applications of Vertical Inclusions and Cost Benefit Analysis

5.1 Introduction

Cost analysis is indeed a crucial aspect of any ground improvement project. It involves the comprehensive assessment of expenses associated with various aspects of the project to ensure effective budgeting, resource allocation, and financial control.

According to Bernhardt and Coffman (2022), some key considerations for the cost analysis of a ground improvement project are site investigation costs, design and engineering costs, material costs, equipment costs, labour costs, construction costs, quality control and testing, contingency funds, permitting and regulatory compliance, risk management, monitoring and inspection, environmental impact assessment, insurance costs, project management and administration and post construction monitoring. A thorough cost analysis helps in establishing a realistic budget, identifying potential cost-saving opportunities, and ensuring the overall financial feasibility and success of the ground improvement project. Furthermore, based on Rinaudo and Aulong (2014), it is crucial to consider both direct and indirect costs to have a comprehensive understanding of the financial implications of the project. The objective of this chapter is to provide a concise overview of the general expenses associated with vertical inclusion ground improvement techniques, including vibro stone columns (VSC), controlled modulus columns (CMC), and bi-modulus columns (BMC) as well as to assess their cost efficiency through a comparative analysis.

5.2 Costs Associated with Vibro Stone Column Installation

According to Abuel-Naga et al. (2012), the effectiveness of a structure's foundation is directly dependent on the quality of the underlying ground, and frequently, the ground requires improvement. The utilization of vibro stone columns, or aggregate piers, has emerged as a cost effective and practical method for improving the ground when the natural soil lacks the strength to support a foundation independently. Consequently, contractors specializing in stone column ground improvement must initially assess the soil properties of a site to design appropriate treatments and establish the most suitable installation methods.

As the cliché states the foundation is the pivotal element of a structure. However, a foundation becomes ineffective if the underlying ground lacks the strength to support it. Based on Castro (2017), the installation of vibro stone columns, also known as aggregate piers, has rapidly gained popularity as a favoured method for enhancing the ground in certain regions worldwide. This is primarily due to its ability to significantly reinforce weak soils at a more cost-effective rate compared to some other techniques such as constructing deep foundations or replacing weak soils with engineered fill.

Nevertheless, it is crucial to grasp the distinction between vibro stone columns and aggregate piers. While these terms are often used interchangeably in the industry, their origins exhibit slight variations.

Kumar and Singh (2019), elaborate in their book titled "Ground Improvement Techniques" that the term "aggregate piers" serves as a general designation for piers constructed from crushed stone, strategically positioned beneath shallow foundation sites across the footprint of a structure. Vibro stone columns encompass the category of aggregate piers, with the distinction lying in the specific reference to vibrating probes, known as Vibroflots. These probes are employed to drill into the ground and subsequently, compress and compact the columns of stone.

While vibro ground improvement techniques have a relatively long history, it is only in recent years that soil improvement contractors have employed vibrating probes for the installation of aggregate piers. Traditionally, these probes were primarily used to compress granular soils.

This approach results in additional cost savings as it eliminates expenses related to spoil removal and drill rig operation. It can be significantly more economical than the conventional rammed method of installing aggregate piers, which frequently necessitates pre-drilling.

5.2.1 Soil Properties and Design for VSC

The soil characteristics of a site can significantly impact both the design and construction costs of a structure.

The design and pre-construction stages of projects involve a meticulous examination of the ground and the stresses imposed by a planned structure. Factors include evaluating the bearing pressure exerted on the soil by the structure's footings, determining acceptable post-construction settlement levels, and assessing whether the existing soil condition can withstand these stresses.

In cases where ground improvement is required, ground improvement contractors examine geotechnical reports produced during this stage in order to decipher which technique shall be employed. The engineer is tasked with creating a suitable ground improvement strategy to enhance the soil's strength according to the requirements of the structure. As an illustration, according to technical specifications on the Subsurface Constructors website, ground improvement contractors typically employ methods such as treating the soil with vibro stone columns or aggregate piers to withstand bearing pressures ranging from 200 to 300 kPa. On occasions, the initial quality of the soil is satisfactory to the extent that the introduction of aggregate piers enables it to endure pressures of up to 4000 kPa. Conversely, when the soil quality is inferior, the bearing pressure it can withstand, even after treatment, is lower.

In addition, ground improvement contractors are responsible for considering the anticipated settlement of a structure when formulating an aggregate pier treatment. Based on Bowles, (1996), for typical building structures, the spread footings often have a required total settlement of 25 mm and a differential settlement ranging from 10 to 15 mm. Nevertheless, certain structures like MSE walls, tanks, and grain bins may, in some cases, experience slightly higher settlements without incurring structural damage.

In rare cases and when soil conditions are extremely poor, ground improvement using vibro stone columns becomes prohibitively costly and must be avoided.

Regardless, structural engineers need to communicate bearing pressure and settlement criteria to ground improvement contractors, facilitating the development of the most suitable and economical ground improvement treatments. Similarly, during the geotechnical investigation phase, ground improvement contractors can examine borings to contribute to the formulation of sensible recommendations for design bearing pressures through the utilization of stone columns and therefore, the most feasible approach can be determined.

5.2.2 Soil Properties and Installation Methodology for VSC

The effectiveness of vibro stone column installation methods is strongly influenced by the characteristics of the soil in which the columns are placed. The selection of the most suitable installation technique is a critical aspect of any vibro stone column project and inappropriate choices can indeed result in significant costs or project failure. The installation phase is where the conceptual plans and designs are translated into practical reality, and it is crucial to choose a technique that aligns with the project requirements, ground specifications, and environmental considerations. Ground improvement contractors must decide which of the following vibro stone column installation methods suit the circumstances:

- **Dry Top Feed** - In cohesive soils, this technique is applied following the creation of a hole by the vibroflot. As cohesive soil does not collapse on its own, the vibroflot can be withdrawn while aggregate is systematically poured into the hole. Subsequently, after each addition, the vibroflot is reintroduced to compress the aggregate, progressively shaping the pier.
- **Dry Bottom Feed** - This method is applied in soils with relatively low stability, such as soft clay and silt beneath the water table. In this approach, vibroflots are inserted and remained in the holes to prevent collapse. A tremie is affixed to the vibroflot to transport aggregate from an upper-side hopper down to the hole's bottom. Subsequently, the aggregate is compacted gradually.
- **Wet Top Feed** - Sandy and silty soils below the water table have a tendency to collapse. In this approach, the vibroflot probes the hole and remains within it. Water is

jetted outward in all directions from the vibroflot, ensuring that the hole stays open while aggregate is gradually and steadily poured in from the top. Subsequent to each addition, incremental compaction takes place.

Although ground conditions generally dictate which installation technique to be selected to construct the vibro stone columns, when it comes to cost considerations, 2 factors are significant:

1) Cost of aggregates.
2) Cost of labour and technology.

In developing regions such as Southeast Asia where labour is cheap and stone column materials can be purchased in an affordable price, vibro stone columns can be a highly attractive approach for ground improvement projects. Furthermore, as mentioned earlier since in vibro techniques pre-drilling is not required, they can be substantially more cost effective than the traditional rammed method of aggregate pier installation.

On the other hand, in developed countries such as Australia, vibro stone columns are not very popular due to the high price of aggregates and the fact that hiring labourers is not inexpensive (Refer to Chapter 4, Interview with Experts). In recent years some investigations have been conducted in order to understand if construction wastes such as crushed concrete can be used instead of aggregates and hence, a less expensive outcome to be achieved. However, the usage of those replacements can cause complications such as clogging effects or reduction in permeability of the stone columns. Therefore, it can be concluded that depending on the location of the ground improvement projects and environmental factors, in some areas vibro stone columns are the most cost-effective approach and in other areas it can be very expensive.

5.3 Costs Associated with Controlled Modulus Column Installation

The Controlled Modulus Columns (CMC) ground improvement method proves to be a successful approach for enhancing the load-bearing capacity of the shallow ground and significantly minimizing settlement. CMC represent a sustainable and economically efficient technology for ground improvement, facilitating the transfer of loads from the foundation to a lower bearing stratum through a stiff load transfer platform and the composite CMC/soil matrix.

The environmental appeal of CMC installation lies in its use of reverse flight augers, which displace the soil laterally. This method accomplishes two objectives:

1) It densifies the soil around the CMC, which improves load transfer into the element.
2) It eliminates spoils and the associated disposal requirements and costs.

5.3.1 Soil Properties and Design for CMC

Similar to vibro stone columns method, when CMC ground improvement is required, ground improvement contractors examine geotechnical reports produced during this stage.

CMC have been installed in a variety of soils including uncontrolled fill, organics, peat, soft to stiff clay, silt, municipal solid waste, and loose sands. Typically, the CMC are installed through the soft or compressible soils and into dense sand, stiff clay, glacial till, or other competent material that serves as the bearing stratum.

Aside from soils prone to liquefaction, CMC are effectively employed in virtually all types of soils worldwide, yielding commendable outcomes.

According to Menard and Junaid, (2016), the construction of CMC involves the use of grout with a strength of 10-20 MPa, and their diameter varies between 275-450 mm.

As mentioned earlier, in some cases and when soil conditions are extremely poor, other ground improvement techniques such as vibro stone columns becomes prohibitively costly and CMC can be used as an attractive alternative.

5.3.2 Soil Properties and Installation Methodology for CMC

While employing conventional augers, commonly utilized for installing auger-cast piles or drilled caissons, may seem to yield a foundation system resembling CMC, it would not incorporate the advantages offered by the CMC installation technique. Furthermore, the hole created by the displacement auger is backfilled with pressurized cement grout that further densifies the surrounding soils. This leads to a CMC element with considerably greater stiffness compared to the surrounding soil. Therefore, the CMC attract load from above, and transmit that load to the more-competent deeper soils or bearing stratum. In the past, CMC have been designed with a central steel reinforcing bar, if additional strength is required.

When selecting the appropriate ground improvement technology, having a thorough understanding of the advantages of each system is crucial. Since CMC are a relatively new technology, many potential users are not aware of their benefits with respect to cost-effectiveness. Some of these benefits include:

- Promotes development of brownfield sites underlain by poor quality soils.
- Avoids excavation and replacement of poor-quality soils and limits spoil, reducing waste generation.
- Avoids driving long steel piles to bedrock.
- Provides a cost-effective solution compared to conventional pile foundation systems.
- Allows for the lengths of CMC to be adjusted in the field without splicing or cutting.
- Reduces schedule for installation.
- Reduces the cost of a structure needing a traditional deep foundation, and its design, by replacing pile caps, grade beams and structural slabs with spread footings and slabs-on-grade.
- Improves the performance of a methane barrier system, when required, by eliminating complex detailing around pile caps.
- Eliminates the need to hang utilities under a structural slab, as utilities are installed directly within the load transfer platform.
- With CMC, the slab-on-grade can be built after the building is erected, in a controlled environment, resulting in a better-quality finish. With traditional pile foundations, the structural slab is typically built before the building.
- Reduces the carbon footprint associated with foundations.

While CMC present an environmentally friendly and appealing choice from a financial perspective as well, it has also been proven that their performance is on par with that of deep pile foundations. According to Menard experts (refer to Chapter 4), standard CMC designs restrict the overall settlement of a structure to 25 mm and aim for a differential settlement of around 12 mm. The foundation subgrade is commonly assessed for both its strength (bearing capacity) and its service (settlement). The traditional approach was to use piles to control settlement at sites with poor quality soils. The piles became the supporting elements for the foundation and were designed to resist lateral and vertical loads applied to the foundation. Nevertheless, the capacity of piles needed to regulate settlement might be considerably less than what is needed to support the foundations. Consequently, achieving the service goal may involve an inefficient system, as the pile system overlooks the strength of the soil surrounding the piles. Ground improvement methods such as CMC technique seems to be more efficient than piles as its design utilizes the strength of the surrounding soil and additional soil-improved strength to meet service load requirements.

5.4 Costs Associated with Bi-Modulus Columns

As thoroughly explained in previous chapters, bi-modulus columns can be a great approach for some specific circumstances such as where the embankment is very thin or as a replacement for load transfer platform in seismic areas and it depends on the conditions. In terms of costs however, it is generally more expensive than conventional CMC technique as 2 different crews and machineries are required, one for installation of the CMC part and another one for capping off the bi-modulus element with aggregates and compacting it. On the other hand, the production rate of bi-modulus columns is significantly lower than CMC for the obvious reasons. Nevertheless, if advancements in technology enables us to construct the bi-modulus columns with a price and production rate which are competitive with CMC and with 1 rig only, then it can be a great replacement for CMC in future and utilized in various ground conditions.

5.5 Utilization of Vertical Inclusions in Soft Soil: A Practical Scenario

In this section the cost of ground improvement for a clayey shallow ground using the above-mentioned techniques are compared with an illustrative scenario. Irrespective of the selected technique, the cost of ground improvement can vary significantly depending on several factors, including the project size, site-specific conditions, required equipment, availability of local experts, cost of local labour and material, and other project-specific requirements.

A local government is planning the construction of a new bridge over soft clay ground in a coastal area. The site is characterized by several layers of soil, including a soft clay layer near the surface, followed by layers of stiff clay and clayey sand. The bedrock is located at a depth of approximately 20 m below the surface. The groundwater table fluctuates slightly, but typically remains at a depth of around 3 m. The thickness of the soft clay layer is approximately 10 m. The bridge approach spans a distance of 150 m and has a width of 20 m to accommodate four lanes of traffic in two directions. The area experiences moderate to heavy traffic loads, including trucks and buses of various weights and sizes, due to its proximity to industrial zones and residential areas. To ensure the stability and longevity of the bridge approach, ground improvement measures are necessary to increase the bearing capacity of the soft clay ground. The desired improvement ratio is set at 60% to withstand the anticipated traffic loads and prevent settlement issues over time. Considering the site conditions and project requirements, two ground improvement techniques are being considered: vibro stone columns (VSC) and concrete modulus columns (CMC). It is known that stone columns involve the installation of compacted stone columns into the soft clay ground to reinforce it and improve its load-bearing capacity. This method is relatively straightforward and cost-effective, making it suitable for projects with budget constraints. However, it may not provide as high a degree of improvement as CMC. Concrete modulus columns (CMC), on the other hand, utilize reinforced concrete columns inserted into the soft clay ground. These columns provide higher strength and stability compared to stone columns, making them ideal for projects subjected to heavy traffic loads and requiring stringent settlement control and long-term durability.

To attain a 60% enhancement ratio in the context of VCS, end-bearing columns measuring 800 mm in diameter and 20 m in length were employed. The materials composing the stone columns were drained, possessing an unsaturated density of 20 kN/m^3 and friction angle of 37º. In contrast, for CMC, an equivalent improvement ratio of 60% was accomplished utilizing floating columns with a diameter of 450 mm and a length of 12 m, interconnected with the sand layer. The concrete utilized in CMC exhibited a total density measuring 25 kN/m^3, along with a modulus of elasticity registering at 20 GPa. The ground settlement was mitigated to a mere 50 mm via both techniques, effectively meeting the stipulated design criteria. This variation in column specifications underscores the distinct methodologies employed to achieve comparable performance improvements in different ground improvement techniques.

In terms of cost, vibro stone columns (VSC) will typically be less expensive to install compared to concrete modulus columns (CMC) due to lower material and labour costs, if the stone column materials are readily available. Furthermore, stone column technique requires less specialized equipment, which makes it a preferred approach in developing countries, resulting in lower overall project expenses. However, while CMC may have higher upfront costs, they offer superior performance and durability over time. Their increased load-bearing capacity and resistance to settlement alongside with very high production rate make them a cost-effective choice for critical infrastructure projects, especially in areas with heavy traffic and challenging soil conditions such as soft clay deposits.

5.6 Discussion

According to industry experts, comparing the costs of semi-rigid and rigid vertical inclusions is not straightforward due to the various scenarios that may arise. Both VSC and CMC techniques generally require a similar workforce, typically around three to four people. For CMC, this includes a rig operator, an offsider, a pump man, and sometimes a fourth person, such as an excavator operator. In some projects, the offsider can also act as the operator. For VSC, the team usually consists of a rig operator, an offsider, a loader operator, and sometimes a fourth person as an offsider assistant, among others. For equipment, the vibro stone column technique requires a crane, a vibroflot, a generator, a compressor, and a loader, while controlled modulus columns need a drilling rig, a drilling tool, and a concrete pump. The price of materials (stone for VSC and concrete for CMC) can vary widely depending on the location of project and the local availability of these materials. While stone costs less than concrete in many developing countries, the replacement ratio in VSC is typically much higher than in CMC, which narrows the cost gap between the two techniques. Regarding load transfer platforms (LTP), some cost savings can be noted for stone columns, as LTP is less critical compared to its importance in the CMC technique. In Australia and other developed nations where labour costs are high, the higher production rate of CMC makes them a more affordable approach. With respect to bi-modulus columns (BMC), since two rigs are required to install the columns at present, the production rate is not as fast as that of CMC. Consequently, BMC is not as cost-effective unless further advancements are made in the equipment used for this technique.

Regardless of which technique is used, all three ground improvement techniques mentioned above, offer effective means to enhance the bearing capacity of the ground and mitigate total and differential settlement to a significant extent. However, assessing their cost-effectiveness involves a complex evaluation process. As discussed earlier, directly comparing these methods proves challenging due to the varied conditions present at different project sites. Several factors come into play when determining the most cost-effective solution for vertical inclusion ground improvement techniques. Firstly, local material availability greatly impacts the feasibility and cost of implementing each technique. For instance, if suitable stone or aggregate materials are readily accessible nearby with low price, stone columns may present a more economical option compared to importing materials from other regions. The cost of renting the heavy machinery plays a crucial role in budget assessment. The cost of employing skilled manpower, required for installation, operation, and supervision, varies for each method and can also significantly influence the overall project expenses. In regions with lower labour costs, manual techniques like stone column installation might be more cost-effective, whereas in areas where skilled labour is expensive, mechanized methods like Controlled Modulus Columns could prove more economical. Furthermore, transportation expenses further complicate the cost comparison. If materials need to be transported over long distances to the project site, it can significantly inflate the overall costs, particularly for bulky materials like gravel or mixed aggregates required for stone columns. Conversely, if the necessary equipment needs to be transported to remote locations, transportation costs can add up. Moreover, site-specific conditions such as soil type, groundwater levels, and existing infrastructure can also impact the suitability and cost of each ground improvement technique. For instance, stone columns shall be preferred in areas with soft or cohesive soils prone to liquefaction, while CMC technique could be more suitable for bridge approaches. Given the complexity of these factors, a comprehensive cost-benefit analysis tailored to the specific context of each project is indispensable. This analysis should consider not only the initial costs of implementation but also the long-term benefits in terms of improved performance, durability, and resilience of the ground. By weighing these factors carefully, engineers and project managers can make informed decisions to select the most economical and efficient ground improvement approach for their particular circumstances. Table 5.1 compares the cost-effectiveness of vibro stone columns (VSC), controlled modulus columns (CMC) and bi-modulus columns based on location.

Table 5.1: Cost-effectiveness comparison between vertical inclusion ground improvement techniques based on location

Technique	Price-related factor	Developing countries	Developed countries
VSC	Aggregate	Low	High
	Labour	Low	High
	Production rate	Low	Low
CMC	Cement	High	Low
	Technology	High	Low
	Production rate	High	High
BMC	Aggregate	Low	High
	Cement	High	Low
	Technology	High	Low
	Production rate	Low	Low

According to Table 5.1, vibro stone columns can be a preferred option in developing countries where the cost of material such as aggregates and additives are not high, and labour can be hired more affordably and the majority of the cost of the project belongs to the availability of the less specialized equipment. In developed countries however, the technology is not an issue, but the cost of material and labour is high. Figure 5.1 compares the cost components of VSC technique based on the locality of the ground improvement project.

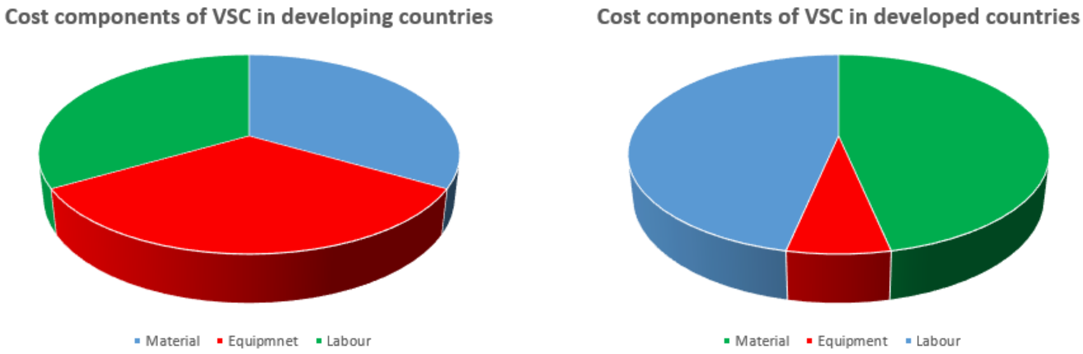


Figure 5.1: Comparison of the typical cost of VSC technique based on the locality of the ground improvement project

However, as depicted in Table 5.1, in developed countries where technology and cement are readily available and affordable, CMC may present a more attractive option. Conversely, based on Basack (2023), in developing countries like India and Middle East, where equipment accessibility is limited, CMC might not be as feasible. Figure 5.2 compares the cost components of CMC technique based on the locality of the ground improvement project.

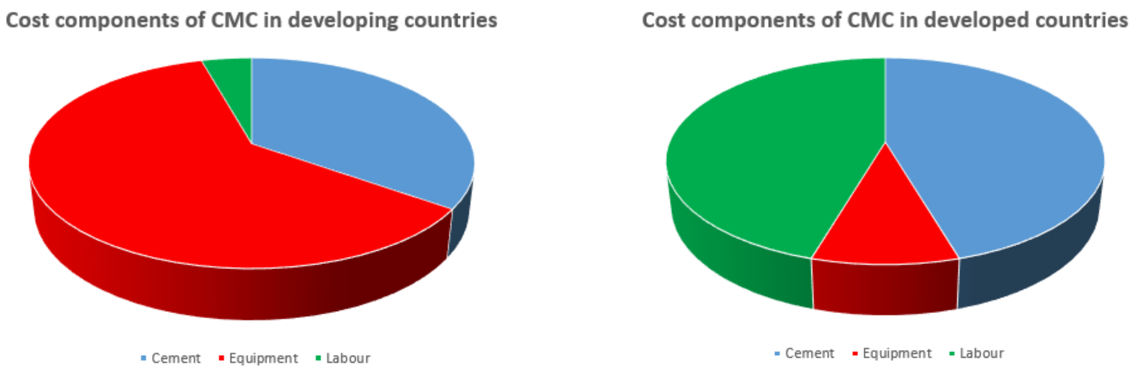


Figure 5.2: Comparison of the typical cost of CMC technique based on the locality of the ground improvement project

Regarding bi-modulus columns, based on Racinais (2023), because it is a recent technology, most developing countries lack access to it. Even in developed countries, it is less appealing compared to the CMC alternative because of its slower production rate, rendering it more costly than the conventional CMC method, which can produce up to 800 meters per day.

Referring to Chapter 4 and expert insights and opinions, the length and diameter of vertical inclusions can also affect the cost of construction. Several factors contributing to this cost increase for stone columns can be found in Table 5.2.

Table 5.2: Factors contributing to the cost increase of stone columns with respect to the size of the columns

Factor	Description
Material Costs	Longer and larger stone columns require more stone material to construct. This means higher costs for purchasing the stone itself.
Labour Costs	Constructing larger and longer stone columns may require more labour, as constructing such columns involves additional steps such as safety measures, and more intricate construction techniques.
Transportation Costs	Longer and larger stone columns may require bigger or more frequent deliveries of materials to the construction site, increasing transportation costs.
Engineering and Design Costs	Designing longer and larger stone columns may require more complex engineering and design work, which can increase costs associated with consulting engineers and architects.
Time and Complexity	Such stone columns may take longer to construct and require more attention to detail, potentially increasing project duration and associated costs.

Therefore, it is clear that the length and dimeter of stone columns can have a significant impact on the overall expense of the project. These dimensions affect material quantities, labour, equipment needs, and may require specialized installation methods. Furthermore, larger columns can affect structural design, potentially leading to additional expenses. Thus, careful consideration of the size of stone columns is essential in project planning to ensure cost-effective construction while meeting ground improvement requirements and project objectives. Table 5.3 outlines the factors contributing to the cost increase of CMC based on the size of the columns.

Table 5.3: Factors contributing to the cost increase of CMC with respect to the size of the columns

Factor	Description
Material Costs	The height and diameter of CMC influence the amount of materials required for construction. This includes materials such as cement, aggregate, and any additional additives used in the columns. Longer and larger columns typically require more material, which can increase costs.
Installation Costs	The height and diameter of CMC also affect the installation process. Longer and larger columns may require more labour, specialized equipment, or additional steps in the construction process, all of which can increase installation costs.
Engineering and Design Costs	Designing longer and larger CMC may require more detailed engineering analysis and design work. This can lead to higher costs associated with consulting engineers and geotechnical experts.
Site Preparation Costs	Longer and larger CMC may require additional site preparation work, such as excavation or grading, to ensure proper installation. These extra site preparation activities can contribute to higher costs.
Quality Control Costs	Ensuring the quality and integrity of longer and larger CMC may require more rigorous quality control measures, such as increased testing and inspection. These additional quality control efforts can add to project costs.

Thus, the height and diameter of controlled modulus columns (CMC) can influence construction expenses due to factors such as installation rig, materials, labour, design, site preparation, and quality control. It is evident that larger columns incur higher costs and thorough evaluation of CMC dimensions is vital during project planning to guarantee economical building practices while fulfilling the project goals such as mitigating the ground settlement and increasing its bearing capacity.

When comparing the costs associated with the height and diameter of columns between the two methods, it becomes evident that larger vertical inclusions result in higher expenses in both cases. However, the production rate of Controlled Modulus Columns (CMC) is notably faster than that of stone columns, thereby mitigating the cost increase associated with enlarging CMC vertical inclusions to some extent, in contrast to stone columns. Additionally, as noted by Vincent (2023), the stone column technique, particularly the dry top feed method, faces limitations concerning specific depths, making it less suitable for projects requiring longer vertical inclusions. These constraints highlight the need for careful consideration when selecting the appropriate ground improvement method.

For a visual comparison, Figure 5.3 provides an illustration depicting the cost implications of increasing the size (height and diameter) of columns for both techniques.

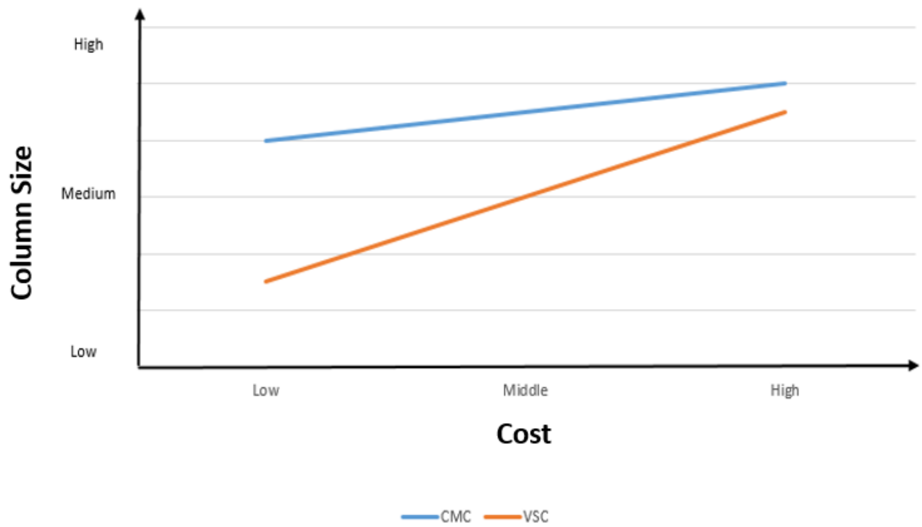


Figure 5.3: Conceptual diagram indicating the effect of column size increase on project cost: VSC versus CMC

As can be seen, it is evident that in both cases, larger vertical inclusions lead to higher expenses. However, due to much higher production rate of CMC, the rise in costs related to expanding CMC vertical inclusions is comparatively lower than that for stone columns.

The comparison of the two techniques can extend to the costs linked with the Load Transfer Platform (LTP). According to Hamidi (2023), it is apparent that because of the high rigidity of CMC, the LTP holds significant importance in the CMC foundation system, necessitating precise and comprehensive design, which can incur costs. In contrast, with the VSC technique, where the columns are semi-rigid, there is not the same level of sensitivity, allowing for potential savings. However, LTP is still necessary.

To illustrate the comparison between Controlled Modulus Columns (CMC) and vibro Stone Columns (VSC) regarding costs associate with Load Transfer Platforms (LTP), an illustrative case study is considered, involving the construction of a large industrial facility on a soft soil site.

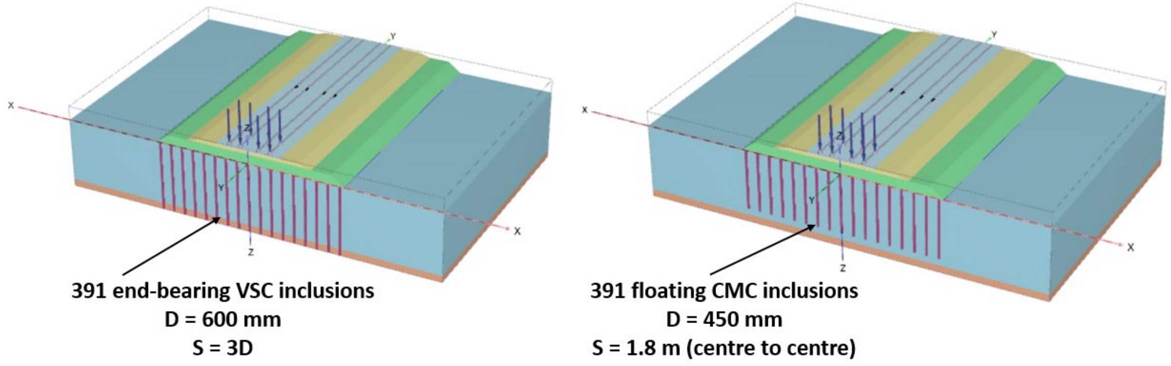
5.6.1 Case Study: Ground Improvement Prior to Construction of an Embankment Road

A leading geotechnical corporation has been commissioned by a client to implement ground improvement for the construction of an embankment road on very soft clayey ground, where the water table is at the surface. This case study examines the cost-effectiveness of the two above-mentioned ground improvement techniques: Vibro Stone Columns (VSC) and Controlled Modulus Columns (CMC) for this project. The specifications of the project requires ground improvement to support an embankment with an allowable design settlement of 60 mm, slightly above the standard practice of 50 mm. For the VSC technique, the project requires 391 end-bearing stone columns arranged in a grid pattern (17 columns along the X-axis and 23 along the Y-axis) with a spacing of 3D, where D is the diameter of the stone columns (650 mm). A granular blanket with a thickness of 0.5 m and dimensions of 30 × 40 m is constructed on top of the stone columns to distribute the load evenly. The length of the end-bearing VSC columns are 11 m and geotechnical properties for the crushed aggregates used in the construction of vibro stone columns. The properties of granular blanket are: the Modulus of Elasticity (E) is 100 MPa, and Unit Weight (γ) is 18 kN/m^3.

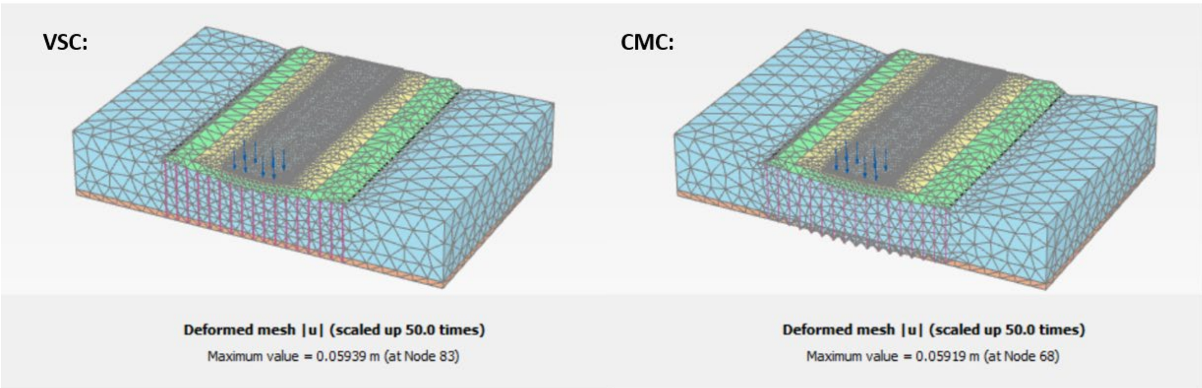
For the CMC technique, in order to achieve similar ground improvement to the VSC technique, the project also requires 391 floating CMC inclusions with a diameter of 450 mm.

Additionally, a Load Transfer Platform (LTP) with a thickness of 0.5 m and dimensions of 30 × 40 m is constructed on top of the CMC to ensure effective load distribution. The length of the floating CMC is 9 m and material properties for the concrete used in the construction of them are as follows: the Modulus of Elasticity (E) is 15 GPa and the unit weight (γ_c): 24 kN/m³.

Figure 5.4 illustrates the numerical models for these two techniques created in PLAXIS 3D and the resultant settlement profiles for each technique.



a)



b)

Figure 5.4: a) the numerical models for VSC and CMC techniques created in PLAXIS 3D; b) the resultant settlement profiles for each technique

According to the Figure 5.4 b, the calculated settlements for both VSC and CMC techniques are nearly identical, with VSC resulting in 59.39 mm and CMC in 59.19 mm.

To determine the cost-effectiveness of each method, the volume of materials used for the VSC and CMC techniques are calculated. The analysis focuses on the volume of crushed aggregates and concrete required for each method. It is proposed that the volume of granular blanket known as LTP in both methos are the same (i.e. $30 \times 40 \times 0.5 = 600\ m^3$):

The total net volume of material (aggregates) for **VSC** is equal to the volume of single stone column times the number of columns: $\pi/4 \times 0.65^2 \times 11 \times 391 = 1427.2\ m^3$ crushed aggregates.

The total net volume of material (concrete) for **CMC** is equal to the volume of single CMC times the number of columns: $\pi/4 \times 0.45^2 \times 9 \times 391) = 559.8\ m^3$ concrete.

Generally speaking, the standard mix ratio for concrete is approximately 1:5 (cement to aggregates) by volume. Therefore, in this example, 93.3 m^3 of cement and 466.7 m^3 of aggregates are utilized.

It is concluded that the CMC technique requires less material compared to the VSC technique, which suggests that CMC may be more cost-effective in terms of material volume. Additionally, the CMC technique has been identified for its faster installation time, making it a preferable option in regions with high labour costs. However, factors such as cost of cement compared to aggregates, the availability of the technique, transportation considerations and site conditions should also be evaluated before making a final decision. Overall, the CMC technique appears to offer a more efficient and potentially more cost-effective solution for mitigating settlement in soft clayey soils.

To demonstrate the efficiency of the CMC technique in terms of reduced material volume in comparison to VSC technique while achieving similar settlement mitigation, a hypothetical model was created in PLAXIS 3D using 221 CMC inclusions (13 columns along the X-axis and 17 along the Y-axis) with a spacing of 5.33D, where D is the diameter of the CMCs (450 mm). Other variables, such as the length of the floating columns, the thickness and dimensions of the Load Transfer Platform (LTP), and the material properties of the concrete, remained constant and identical to the previous model with 391 CMC inclusions. Figure 5.5 illustrates the numerical model created in PLAXIS 3D with a spacing of 5.33D and the resulting settlement profile.

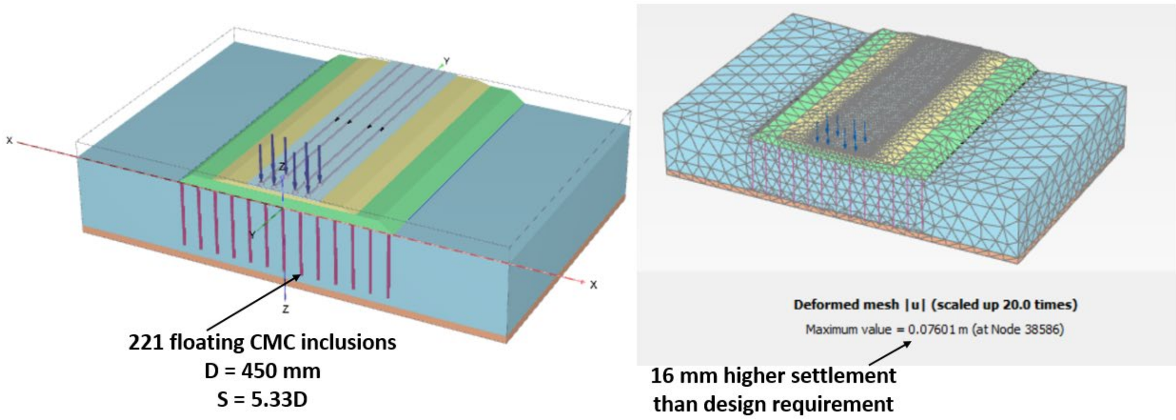


Figure 5.5: The numerical model created in PLAXIS 3D with a spacing of 5.33D and the resultant settlement profile

Referring to Figure 5.5, it is observed that the ground settlement at the surface exceeds the design specification by 16 mm, which may be deemed negligible in less sensitive situations. However, a significant cost-saving is achieved in terms of concrete usage and production rate, with an approximate reduction of 45% compared to using 391 CMC inclusions. This underscores the exceptional utility of the CMC technique in ground improvement projects.

5.7 Summary

In summary, conducting a cost-benefit analysis for vertical inclusions ground improvement techniques, such as vibro stone columns (VSC), controlled modulus columns (CMC), and bi-modulus columns (BMC), involves comparing the initial investment and operational costs with the expected benefits, which include increased load-bearing capacity, reduced settlement, and enhanced stability. The cost of installing vertical inclusions can vary based on factors such as the location of the project and its complications, the depth and diameter of the columns, the type of materials used, and site-specific conditions. Generally, VSC is less expensive due to simpler materials and installation processes, whereas CMC might incur higher costs due to the use of specialized equipment and materials; however, the very fast production rate of CMC often makes it the less expensive and better option in many aspects. In terms of BMC, since it is a novel approach, advancement is required to install the entire element with one rig; otherwise, despite its several benefits, it is not the most cost-effective approach.

The primary benefits of these techniques include improved soil stability, increased bearing capacity, and reduced settlement, leading to longer lasting and more reliable structures. This can translate into savings on foundation repairs and maintenance, as well as enhanced safety and performance of the supported structures. Over time, the initial investment in vertical inclusions can result in significant cost savings by preventing structural failures, minimizing maintenance needs, and extending the lifespan of infrastructure. Additionally, the improved load distribution and stability can lead to more efficient designs and reduced material usage in the construction phase. Overall, the decision to use VSC, CMC, or BMC techniques should consider the availability and cost-effective price of materials and equipment, as well as the upfront costs and long-term benefits, ensuring a comprehensive evaluation of the project's economic and technical feasibility.

6

Conclusions and Recommendations

6.1 General Summary

The need to build transportation infrastructure carrying increased freight such as highways and heavy haul railways on marginal areas underlain by soft alluvial soil is inevitable in coastal areas. Utilizing vertical inclusions like Vibro Stone Columns (VSC) and Concrete Modulus Columns (CMC) has become a widely adopted method for enhancing the stability of the soft ground prior to building transport infrastructure. VCS are favoured for their capability to reduce drainage paths and enhance the ground's stiffness and load-bearing capacity. CMC, on the other hand, are reserved for more demanding situations with rigorous design specifications. As a novel approach recently introduced, bi-modulus columns represent an innovative method for ground improvement. This technique involves the installation of vertical columns made from materials with dual stiffness properties (CMC segment at the bottom and VSC part at the top). By incorporating both rigid and flexible elements, bi-modulus columns aim to optimize ground stabilization and load distribution, particularly in challenging soil conditions. This innovative method apart from increased cost of installation and slower production rate has shown promise in enhancing the performance and longevity of infrastructure projects, offering a more versatile solution compared to traditional ground improvement techniques.

This thesis endeavours to present findings aimed at enhancing comprehension regarding the performance of semi-rigid (VSC), rigid (CMC), and bi-modulus vertical inclusions beneath transportation infrastructure, particularly concerning the deformation characteristics of the composite ground. Another aspect of this thesis involves acquiring perspectives from professionals and industry experts through interviews, as well as conducting cost analyses to compare various types of vertical inclusions in relation to cost efficiency.

Chapters 1 and 2 of this study provided an extensive examination of existing literature and identified pertinent issues. In Chapter 3, a numerical analysis was conducted, considering diverse scenarios and ground conditions, to assess the reinforcement of shallow clayey ground with vertical inclusions underlying an embankment subjected to both static and dynamic loading conditions. The accuracy and validity of the analysis were initially confirmed by comparing the results with previously recorded in-situ data. Chapter 4 focused on interviews conducted with industry experts globally. This chapter entailed posing a series of inquiries to professionals and stakeholders regarding the benefits and limitations associated with semi-rigid (VSC), rigid (CMC), and innovative bi-modulus columns vertical inclusions. Drawing upon their extensive expertise and experience, conclusions were derived from the insights provided. Chapter 5 carried out a cost-benefit analysis, comparing the cost-effectiveness of vertical inclusion ground improvement methods based on project location, materials utilized, and project duration.

6.2 Concluding Remarks

This study has tried to assess the efficacy of vertical inclusion ground improvement techniques through rigorous numerical analysis, aiming to ascertain their utility and facilitate a comprehensive comparison among them.

Generally, vertical inclusions such as vibro stone columns (VCS), controlled modulus columns (CMC), and the innovative bi-modulus columns (BMC) represent versatile and effective ground improvement techniques with proven track records in enhancing the performance of weak or compressible soils. Through a combination of densification, reinforcement, and confinement mechanisms, these inventive solutions have been successfully employed in a wide range of geotechnical projects worldwide.

The effectiveness of VCS, CMC, and BMC lies in their ability to address various geotechnical challenges, including settlement mitigation, bearing capacity enhancement, liquefaction mitigation, and lateral load resistance. By altering the engineering properties of the surrounding soil mass, these vertical inclusions can significantly improve the overall stability, durability, and performance of engineered structures. Given the inherent stiffness of CMC, it is evident that such columns exhibit significantly reduced settlement, typically ranging from three to ten times less than VCS. Moreover, CMC demonstrate versatility across various soil types and ground conditions. Nevertheless, in specific soil deposits characterized by liquefaction susceptibility for instance, stone columns emerge as the sole dependable solution. The significance of stone columns also lies in their capacity to serve as an efficient drainage pathway, facilitating the rapid dissipation of excess pore pressure within the ground. The utilization of bi-modulus columns presents an opportunity to leverage the advantages of two distinct techniques simultaneously, thereby capitalizing on the strengths inherent in each approach. In general, the bi-modulus columns offer a highly appealing solution in situations where issues related to load transfer platforms (LTP), such as the occurrence of mushroom effects, are present.

Another component of this thesis involved conducting interviews with industry professionals from various regions across the globe. According to them advancements in construction methodologies, material technologies, and design optimization have further enhanced the efficiency and reliability of these ground improvement techniques. However, ongoing research and development efforts are required to continue to refine design guidelines, improve construction practices, and expand the applicability of VCS, CMC, and BMC in diverse geotechnical conditions and project requirements. The experts underscored the importance of acknowledging that the selection and implementation of vertical inclusions should be carefully tailored to site-specific conditions, including soil properties, loading conditions, environmental considerations, and project objectives. Close collaboration between geotechnical engineers, designers, contractors, and stakeholders is paramount to ensuring successful project outcomes and maximizing the benefits of vertical inclusion technologies.

Ultimately, a cost-effectiveness analysis was undertaken to compare the vertical inclusion ground improvement techniques. According to the findings of this study, it becomes evident that vertical inclusions represent an economically viable choice, contingent upon the site's geographical context. VCS emerge as particularly advantageous in regions undergoing development, such as India and the Middle East. Conversely, CMC consistently prove to be the optimal solution in developed regions such as Australia. This distinction underscores the importance of aligning ground improvement strategies with the economic and developmental context of the respective location. With respect to feasibility of bi-modulus columns, they represent a novel approach that necessitates dedicated investment of time and resources to enhance its economic viability.

In summary, the effectiveness of VCS, CMC, and bi-modulus columns in ground improvement applications is well-established, offering cost-effective, sustainable, and reliable solutions for addressing soil-related challenges in various infrastructure and construction projects around the world. With continued research, innovation, and collaboration, these vertical inclusion techniques will continue to play a crucial role in advancing the field of geotechnical engineering and meeting the evolving needs of modern infrastructure development.

6.3 Recommendations for Future Studies

6.3.1 Comprehensive Laboratory Tests

Laboratory tests for future studies on vertical inclusions ground improvements typically include a combination of geotechnical and material testing to assess the properties of both the native soil and the vertical inclusions being considered. In forthcoming research endeavours, a variety of crucial laboratory examinations can unveil the unfamiliar and offer indispensable perspectives. Soil classification tests, including grain size analysis and Atterberg limits tests, elucidate the soil's particle distribution and plasticity. Index property tests, such as specific gravity and moisture content tests, assess soil density and water content. Shear strength tests like direct shear or triaxial tests measure parameters such as cohesion and friction angle. Consolidation tests, like the Oedometer test, evaluate compression and settlement under load. Permeability tests gauge hydraulic conductivity, while load-bearing capacity tests such as the plate load or CBR test determine soil strength pre- and post-improvement. Vertical inclusion testing involves compression and pull-out tests to assess load-bearing capacity and bond strength. For materials like concrete in columns, various tests including compressive and tensile strength, as well as durability tests under different environmental conditions, can be conducted. Furthermore, compatibility tests to ensure proper interaction between vertical inclusions and native soil can be extremely advantageous. These comprehensive laboratory tests offer crucial data for optimizing design, ensuring effectiveness, and maintaining long-term stability of ground improvement techniques.

6.3.2 Field Measurements

Field measurements for ground improved with vertical inclusions, such as stone columns and controlled modulus columns, are crucial for assessing the effectiveness of the ground improvement technique and monitoring the behaviour of the improved ground.

For future studies concerning ground improved with vertical inclusions, several common field measurements may be conducted to assess their effectiveness and performance. Settlement measurements involve regular monitoring of ground settlement using markers or surveying instruments such as total stations or GPS receivers, enabling evaluation of settlement reduction over time. Vertical deformation profiles are measured at various depths within the improved ground using settlement plates, extensometers, or inclinometers, providing insight into deformation distribution and vertical inclusion performance. Load transfer tests, such as plate load tests or dynamic load tests, evaluate the load-bearing capacity of the improved ground and the efficiency of vertical inclusions in transferring loads to deeper, more competent soil layers. Continuous vibration monitoring during construction activities or dynamic loading using sensors helps assess impacts on nearby structures and ensures compliance with vibration limits. Monitoring pore water pressures within the improved ground using piezometers aids in evaluating drainage improvement and reducing excess pore pressures. Ground penetration testing, including Cone Penetration Testing (CPT), assesses soil resistance and stratigraphy before and after ground improvement, revealing improvements achieved and any changes in soil properties. Cross-Hole Sonic Logging (CSL) tests assess the integrity and quality of deep foundation elements, aiding in identifying defects or material property variations. Instrumentation tests involve installing strain gauges, settlement gauges, and pore pressure transducers to monitor soil and vertical inclusion behaviour. Tilt meters or horizontal deformation monitoring devices are installed to measure lateral movements or tilting of nearby structures, ensuring stability, and detecting potential issues related to ground movement. Finally, regular visual inspections of the ground surface and structures identify signs of distress, cracking, or settlement issues, indicating any ground improvement-related problems.

Future researchers have the opportunity to contribute through conducting these field measurements, enabling engineers and geotechnical specialists to evaluate the effectiveness of ground improvement methods and implement any required modifications to guarantee the stability and long-term reliability of the enhanced ground.

6.3.3 Effect of Groundwater and Soil Suction on Behaviour of Rigid and Semi-Rigid Inclusions

Investigators in future can contribute significantly to understanding the effects of groundwater and soil suction on the behaviour of rigid and semi-rigid inclusions through various means:

To begin with, experimental studies involving laboratory simulations under different moisture conditions provide insights into their behaviour. Furthermore, field measurements, including long-term monitoring of groundwater levels and inclusions' performance, offer valuable real-world data. Utilizing advanced numerical modelling that incorporates environmental factors predicts performance across varying conditions accurately and cost-effectively. Employing numerical models facilitates the conduct of parametric studies to analyse the influence of diverse factors, thereby optimizing inclusion design for varying sites. Case studies examining past projects' performance additionally, offer practical insights for future practices. Finally, material characterization studies on permeability, stiffness, and moisture susceptibility shall enhance inclusion durability and effectiveness. By focusing on these areas, future researchers can advance our understanding of how groundwater and soil suction influence the behaviour of rigid and semi-rigid inclusions, ultimately leading to more effective and resilient ground improvement practices.

6.3.4 Expanding Expert Interviews to Include a Broader Range of Stakeholders

Expanding expert interviews in ground improvement projects to include a broader range of stakeholders is pivotal for enriching research outcomes and achieving a more comprehensive understanding of the subject. To achieve this, future researchers can adopt several strategies. Firstly, they should identify relevant stakeholder groups such as engineers, geotechnical specialists, contractors, project owners, government agencies, academics, environmentalists, and community representatives. Secondly, diversifying interviewee selections within these groups by considering factors like geographic regions, professional backgrounds, and industry sectors is essential. Collaborating with industry associations can provide access to a wider network of stakeholders, while engaging with government agencies enables insights into policy, regulation, and funding aspects. Involving community representatives is crucial for addressing social and environmental concerns associated with ground improvement projects. Additionally, employing a mixed-methods approach incorporating surveys, focus groups, workshops, and site visits alongside expert interviews can capture diverse perspectives effectively. Promoting collaboration and knowledge exchange through various platforms further enhances the impact and applicability of research findings. By implementing these strategies, researchers can broaden the scope of their expert interviews, ultimately advancing the relevance and effectiveness of their research in the field of ground improvement.

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