Effects of installing controlled modulus columns on previously installed columns

Effets de l'installation de colonnes à module contrôlé sur les colonnes précédemment installées

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ABSTRACT: Controlled modulus columns (CMC) ground improvement technique is an attractive geotechnical solution for modification of soft soils. This technique uses a displacement auger during column installation, aiming to reduce the construction cost and disposal of excavated materials. However, lateral and vertical soil movement induced by the installation process may pose potential risks to the adjacent previously installed columns. Only a handful of studies have been attempted in quantifying such effects. This paper presents the results of a numerical investigation on the effects of CMC installation sequence on the already installed columns using the three-dimensional finite difference software package *FLAC*^{3D}. The results indicate that the installation sequence should be taken into account in the design process to minimise any adverse effects of installing new CMCs on the existing columns.

RÉSUMÉ : La technique d'amélioration du sol des colonnes à module contrôlé (CMC) est une solution géotechnique attrayante pour la modification des sols mous. Cette technique utilise une tarière de déplacement lors de la formation des colonnes, visant à réduire le coût de construction et l'élimination des matériaux excavés. Cependant, le mouvement latéral et vertical du sol induit par le processus d'installation peut présenter des risques potentiels pour les colonnes adjacentes précédemment installées. Seule une poignée d'études ont été tentées pour quantifier de tels effets. Cet article présente les résultats d'une étude numérique sur les effets de la séquence d'installation CMC sur les colonnes déjà installées en utilisant le logiciel tridimensionnel de différences finies *FLAC*^{3D}. Les résultats indiquent que la séquence d'installation doit être prise en compte dans le processus de conception pour minimiser les effets néfastes de l'installation de nouveaux CMC sur les colonnes existantes.

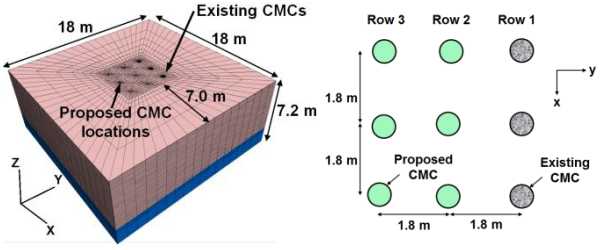
KEYWORDS: Cavity expansion, ground improvement, controlled modulus column, installation effect, installation sequence.

1 INTRODUCTION

The controlled modulus column (CMC) ground improvement technique uses rigid inclusions to stiffen the ground mass, combined with a load transfer platform, to reduce short and long term ground deformation (Plomteux et al. 2004). CMC rigid inclusions are cast-in-place plain concrete columns, having lower strength than normal concrete, for ground improvement purposes. To form such inclusions, a rotational displacement auger is utilised to penetrate the ground to the desired depth, typically 1.0 m into the stiff soil. As the auger moves up, high slump concrete is pumped into the cavity through the hollow auger stem. During the downward movement of the auger and the grout pumping, the induced lateral soil movement can be excessive. When proposed columns are closely spaced, if proper installation sequence is not considered, the risk of damaging adjacent already installed columns due to lateral soil movement induced by installation of new columns could be unacceptable (Plomteux et al. 2004, Hewitt et al. 2009). The effect of pile driving on the previously installed pile has been investigated by Poulos (1994), which indicates that the soil movement due to pile driving may generate excessive forces and moments in the already-installed piles. For ground improvement, the majority of the past literature focused on the installation effects of ground improvement activities on the surrounding soil. Assessment of the CMC installation effects on the previously installed columns has not been reported in the literature. Lateral soil movement analyses including the interaction between soil movement and previously installed columns are complex interaction problems. Numerical modelling of column installation process often involves large mesh distortion. This paper presents a 3D numerical model to analyse the response of existing CMCs subjected to loading due to the lateral soil movement induced by installing new nearby CMCs. In the model, the effect of using different installation sequences on the existing CMC is investigated.

2 NUMERICAL MODELLING

To simulate the CMC installation process, 3D numerical modelling using *FLAC*^{3D} v.5.01 was carried out in large strain mode. 3D grids were created to represent a soil profile consisting of a 5.4 m thick soft clay layer, overlying 1.8 m thick stiff ground (Figure 1a).



(a) (b)

Figure 1. (a) Finite difference grid and (b) the layout of CMCs.

Three existing CMCs (i.e. Row 1) and six proposed CMC locations (i.e. Rows 2 and 3) were located in the centre of the 3D model (Figure 1b). The radial cylindrical and hemispherical mesh represents CMCs, while the cubical meshes form the outer soil regions. The lateral boundaries were extended 15 times the CMC diameter, from the outmost CMC to minimise the boundary effects. CMCs had a diameter D = 450 mm. CMCs were spaced at 1.8 m centre to centre in a square pattern, which corresponds to 4D, a minimum possible column spacing when installing displacement piles. All CMCs were embedded 0.9 m into the stiff ground. Since the CMC embedment is in stiff clay and the problem being considered is mainly related to the soil lateral movement, it is considered that the bottom boundary effect is present but not insignificant. The installation

of new CMCs along Rows 2 and 3 was simulated in this study. The model grid shown in Figure 1a was generated using *FISH* language comprising 105,651 zones and 107,898 grid points.

2 .1 *Material model*

Soil properties were derived from site investigation data from a highway upgrade project in New South Wales, Australia. The modified Cam-Clay (MCC) material model was adopted to represent the behaviour of the soft clay. The adopted parameters include the slope of normal consolidation line (NCL) λ = 0.29, and the slope of elastic swelling line κ = 0.073. The NCL line is defined by a reference pressure p'_{ref} = 74 kPa and a specific volume v_{ref} = 2.55. Based on the oedometer results, an overconsolidation ratio OCR of 1.6 was applied for the entire depth. Hence, the pre-consolidation pressure varied linearly with depth. The effective friction angle ϕ' was 28° and the critical state stress ratio M=1.11. The lateral stress coefficient K_0 for lightly overconsolidated clay could be related to that of the normally consolidated clay via OCR and was estimated to be 0.75. A dry density of 1300 kg/m^3, a porosity of 0.5 and an effective Poisson's ratio ν' = 0.3, were also adopted. It is noted that for a structured clayey soil, due to increase in the mean effective stress as well as deviatoric stress, cementation degradation may occur influencing the deformation of the ground immediately after the installation (Nguyen et al. 2014).

The stiff ground was characterised by the Mohr Coulomb (MC) material model, with a drained Young's modulus of 12 MPa, a Poisson's ratio of 0.3, a cohesion c' = 10 kPa and an effective friction angle ϕ' = 25°. CMCs were considered impermeable and modelled using solid elements. The MC model was used to represent CMC behaviour. It was assumed that the CMC grout set relatively quickly after injection. Hence, a grout density of 2400 kg/m^3, bulk modulus K = 3.23 GPa, shear modulus G = 2.42 GPa, cohesion c' = 300 kPa, friction angle ϕ'= 30°, and a tensile strength σ^t = 500 kPa were adopted for CMC. The stiffness and the tensile strength of CMCs were estimated according to Eurocode BSI (2004) using a characteristic compressive strength of sand concrete f_{ck} = 10 MPa. It is understood that the time-dependent setting of the grout plays a significant role in assessing the installation effects. For the purpose of this paper, the CMC compressive strength (σ_c) gained in the short term was 10 MPa, which is approximately half of the long term compressive strength of 20 MPa, commonly adopted in the CMC design.

2 .2 *Interfaces, boundary, and initial conditions*

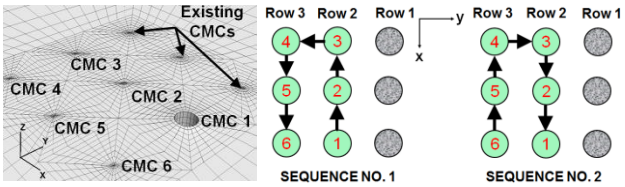
Interface elements with insignificant tensile strength were employed to allow sliding between the ground and CMC. The interface behaviour is determined by the friction angle and cohesion, which were set equal to those of the surrounding soils. The interface normal and shear stiffnesses, k_n and k_s, were estimated using Eq. 1 as recommended by Itasca (2012).

$$k_n = \quad k_s \quad \approx \quad 10 \times \left[\frac{K + \frac{4}{3}G}{\Delta z_{min}} \right] \qquad (1)$$

where K and G are maximum values of soil bulk and shear moduli, respectively; and $\Delta z_{\min}$ is the minimum mesh size in the elements adjacent to the interface. The soil at the side boundaries, shown in Figure 1, was fixed against the displacement normal to the boundary planes. The top boundary was free and was considered free draining. The bottom boundary was restrained. The initial conditions included the initial hydrostatic pore water pressure, assuming the groundwater table to be at the ground surface; and the initial effective stresses to be due to soil self-weight, presuming a gravitational acceleration of 9.81 m/s^2. However, near surface soils in reality may be partially saturated and a more realistic coupled flow-deformation behaviour of unsaturated soils should be considered (Ho et al. 2015). Once the in-situ stresses were established, the CMCs along Row 1 were installed "wished-in-place" (i.e. no installation effects were considered) by simply changing material properties in the existing CMC zones, from those of soil to CMC and the system was stepped to equilibrium.

2 .3 *Modelling CMC installation*

The simulation of the CMC installation was executed in two stages: (i) creating a borehole and (ii) backfilling the borehole with grout. Cavity creation is most easily modelled numerically by expanding a pre-existing cavity of initial radius r_i to a new cavity of radius r_f, as recommended by Carter et al. (1979). Assuming undrained expansion, the condition of constant volume was considered; hence the radius r_f at end of the expansion was readily estimated using a simple relationship: $r_f = (r_i^2 + r_{CMC}^2)^{0.5}$ where r_{CMC} = 225 mm. An optimal initial radius r_i was determined, being sufficiently small to maintain reasonable numerical accuracy. At the same time, this radius should not be too small, to avoid excessive mesh distortion. Parametric studies indicated that r_i = 65 mm ($r_{CMC}/4$) was adequate for the adopted geometry and mesh. The first step of creating a cavity was to turn the soil within the initial cavity into "null" material (i.e. material removed). Outward normal velocities were then applied to the cavity wall so that, upon mechanical stepping in a large strain mode, the wall was displaced in the normal direction until achieving a cavity with r_f = 234 mm. Figure 2a shows the deformed mesh, as a result of the first cavity creation.



(a) (b)

Figure 2. (a) Deformed mesh after undrained cavity expansion at CMC 1 ; (b) The two construction sequences illustrated by arrows

Before filling the borehole with CMC grout, the applied velocities at the wall were removed. Concrete over-break was not taken into account in this study. The soil/CMC interface elements were inserted and the system was stepped to equilibrium to complete the CMC installation. The subsequent CMC installations were simulated in a similar manner.

As shown in Figure 2b, two installation sequences have been adopted in the simulations to compare the effect of using different orders of installation on the existing CMC. Arrows in Figure 2b implies that Sequence No. 1 starts with Row 2 while Sequence No. 2 starts with Row 3. It is expected that the middle existing CMC (i.e. column adjacent to CMC2) would be the most affected column by new CMC installations at the proposed locations. Hence, the response of this particular CMC to the installation process is reported in the next section.

3 RESULTS AND DISCUSSION

The CMC installation induces lateral and vertical displacement of the surrounding soil. Predicted lateral and vertical movements in the soil between the two adjacent existing CMCs, induced by CMC installations, are shown in Figure 3. The result indicates that the installation Sequence No. 2 induces more soil movements than Sequence No. 1. Figures 4 and 5 show that the calcuated soil heave between newly installed CMCs ranges from 50 mm to 100 mm. This implies that the induced soil heave should be considered in the subsequent earthworks to build the finish platform level.

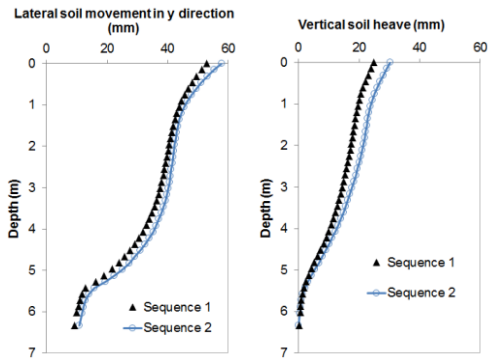


Figure 3. Soil movement between two adjacent existing CMCs

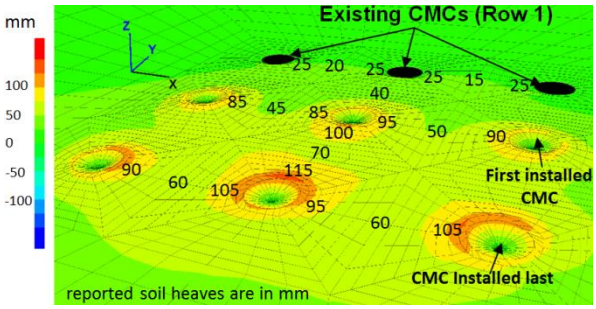


Figure 4. Contour of vertical soil movement (Sequence No. 1)

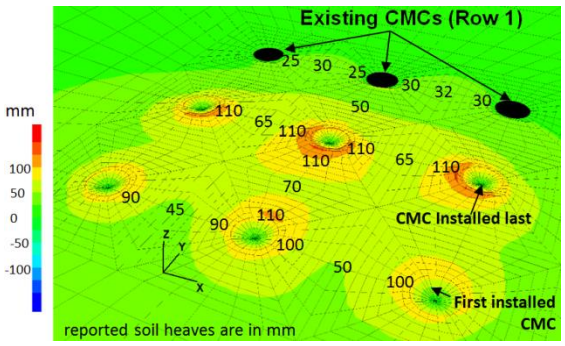


Figure 5. Contour of vertical soil movement (Sequence No. 2)

The soil movement generally displaces the existing CMC in the positive y direction. The movement of the existing CMC head away from the initial location for each sequence are plotted schematically in Figure 6. During the course of installation, the CMC head also moves slightly sideway (i.e. in x direction). The side-way movement of column head is the consequence of the change in directions of the lateral soil movement induced by installation of different CMCs.

The ensuing vertical soil movement which interacts with the existing column also causes uplift or vertical heave of the existing CMC of approximately 5 to 6 mm, which is around 1% of the column diameter (Figure 7). The uplift of the existing CMC due to installation Sequence No. 2 is slightly greater than the uplift induced by Sequence No. 1. The uplift of the CMCs could potentially be a factor in the short and long term settlement of the composite soil-column ground at a later stage. Geotechnical practitioners may wish to apply short term surcharge on the CMC-reinforced ground to compensate for installation-induced uplifts.

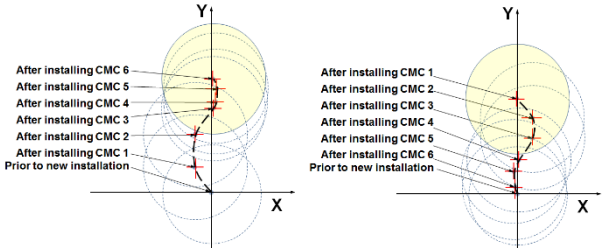


Figure 6. Schematic diagram of lateral movements of the existing CMC head (a) sequence No. 1 (b) sequence No. 2

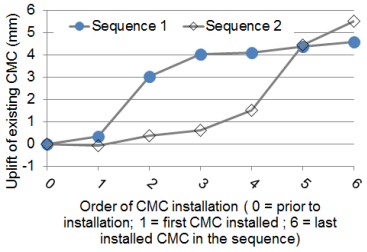


Figure 7. Uplift of existing CMC due to installation of new CMCs

Figure 8 presents the contours of the excess pore water pressure and the deformed shape of the existing CMC, at the completion of all CMC installation. It is observed that the pore water pressures increase around the newly installed CMCs, and in front of the existing CMCs, due to the undrained cavity expansion. At the base of the existing CMC, the pore water pressure reduced significantly, from the initial hydrostatic pressure of 70 kPa, to approximately 25 kPa, possibly due to the uplift effects. The excess pore pressure is expected to decay inducing elastic visco plastic deformation (Le et al. 2015).

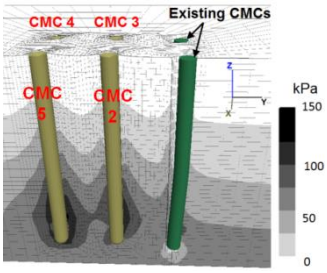


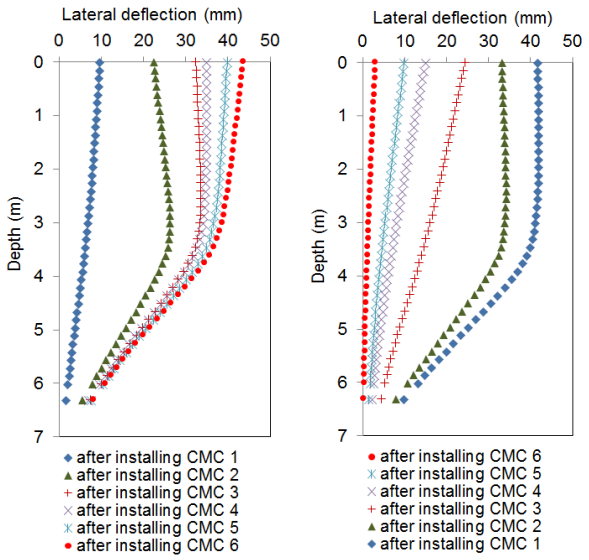
Figure 8. Contour of pore water pressures in the soil, and magnified deformed shape of the existing CMC, due to nearby installations (installation Sequence No. 1)

The response of the existing CMC to the soil movement induced by the CMC installation process was recorded in terms of lateral column deflection in y direction (Figure 9). The existing CMC moves away from the installation locations as may be expected. It is clearly shown that the installation of Row 2 CMCs, especially CMC 2, results in the most significant lateral deflection of the middle existing CMC in both installation sequences. However, the presence of the stiff clay layer tends to restrain the column movement near the base.

For the Sequence No. 1, the lateral deflection of the existing CMC increases quickly after the installation of Row 2. An insignificant effect is observed due to the installation of Row 3 (i.e. CMCs 4, 5 and 6). In fact, once embedded in the stiff clay, the newly installed Row 2 columns form a stiffer ground composite, which acts as a barrier between the new installations along Row 3 and the existing columns along Row 1. As a result, the bottom part of the existing CMCs experienced insignificant lateral movement (Figure 9a). The installation of the subsequent

CMCs along Row 3 merely caused the top portion of the existing CMCs to deflect away from the installation locations. This partly resulted in straightening up the existing CMC and hence slightly reduced its bending moment. It is also noted that if the setting of the CMC grout in Row 2 columns were very slow, the barrier effect induced by the formation of Row 2 columns, as observed, may not be significant.

For the Sequence No. 2, the deflection of the existing CMC increased steadily due to the installation of each of the first three CMCs (i.e. Row 3), before a significant amount of column deflection was observed due to the installation of subsequent columns along Row 2 (Figure 9b). Due to the CMC installation effects along Row 3, the state of the ground between Row 1 and Row 3 has already been altered, with some increase in the excess pore water pressure and the total soil stress. Installation of CMCs in this modified ground further increases the excess pore water pressure and lateral soil displacement.



(a) Sequence No. 1 (b) Sequence No. 2

Figure 9. Cumulative lateral deflection of the existing CMC (the middle column) due to the installation of each proposed CMCs.

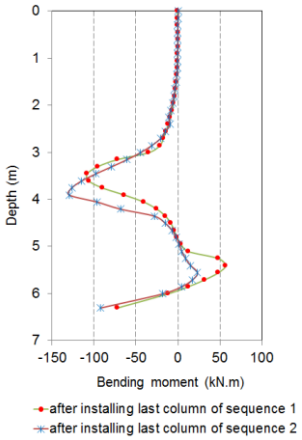


Figure 10. Comparison of calculated bending moment profiles of the existing CMC for the two adopted installation sequences

The calculated bending moment profiles of the existing CMC due to installation Sequence Nos. 1 and 2 are shown in Figure 10. The maximum bending moment in the existing CMC occurred at depths of approximately 3.5 m and 4 m for installation Sequence Nos. 1 and 2, respectively. The calculated maximum bending moment in the existing CMC due to installation Sequence Nos. 1 and 2 was approximately 108 kNm and 130 kNm, respectively. This finding indicated that the maximum bending moment developed in the existing CMC due to installation Sequence No. 2 was approximately 20% greater than that due to installation Sequence No. 1. Therefore, it may be concluded that to reduce the maximum bending moment of the existing CMCs, the Sequence No. 1 is more preferable than Sequence No. 2. Field trials and extensive laboratory tests would facilitate with refinement of the conclusions.

4 CONCLUSIONS

The installation process of controlled modulus columns (CMCs) in soft soils was simulated using *FLAC3D* to investigate the short-term installation effect on the previously installed CMCs. The numerical results show that:

- The lateral soil movement and soil heave induced by the installation of new nearby CMCs can cause uplift of the existing CMCs, approximately 1% of CMC diameter. The ensuing uplift may require short term surcharge to allow the columns to settle back to their required depth.
- The maximum bending moment developed in the existing CMCs induced by installing new columns towards from the existing columns (Sequence No. 2) may be 20% greater than that caused by the installation of columns away from the existing CMCs (Sequence No. 1).

The results highlight the need to select an appropriate installation sequence, especially if the CMCs are designed to resist tension loads and bending moments (e.g. with columns located near the embankment batters or slopes, or cases where CMCs would experience large lateral deformations due to site geometry or loading conditions).

5 ACKNOWLEDGEMENTS

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