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Analyzing surface settlement factors in single and twin tunnels: A review study

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ABSTRACT

Surface settlement (SS) resulting from tunnel excavation operations is a critical concern in tunnel engineering due to its potential impact on adjacent structures. This review synthesizes current knowledge on factors influencing SS induced by tunneling activities, focusing on tunnel geometry, soil properties, and operational parameters. Empirical formulas, numerical analyses, and machine learning (ML) techniques are examined for the effectiveness in predicting SS, highlighting the limitations and potential. Key findings underscore the significant influence of tunnel geometry, soil properties and tunnel operational parameters on SS outcomes. However, limitations exist in current studies, including the lack of consideration for diverse soil types and operational parameters like jack force thrust and penetration rate. The study underscores the importance of proper management of tunneling operations, including optimizing face pressure, to mitigate SS risks. Practical implications for practicing engineers include thorough site investigations, risk assessments and comprehensive monitoring programs. Leveraging historical data and ML algorithms can enhance SS prediction accuracy and aid in proactive risk management. Ultimately, mitigating SS risks is crucial for safeguarding existing infrastructure in congested urban areas.

Introduction

Tunnelling plays a pivotal role in constructing underground infrastructure, particularly for urban transportation systems. Various methods such as cut and fill, blasting, and tunnelling machines are employed to construct the tunnel, each with its distinct impacts on the surrounding environment. In modern times, tunnel boring machines (TBMs) have revolutionized tunnelling, offering mechanization and automation to expedite construction while enhancing worker safety [9].

The history of TBMs dates back to the early 19th century, with notable advancements such as Marc Isambard Brunel's circular shields in 1818, which laid the groundwork for modern TBMs (Wood et al., 1994). Today, earth pressure balance machines (EPBs) are widely used, particularly in soft ground conditions, owing to the ability to excavate and stabilize tunnel faces efficiently [85].

Despite technological advancements, tunnelling machine poses

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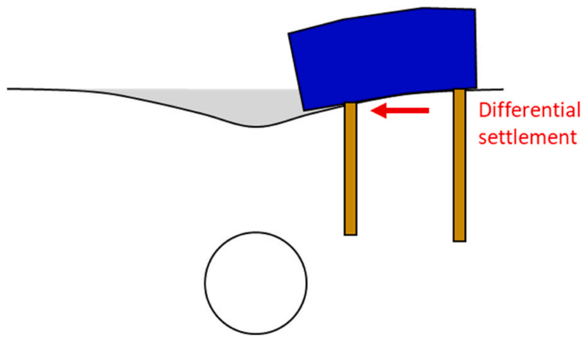


Fig. 1. Tunnelling induced SS impact on the existing structure.

challenges such as surface settlement (SS), especially in urban areas with soil as the primary geomaterial. SS resulting from tunnelling can jeopardize the integrity of existing structures, leading to structural distortion and cracks due to the differential settlement as illustrate in Fig. 1.

To address the significance of SS induced by tunnel excavation, it's crucial to identify key parameters influencing it. Peck [68] pioneered settlement estimation by introducing the concept of influence zones, where settlement diminishes with increasing distance from the tunnel axis. The Gaussian distribution, characterized by a bell-shaped curve, describes settlement behavior around a tunnel excavation, with maximum settlement occurring at the center (tunnel axis) and decreasing symmetrically with distance [68].

In general, factors influencing SS can be categorized into tunnel geometry, soil properties, and operational parameters during tunnelling [76,63,2].

Tunnel geometry factors such as diameter and overburden depth affect SS, with larger diameters and greater depths potentially causing more significant settlement [1,44]. Soil geotechnical properties such as effective soil strength, stiffness, and groundwater level also influence SS, with lower strength and stiffness, and higher groundwater levels correlating with higher settlement [70,3]. Tunnelling operational parameters such as face pressure are crucial for tunnel face stability, which directly impacts SS [18]

In area of geotechnical engineering, many researchers have proposed machine learning models to solve numerous problems [10,11,12,35,37,38,42,67,72,89]. Various methods including empirical formulas, numerical analyses, and machine learning have been employed to identify effective factors on SS induced by tunnelling. Researchers have developed empirical formulas based on field records, while numerical analyses and case studies have explored influential parameters further [15,23,57,58,68,75,29].

In this paper, we aim to investigate SS induced by tunnelling construction, focusing on single and twin tunnelling configurations by identifying factors influencing SS based on the studies carried out using empirical formulas, numerical analyses. and machine learning techniques.

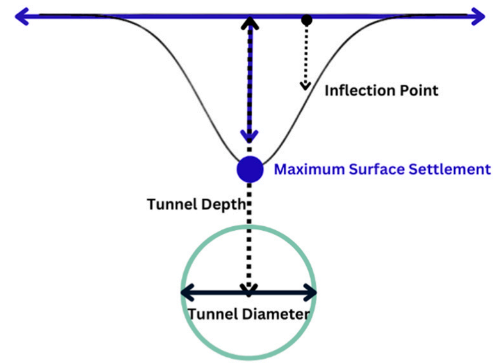


Fig. 3. Settlement perpendicular to the direction of tunnelling.

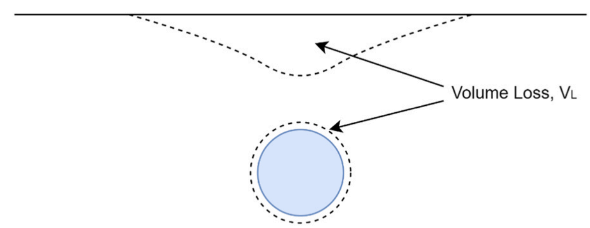


Fig. 4. Tunnelling-induced loss of volume.

Table 1
Summary of k for various types of soil.

Author (s)	Soil Type	k
O'Reilly and New [64]	Siff Fissured Clays, Glacial deposits	0.4–0.5
	Silty clay	0.5–0.6
		0.6–0.7
Mair et al. [58]	Granular soil	0.2 – 0.3
	Stiff clays	0.4 – 0.5
	Soft silty clays	0.7

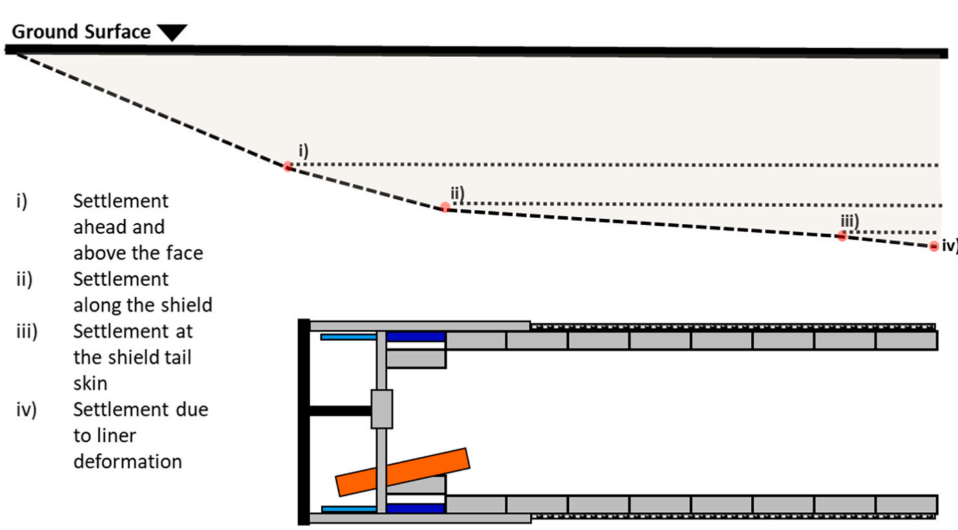


Fig. 2. Settlements along the tunnelling shield.

Table 2
Various V_L values for different ground conditions and tunnelling methods.

Author(s)	Ground condition	V_L (%)	Tunnelling construction method
Kavvadas et al. [46]	Weak rock	0.2	New Austrian Tunnelling Method (NATM)
Mair and Taylor [59]	Stiff clay	1.0 – 2.0	Open face method
	Siff clay	0.5 – 1.5	NATM
	Sand	0.5	Closed face Tunnelling Boring Machine
	Soft clay	1.0 – 2.0	Closed face Tunnelling Boring Machine
Hsiung [41]	Sand	0.38 – 0.53	Shield-machines bored tunnel

Based on previous research studies, this review aims to study the connections between tunnel geometry, soil geotechnical properties, and tunnelling operational parameters concerning SS. The goal is to equip engineers with an understanding of these interactions, enabling them to take proactive measures to mitigate SS risks arising from tunnelling construction using tunnel machine.

SS induced by Tunnelling

Excavating underground inevitably disrupts the soil and alters the initial stress distribution, leading to subsequent ground settlement around the excavation. According to Leca and New [51], with the mechanised tunneling, the SS induced by tunnelling can be divided into four (4) categories: settlement occurring in advance and above the tunnel face, settlement along the shield, settlement at the tail of the shield, and settlement resulting from the lining as illustrated in Fig. 2. Settlements occur in different areas during and after construction. Settlement at the face results from ground displacement ahead of the face and is observed above the shield towards the opening. Along the shield, settlement can occur due to overcutting, difficulties with shield guidance, tapering, and the roughness of the cutting wheel. Settlements at the shield tap happen due to the formation of a gap between the ground and the outer face of the liner segment. Settlements due to lining deformation arise when radial deformation occurs in prefabricated concrete segments placed inside the tail skin. Transverse settlement caused by tunnelling can be expressed as empirical formula proposed by Peck [68] for the estimation of the SS due to tunnelling where this formula (Eq. 1) is developed from the field observation and simplified version of Litwiniszyn [55]'s formula.

$$S = S_{max} e^{\frac{-x^2}{2i^2}} \quad (1)$$

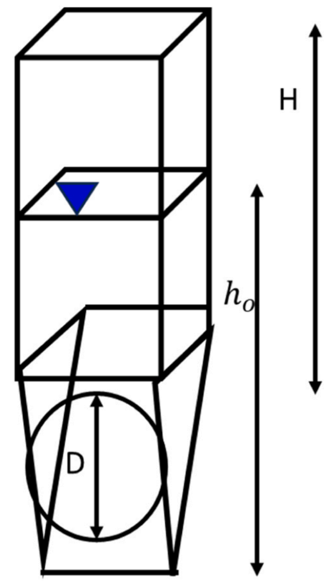


Fig. 6. Sliding mechanism.

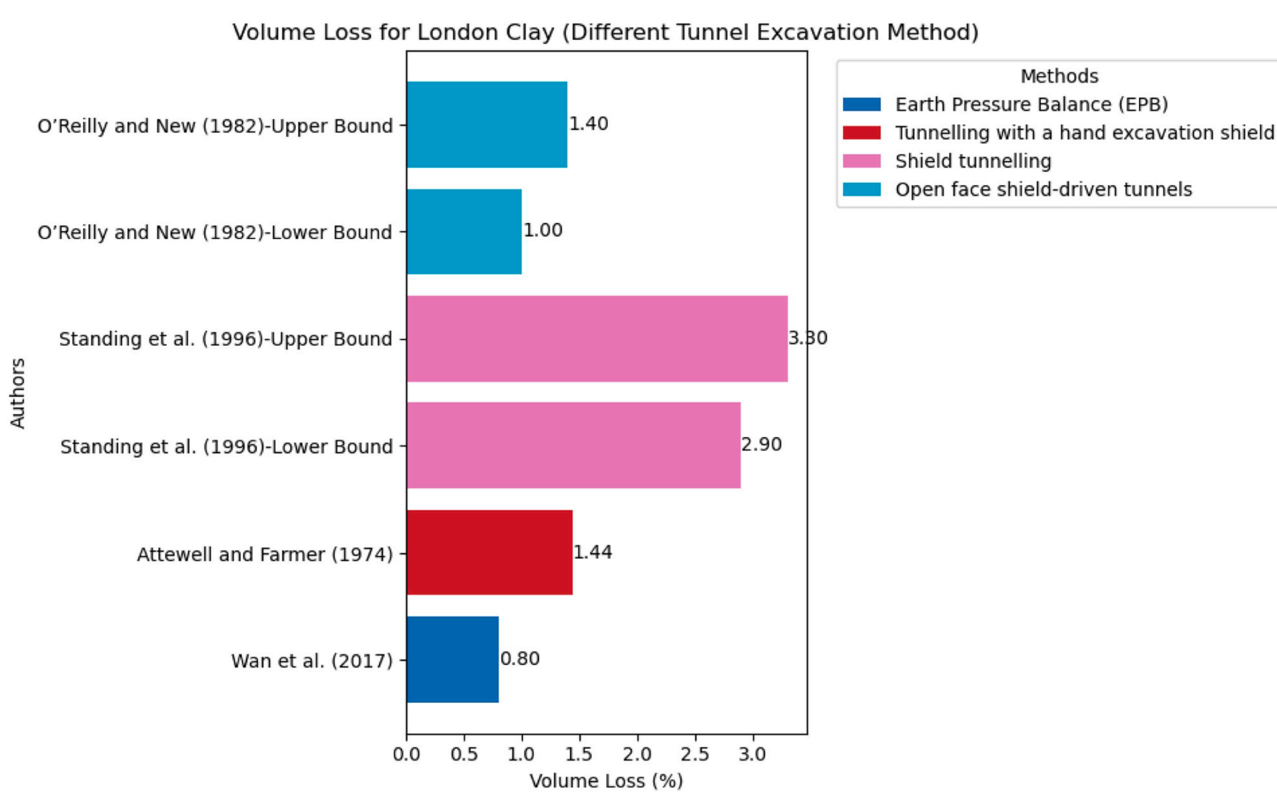


Fig. 5. Volume loss for London Clay with different tunnel excavation.

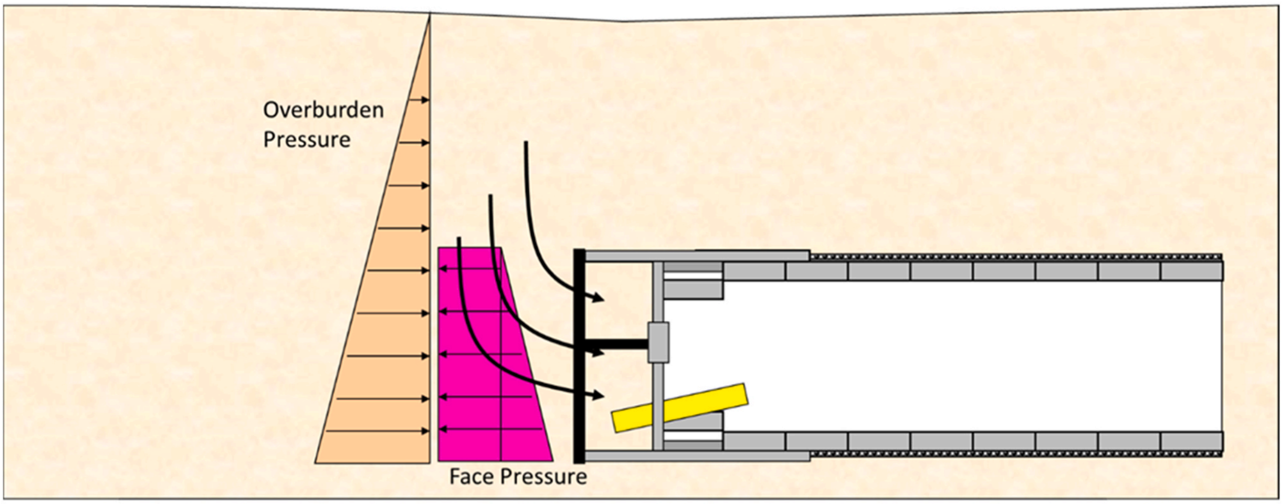


Fig. 7. Face pressure uses to withstand the overburden pressure from the ground.

Table 3
List of the formulas for calculation of SS due to single tunnel.

Author(s)	Equation
Peck [68]	$S = S_{max} e^{\frac{-x^2}{2i^2}}$, where: $S_{max} = \frac{V_s}{\sqrt{(2\pi)} x\ i}$
Herzog [39]	$S_{max} = 0.785(\gamma.z+\sigma).(\frac{D^2}{i.E})$
Loganathan and Poulos [56]	$S = 4(1-\nu)\varepsilon R^2 \quad \frac{z}{z^2+x^2} \quad e^{[-\frac{1.38x^2}{(C+R)^2}]}$
Verruijt and Booker [78]	$S = 4(1-\nu)\varepsilon R^2 - \frac{Z_0}{Z_0^2+x^2} - 2\delta R^2 \frac{z(x^2-z^2)}{(z^2+x^2)^2}$
Chakeri and Ünver [20]	$S_{max} = 3198.744\left(\frac{D}{Z_o}\right)x\left(\frac{\gamma z+\sigma_s-(c+0.3\sigma_T)}{E}\right)(1-\sin\Phi))^{0.8361}$
Moeinossadat et al. [61]	$S_{max} = \frac{111Z}{D} + 0.031c + 0.643\Phi - 0469E + 0.828V - 2.028F\prime + 84.699P\prime + 0.085\ n$
Moghaddasi and Noorian-Bidgoli [62]	$S_{max} = 1.0236 - 0.1814HR - 0.2338c - 0.8664E$
Anato et al. [8]	$S_{max} = -1.1x10^{-5}EI_{lining} - 3.63x10^{-4}E_{grout} + 3.11x10^{-4} - 3.14x10^{-3}V - 35.136$

z is Depth of tunnel; σ is Overburden pressure; γ is Unit weight; E is Young's modulus ν is Poisson ratio; ε is Equivalent undrained ground loss; R is Tunnel radius; σ_T is Face support pressure; c is Soil cohesion; Φ is Soil friction angle; V is Penetration rate; F' is Thrust force; P' is Grouting pressure; n is Percentage of grout fill; HR is Horizontal to vertical stress ratio; EI_{lining} is Flexural stiffness of tunnel lining; E_{grout} is Elastic modulus of grout

where,

S—SS in the transverse section at distance

x— Distance from the centerline of the tunnel

i— Point of inflection (settlement trough)

and S_{max} can be expressed in Eq. (2):

$$S_{max} = \frac{V_s}{\sqrt{2\quad x\pi \quad x \quad i}} \tag{2}$$

where,

S_{max}— Maximum surface settlement

V_s— Volume loss of the soil (m^3/m).

According to these formulas, the primary contributor to ground settlement is the ingress of soil into the tunnel, a phenomenon linked to the construction method(s), soil type, groundwater conditions, geometry, and tunnel depth. Eqs. 1 and 2 show that the settlement pattern resulting from ground loss can be estimated using a Gaussian probability curve and Fig. 3 shows the transverse settlement with the shape of gaussian probability curve. For low-permeability soils like stiff clay, the initial reaction of the ground due to tunnel construction is termed undrained [74]. As a result, SS volume trough can be estimated as equivalent to the volume of soil excavated that exceeds the theoretical volume of the tunnel. The Gaussian curve representing the tunnel SS profile in Fig. 4 depicts this excess volume as a percentage of the theoretical tunnel volume and Eq. 3 show the formula.

$$V_L = \frac{V_s}{0.25\pi D^2} \tag{3}$$

where,

V_L— Volume loss (%)

D— Tunnel diameter

Trough width, i is the parameter controlled by the settlement trough width factor, k, which can be defined as in Eq. 4 [64]:

$$i \quad = kz \tag{4}$$

Due to undrained condition, maximum SS of the tunnelling can be defined in Eq. 5:

$$S_{max} = \frac{0.313 \quad V_L \quad D^2}{i} \tag{5}$$

The settlement trough's size and shape are determined by the parameters V_L and i. V_L is influenced by the excavation method and the ground conditions, while i is primarily influenced by the soil type [80]. Table 1 summarises some of the values for i in different types of ground, and Table 2 summarises values of V_L based on percentage for different

Table 4
Brief findings presentation by numerical analysis in the area of SS induced by tunnel construction in single tunnels.

Author (s)	Findings from numerical analysis
Chakeri and Ünver [20]	The maximum SS brought on by tunnelling depends on a number of factors. These include the tunnel diameter, the stiffness and poisson ratio, the tunnel depth, the angle of internal friction and cohesion of the soil, the support pressure at the tunnel face, the surface surcharge, and the unit weight of the soil. These findings emphasis the intricate nature of tunnel-induced SS and underscore the necessity of considering multiple factors during tunnel design and construction. The study concludes that using numerical techniques can yield a more precise relationship for estimating the maximum SS.
Meng et al. [60]	If the support pressure applied during tunnel construction is excessive, it can cause a "loading effect" and result in significant soil disturbance. The settlement reduces as the support pressure increases from 0.8 to 2.4 times support pressure. However, there is a sudden increase in settlement when the support pressure is between 2.6 and 2.8 of support pressure.
[6])	The presence of cohesion significantly reduces the pressure required to prevent face collapse during tunneling, regardless of the tunnel geometry. However, the extent of this effect is highly dependent on the soil friction angle, with the influence of cohesion diminishing as the friction angle increases.
[87]	The study on ground movement caused by tunnel construction reveals that the geometry of tunnel characteristics, such as its depth and contraction factor, have a greater influence on such movements than soil stiffness and shear strength parameters, though the latter factors do contribute to a certain extent. Furthermore, the research highlights the vital role of the soil's friction angle, primarily determined by soil plasticity and governed by the parameter Φ, in the surface volume loss. These findings underscore the need to consider both material and geometric factors when analyzing and predicting ground movements resulting from tunneling activities.
Aswathy et al. [14]	The maximum SS in young alluvial soils was predicted using a numerical approach, taking into account variations in tunnel diameter and face pressure. The findings indicate that these factors have a substantial influence on settlement values.
Zhong et al. [88]	Soil elastic modulus is a crucial determinant in the SS resulting from tunnelling activities. The study concludes that the settlement magnitude decreases with an increase in the elastic modulus of the soil. These results underscore the significance of precise characteriszation of soil properties, including the elastic modulus, to accurately predict and mitigate SS during tunnel construction.

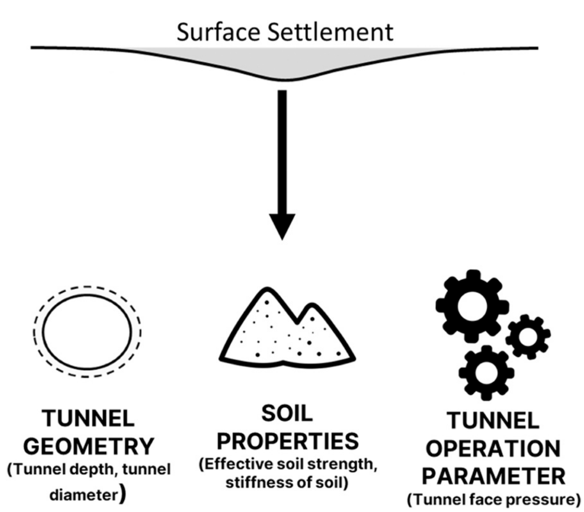


Fig. 8. Three (3) main parameters affect the tunnelling.

tunnelling methods and ground conditions. Based on the Table 2, it can be clearly seen that the range of. V_L is varies from 0.2% to 1.0% which implies different ground conditions with different tunnelling excavations show different V_L. For better comparison, Fig. 5 shows the comparison of the same ground type for London Clay but different excavation methods have clearly shown the range of V_L from 0.8% to 3.3%. This imply the tunnel excavation method is one of the main parameters that affect the V_L.

In this modern area, tunnelling machine is widely use to construct the tunnel. One of the important parameters during the excavation using tunnelling machine is face pressure. During tunneling, the soil in front of the excavation chamber tends to shift towards the bored tunnel created by the tunnelling machine and the amount of soil moving towards the tunnel face is influenced by the support pressures applied, which can be regulated by adjusting the face pressures [79]. In shallow tunneling, it is necessary to maintain a support pressure at the tunnel face and sufficient to prevent the collapse of the excavation chamber, while also being cautious not to exceed a certain limit that could cause blowouts. Hence, to maintain adequate stability of the excavation chamber and account for the three-dimensional effects, it is imperative to apply a support pressure that is no less than the combined horizontal effective soil pressure and water pressure. Researchers [13,16,7] have commonly used the wedge model to ascertain the minimum support pressure required. It involves analyzing the stability of the wedge-shaped soil mass ahead of the excavation face and considering factors such as the strength of the soil, groundwater conditions, and the applied support pressure. Anagnostou and Kovári [7] proposed this equation to calculate supporting face pressure which is based on based on 3-dimensional sliding mechanism proposed by Horn [40] as shown in Fig. 6.

$$FP = F_o\gamma D - F_1 c + F_2\gamma'\Delta h - F_3 c\frac{\Delta h}{D} \tag{6}$$

where F_o to F_3 are dimensionless coefficients that depend on the Φ, D, H is overburden, h_F is the piezometric head in the chamber, h_o is the elevation of the water table and Δh is the head difference h_o - h_f

If the support pressure at the tunnel face is excessive, it can cause the soil column above to be pushed upwards. In cases where there is no consideration of the friction between the failing soil body and the surrounding ground, hence, Vu et al. [79] suggested a simple approach for estimating the maximum support pressure as the total vertical stress exerted by the soil. Hence, to maintain adequate stability of the excavation chamber and account for the three-dimensional effects, it is imperative to apply a support pressure that is no less than the combined horizontal effective soil pressure and water pressure. Face pressure functions as a counterforce to external pressures exerted on the tunnel face, such as the weight of overlying soil and groundwater pressure. This support is crucial for stabilizing the tunnel face and preventing collapse or deformation. Properly managed face pressure also regulates ground movements around the tunnel face by maintaining a balance between internal tunnel pressure and external soil pressure, thereby reducing ground deformation and settlement. Fig. 7 visually demonstrates how face pressure withstands the overburden pressure from the ground.

Important Factors for SS Induced by Single Tunnel

Three categories of the main influential factors were discussed in introduction section. Based on these factors, this section will give an overview regarding each category. Some researchers have developed empirical formulas to determine the SS due to single tunnel which is presented in Table 3.

In these empirical equations, most formulas are considering tunnel geometry in the formula and limited empirical formula considers the tunnelling machine operational parameter. As for the numerical analysis approaches, several researchers also carried out sensitivity analyses to determine the important factors of SS due to single tunnels and a summary of the findings is presented in Table 4.

Based on the Table 3 and Table 4 findings from every author, one can conclude that three (3) core parameters affect the single tunnel which

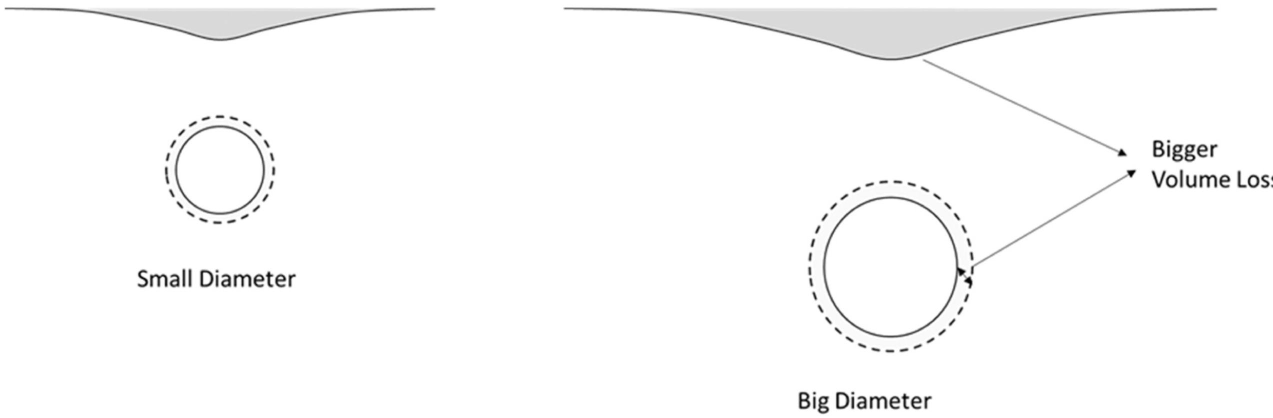


Fig. 9. Illustration of Small and Big Tunnel Diameter impact on the SS.

are soil properties, tunnel geometry and tunnelling operation parameter as shown in Fig. 8.

Several researchers [20,6,61,87] using numerical and empirical formula as shown in Table 3 and Table 4 highlighted the importance of the effective cohesion and friction angle of the soil affecting the SS induced by tunnel. Effective cohesion is the measure of the shear strength of the soil, which is the ability of the soil to resist deformation or failure due to stresses applied to it [24]. A higher effective cohesion indicates a stronger soil and, therefore, a lower likelihood of SS. The friction angle, on the other hand, is the angle at which the soil particles begin to slide past each other. A higher friction angle means that the soil is more resistant to shear stress [69] and as shown by Yin et al. [83] area with larger friction angle has small ground deformation. According to Khezri et al. [47], it is of utmost importance to thoroughly understand the stability condition at the tunnel face during open face excavation to prevent collapse and reduce the risk of SS induced by tunnelling. The authors conducted simulations, gradually reducing the soil strength parameters c and Φ until a collapse occurred and the safety factor equaled the ratio of the original soil strength. The study concluded that both c and Φ significantly influence the stability of the tunnel face, directly impacting the level of SS.

During the tunnelling works, the ground is excavated and replaced by the support system of the tunnel. This process can lead to changes in the effective cohesion and friction angle of the soil, which in turn affect the likelihood of SS. These reviews have shown the impact of soil strength parameters, such as c and Φ, on tunnel face stability, directly affecting the occurrence of SS.

Other than effective strength parameter, tunnel geometry also emphasize by the authors [39,87], as one of the important parameters. According to Zhang et al. [86], the Φ, c, and $\frac{C}{D}$ ratios where C is overburden depth are related to each other and affect the support pressure ratios for face stabilization during tunnel excavation. This is indirectly related to SS because if the support pressure ratio remains the same but the effective friction angle and cohesion change due to the changes of the soil profile, it can affect the stability of the tunnel and lead to SS.

A tunnel with a larger diameter displaces a greater volume of soil, consequently extending its influence zone. Within this widened area, soil undergoes stress redistribution as it seeks a new balance. This expanded region of stressed soil results in increased surface settlement, as depicted in Fig. 9.

Additionally, Moeinossadat et al. [61] found that c, Φ, and E are three parameters that have a similar effect on SS induced by tunnel excavation. In the study conducted by Sirimontree et al. [73], six (6) key parameters were identified as influential factors affecting the stability of elliptical tunnels. These parameters are tunnel cover, tunnel depth, tunnel width, unit weight of the soil, effective cohesion, (c') and Φ. The research findings indicate that the relationship between the Φ and the stability factor $\frac{\sigma_s}{c'}$, is highly non-linear. Specifically, as the soil friction increases, the strength of the tunnels also increases, leading to a reduced likelihood of tunnel instability, or SS.

Clay is known for its high cohesion, attributed to fine particle size, allowing to resist deformation under stress. Consequently, in clayey soil, initial tunneling-induced surface settlement tends to be relatively low. However, despite its cohesive properties, clay has a low friction angle, indicating limited resistance to shear forces. While cohesion aids in settlement mitigation, the low friction angle implies that once cohesive bonds are surpassed, clay may undergo significant deformation and settlement. Therefore, prolonged tunneling through clay can lead to gradual increases in SS as the clay mass compresses and consolidates over time.

In contrast, sand lacks cohesion and primarily relies on interparticle friction to resist deformation. Consequently, tunneling through sandy soil results in immediate SS due to the minimal cohesive strength supporting the overlying soil mass. Although sand possesses a higher friction angle compared to clay, providing some resistance to deformation, settlement in sandy soil is predominantly governed by frictional resistance between particles.

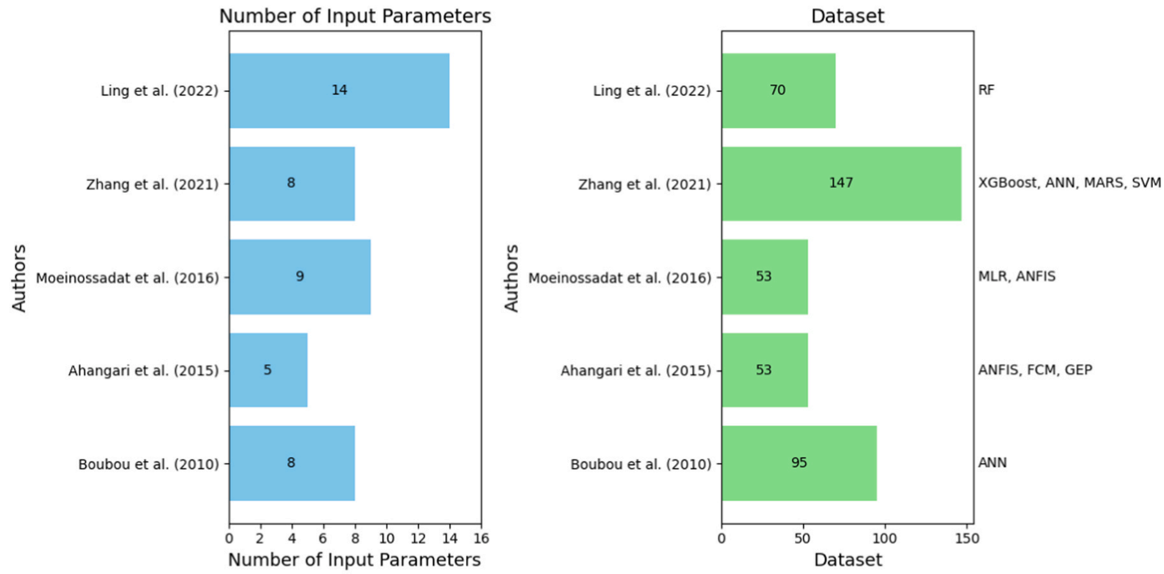
Other than numerical approaches, several researchers propose ML methods to estimate the SS due to single tunnels and are listed in Fig. 10. It can be seen that the most of the dataset used for the ML application is less than 100. Besides, many variables are considered as the inputs for the ML algorithm. Although additional input parameters can provide the algorithm with more information, allowing the algorithm to be better capture complex relationships in the data, however it is not practical to have many parameters for the actual tunnelling works. Therefore, identification the suitable and important parameters for the ML application is crucial.

As such, several researchers using various methods to determine the importance of the factors used (see Table 5).

Different methods yield varying importance parameters from this table. The authors utilize statistical approaches and field observation, resulting in parameter importance being contingent upon the type of data gathered. ML algorithm can be used to identify the importance of the parameters and this method has been adopted by several researchers [54,77]. Unlike statistical approaches, ML techniques can consider multiple variables in determining importance, as opposed to solely relying on one variable in the computation.

Important Factors for SS Induced by Twin Tunnels

The primary distinction between single and twin tunnels lies with the distance between the tunnels and two different tunnel operational parameters. Several researchers have developed empirical formulas to estimate the twin tunnel induced SS, as tabulated in Table 6. Based on the summary of the empirical formula presented in Table 6, most empirical formulas considered the tunnel centre-to-centre distance, d, as



	TYPE OF INPUTS
Boubou et al. (2010)	Duration for excavating and installing one tunnel lining ring, Hydraulic pressure applied to the cutting wheel, Horizontal and vertical guidance capabilities of the TBM to adhere to the theoretical path, TBM advance rate, Confining pressure at the tunnel face, Volume of tail void grout filling, Thrust force, and Soil geological profile
Ahangari et al. (2015)	Tunnel depth and diameter, Elastic modulus, Friction angle and Cohesion
Moeinossadat et al. (2016	Tunnel depth, Tunnel diameter, cohesion, friction angle, elastic modulus, Penetration rate, Thrust force, Grouting pressure, Volume of grouting
Zhang et al. (2021)	Tunnel cover, Advance rate, Earth pressure, Grout pressure, Mean moisture content, mean soil elastic modulus, mean Standard Penetration Test (SPT) above crown level, Mean tunnel SPT
Ling et al. (2022)	Thrust of the cutterhead, Grout quantity, Advance rate, Torque of the cutterhead, Pressure in the chamber, Elevation deviation at the cutting ring of the shield, Elevation deviation at the shield tail, Grout pressure, Tunnel Cover, Geological conditions (5 layers)

where, Artificial Neural Network (ANN), Adaptive Neural Fuzzy Inference System (ANFIS), Fuzzy C Means Clustering (FCM),Gene Expression Programming (GEP),Multi Linear Regression (MLR), Extreme Gradient Boost (XGBoost),Adaptive Regression Splin (MARS),Support Vector Machine (SVM) and Random Forest

Fig. 10. ML techniques to predict SS induced by single tunnel.

a component in determining the SS induced by twin tunnelling.

Moreover, the empirical formulas incorporate tunnel geometry variables such as tunnel depth and diameter for the same purpose. Thus, it can be inferred that *d*, *C*, and *D* are crucial factors in predicting twin tunnelling-induced SS as shown in Fig. 11.

The distance between tunnel centers plays a crucial role in determining how adjacent tunnels interact during construction. When the distance between tunnels decreases, the level of interaction between tunnels increases, leading to a rise in maximum SS risks. The degree of interaction relies on various factors, including the excavation method, ground conditions, and the stiffness of the tunnel lining. Variations in the settlement pattern arise from the rearrangement of soil displacement, predominantly driven by changes in soil stiffness. Researchers consistently find similar results regarding the distance between tunnels, which suggest that there is no interaction between twin tunnels at a certain distance, as summarized in Table 7.

From this, it can be inferred that for distances between tunnels of 3D to 4D and above, there is no significant interaction between the first and second bored tunnel as the finding based on the Table 7 shows that minimum of 3D spacing has shown no interaction. In the investigation conducted by Chen et al. [21], it was observed $\frac{C}{D}$, exhibits a significant relationship with support face pressure, thereby indirectly influencing

Table 5
Variables influencing SS due to tunnelling boring process.

Reference	Technique	Most Influential Parameters
Kim et al. [48]	Relative Strength of Effects (RSE)	1) Tunnel depth 2) Ground water inflow rate 3) Type of rock mass 4) Type of tunnel 5) Tunnel excavation velocity
Kobayashi et al. [49]	Field Observation	1) Shield Passage 2) Tail void closure
Santos and Celestino [71]	Sensitivity Analysis	1) Overburden tunnel 2) Depth of the tunnel beneath the water table 3) Rate of advancement pre and post.
Ocak and Seker [66]	Field Observation	1) Face Pressure 2) Penetration rate 3) Volume of material excavated per tunnelling ring. 4) First and second bored tunnel of percentage tail void grout filling
Hasanipanah et al. [36]	Cosine Amplitude Method	1) Ratio of horizontal to vertical stress

Table 6
Empirical formula to determine SS due to twin tunnels.

Author(s)	Equation
O'Reilly and New [64]	$S = S_{\max}\left[e^{-\frac{x_1^2}{2i_x^2}} + e^{-\frac{(x_1-d)^2}{2i_x^2}}\right]$
Herzog [39]	$S_{\max} = M\, x4.71\,(\gamma.z+\sigma_s).\,(\frac{D^2}{(3i+P).E})$
Yang and Wang [82]	$S = \frac{2\,\pi A\blacktriangle A\tan\beta}{C}\quad e[^{-\frac{\pi x\tan^2\beta}{C^2}}(\boldsymbol{x}-\frac{d}{2})^2]$
Gui and Chen [34]	Superposition method; $S_{\max} = S_1 + S_2 \quad S_{1,2} = \left[\frac{\pi v D^2}{10i}\right]e^{\frac{-x^2}{2i^2}}$ Equivalent circle method $S_{\max} = S_{12} \quad S_{12} = \left[\frac{\pi v D_{12}^2}{10i}\right]e^{\frac{-x^2}{2i^2}}$
Ocak [65]	$S = S_{\max}x[e^{\left(-\frac{x^2}{2i^2}\right)} + \left[1+\frac{D}{d}\right]\quad e^{-\frac{(x-d)^2}{2\,i^2}}]$

d is Tunnel centre-to-centre distance; σ_s is Surface surcharge; *P is* Pillar width; *M is* Modification factor; ▲*A is* Uniform convergence value of the tunnel cross section; *β is* Influence angle of the settlement; *A* is Initial radius; S_1 is SS of the first bored tunnel; S_2 is SS of the second bored tunnel; S_{12} *is* SS due to twin tunnel; D_{12} *is* Equivalent diameter of first and second bored tunnel

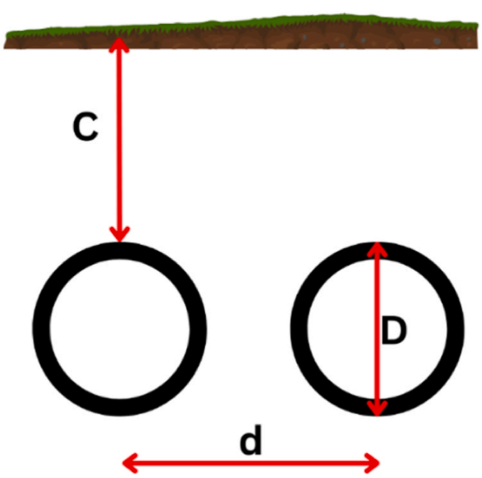


Fig. 11. Geometrical parameters in twin tunnel.

Table 7
Summary of the distance between twin tunnel with no interaction.

Author (s)	Type of ground	Distance between the tunnel centre to centre that shows no interaction
Divall and Goodey [27]	Clay	3D
Chakeri et al. [19]	Stiff clay with medium dense sand, dense sand and very dense sand	Beyond a spacing of 3D, the settlement shape undergoes a transformation and resembles the curve formed by two separate tunnels. Spacing larger than 4D, the interaction factor is almost zero.
Koungelis and Augarde, [50]	London Clay	^{3}D–^{4}D pillar width show no interaction
Islam and Iskander [43]	-	Pillar distance of 3D
Kannangara et al. [45]	Silty Sand	At a spacing of 4D, the subsequent settlement resulting from the second excavation has negligible impact on the initial settlement from the first excavation.

SS during tunnelling activities. Specifically, their research revealed that when the relative depth $\frac{C}{D}$ is less than or equal to 1, there is a notable increase in normalized support pressure as $\frac{C}{D}$ increases. Conversely, when $\frac{C}{D}$ exceeds 1, the rate of increase in normalized support pressure with respect to $\frac{C}{D}$ is observed to slow down. Moreover, it was noted that for a given $\frac{C}{D}$ ratio, the normalized support pressure decreases as the friction angle (Φ) increases. As such these geometry parameter play important role for twin tunnelling induced SS. In addition to empirical approaches, numerous researchers have conducted sensitivity analyses using numerical models to investigate the correlation between twin tunnelling and SS. These insights are documented in Table 8.

According to Table 8, various studies on twin tunnel construction's impact on SS reveal important insights. Predictions often overestimate SS width due to uniform soil stiffness assumptions, highlighting the need for considering diverse soil properties. Tunnel spacing plays a crucial role, with closer tunnels showing significant interaction, while wider spacing reduces this effect, emphasizing the importance of careful spacing selection. Strategic excavation planning is vital, as symmetrical excavation of the second tunnel can significantly increase settlement above the first tunnel. Additionally, excavation of the first tunnel can alter soil stiffness around the second tunnel, affecting settlement significantly. Deeper tunnels generally decrease total settlement, whereas larger diameters increase it, with water levels also contributing to higher settlement. Empirical formulas show a roughly 10% difference compared to finite element analysis results, indicating the importance of accurate modeling techniques.

Many researchers [26,31,4,53] have found that the face pressure contributes to the SS due to tunnelling from the numerical analysis. Although grouting pressure is part of the tunnelling process, but grout pressure shows no firm correlation between SS and the grouting pressure [30,31]. Several researchers have proposed different ratios of face pressure to overburden ratio, which vary depending on ground conditions. Farrokh et al. [33] suggested an optimal range of 0.3–0.5 for the face pressure to overburden ratio, while Wongsaroj et al. [81] specified a minimum average ratio of 0.2 for clay. Wongsaroj et al. [81] also noted that grouting pressure remained relatively consistent throughout the tunneling process, resulting in relatively small volume losses. Consequently, field data may not provide clear correlations. Injection ports equally spaced within the tunnelling shield are utilized to fill the gap with grout between the segmental lining and the soil in the tail region. Nevertheless, according to Cao et al. [17], SS occurs when the grout pressure falls below the initial earth pressure. Thus, it can be concluded that the first and second bored tunnel with the same tunnel geometry and geotechnical properties could induced different SS due to difference

Table 8
Brief finding from the finite element analysis of twin tunnelling induced SS.

Author (s)	Findings from numerical analysis
Chen et al. [22]	The numerical analysis indicated that the anticipated width of SS exceeded both the observed field measurements and estimations derived from empirical equations. This variance can be ascribed to the utilization of a uniform stiffness of the soil, resulting in a broader settlement trough, contrary to the non-uniform modulus distribution observed in the field. These findings underscore the importance of considering the heterogeneous nature of soil properties when predicting and addressing soil settlement resulting from tunneling activities.
Chakeri et al. [19]	A robust correlation exists between the numerical models and the SS monitoring data gathered from field measurements. The study found that when the distance between twin tunnels is less than three times the diameter of the tunnel (3*D*), there is a significant interaction observed on the SS curve. However, when the distance is exceeded four times the tunnel diameter (4*D*), there is little to no interaction factor. These findings indicate that choosing an appropriate tunnel spacing is essential to reducing SS during the construction of twin tunnels
Do et al. [28]	This study highlights the significant impact of tunnel spacing on SS during twin tunnel construction. The research shows that reducing the distance between tunnel centers resulting in a reduction of the trough parameter and the highest settlement above the new tunnel on the right. On the other hand, increasing the distance between the tunnels, leads to higher maximum settlement due to the diminished impact of the initial tunnel excavation on the second tunnel. Nevertheless, it is crucial to highlight that the disparity in the maximum additional settlement along the centerline of the second tunnel did not show significance across all tested *P* values. These findings underscore the importance of carefully selecting tunnel spacing to minimize SS during twin tunnel construction.
Fargnoli et al. [31]	The study reveals that when the second tunnel is excavated symmetrically, it results in an increase in settlement above the axis of the first tunnel. This increase is usually the largest compared to other observed increases. These findings emphasize the importance of carefully planning the timing and sequence of tunnel excavations to minimize the SS caused by twin tunnel construction.
Zhang et al. [84]	The numerical analysis conducted in this study revealed that the excavation of the first tunnel can lead to changes in the soil stiffness around the second tunnel. This effect is closely associated with the relative changes in stress paths induced by the two tunnel excavation events and can have a significant impact on SS. These findings underscore the importance of taking into account the intricate interplay between tunnel excavation activities and the encompassing soil, particularly in the context of twin tunnel construction.
Anato et al. [8]	Ground SS is inversely proportional to the shield-driven speed; as the speed decreases, the settlement increases. An increase in the elastic modulus of grout leads to a decrease in ground settlement.
Deng et al. [25]	A larger separation between tunnel excavation faces corresponds to reduced mutual influence, yielding smaller settlement values and a more pronounced impact on the surrounding soil. As tunnel depth increases, the ground settlement curve transitions from a W-shape to a V-shape. The ground lateral settlement curve shifts from a V-shaped to a W-shaped configuration with increasing tunnel spacing. Higher water levels contribute to higher ground settlement values. The primary factor affecting surface settlement is the distance between tunnel excavation faces, followed by tunnel spacing and depth, with water level exerting the least influence.
Ahmed et al. [5]	The study reveals that the total settlement decreases as the tunnel depth increases, with a decrement of approximately 11% for every 5 m increment in depth. Conversely, the relationship is opposite when considering changes in tunnel diameter. The settlement value increases with an increment in diameter, showing an approximate 20% increase for every 1 m increment in diameter. Additionally, the maximum total settlement decreases with an increase in tunnel depth and increases with an increase in tunnel diameter. Comparing the results obtained from the 3D finite element analysis (using Plaxis 3D) with empirical formulas, the percentage of difference is approximately 10%.

tunnelling operation parameter. Hence, it is crucial to take into the consideration for monitoring SS at the tunnelling operation parameter during the excavation. Fig. 12 illustrates the summary of the parameters affecting the SS caused by the excavation of twin tunnels

Discussion

SS resulting from tunnel excavation operations is one of the focal point of discussion within tunnel engineering field, primarily due to the impact to the adjacent structures.

Based on the previous findings, it can be deduced that tunnelling induced SS are governed by three main parameters namely tunnel geometry of tunnel, soil properties and operational parameters during tunnelling.

Most empirical formula are considering tunnel geometry in the formula for the computation of the SS due to single and twin tunnels.

Nevertheless, authors often present various empirical formulas, reflecting the fact that these formulations are developed from datasets specific to particular projects. Through statistical analysis, these formulas discern patterns and correlations between input parameters and the resulting SS. Besides, there are limited variables considered in the empirical formulas. Other than that, several author (s) can be seen did not consider the tunnelling operation parameter in the formula. Hence, this approach is limited to a certain scenario of the project condition and can be used as preliminary design.

In comparison to the ML method, more variables can be considered as input into the analysis for the prediction of the SS due to tunnelling. However, it is good to consider only relevant and important inputs because in tunnel construction industry, not all the parameters can be easily assessed.

To the best of the authors' knowledge, the predominant trend in current studies involves the utilization of ML techniques for predicting soil settlement (SS) in single-tunnel scenarios. Given the multiple of factors influencing SS outcomes resultant from tunneling construction, ML methodologies can be regarded as integral tools for identification of the SS due to the excavation of twin tunnels.

Fig. 13 shows the brief comparison of the empirical formula, numerical analysis, and ML methods limitation to determine the SS.

Nevertheless, from the studies, tunnel geometry of $\frac{C}{D}$ and P, both show strong influence to the SS for twin tunnel. The relationship of $\frac{C}{D}$ is affected with the face support pressure of the soil. When the $\frac{C}{D}$ is less than 1, normalized support pressure increases, however, when the $\frac{C}{D}$ is more than 1, the normalized pressure increase at slow rate with the increase of $\frac{C}{D}$. O. In addition, the effective strength parameter and stiffness of the soil play pivotal roles, as these factors influence SS during tunneling operations. Higher values of the effective strength parameter and soil stiffness correspond to reduced susceptibility to SS. If encountering lower soil properties in terms of effective strength parameters during tunneling, engineers have the option to enhance ground properties through compaction grouting. This method involves injecting a flowable grout into the soil under pressure. As the grout permeates the soil and fills voids, it consolidates the soil, potentially increasing its cohesion. Additionally, the injected grout can adhere to soil particles, bridging gaps and reinforcing the soil structure. Compaction grouting also has the potential to enhance the soil's friction angle by compacting the soil mass and increasing particle interlock. This process strengthens the soil's resistance to shear forces, reducing the risk of deformation and settlement. Fig. 14 illustrates the simplified process of compaction grouting.

Diverse tunneling operation parameters, such as face pressure during boring, may lead to varying magnitudes of soil SS for each twin tunnel. Achieving the ideal design value for face pressure control is crucial for managing surface settlement (SS). Therefore, it's essential to utilize real-time monitoring and control systems that continuously measure and

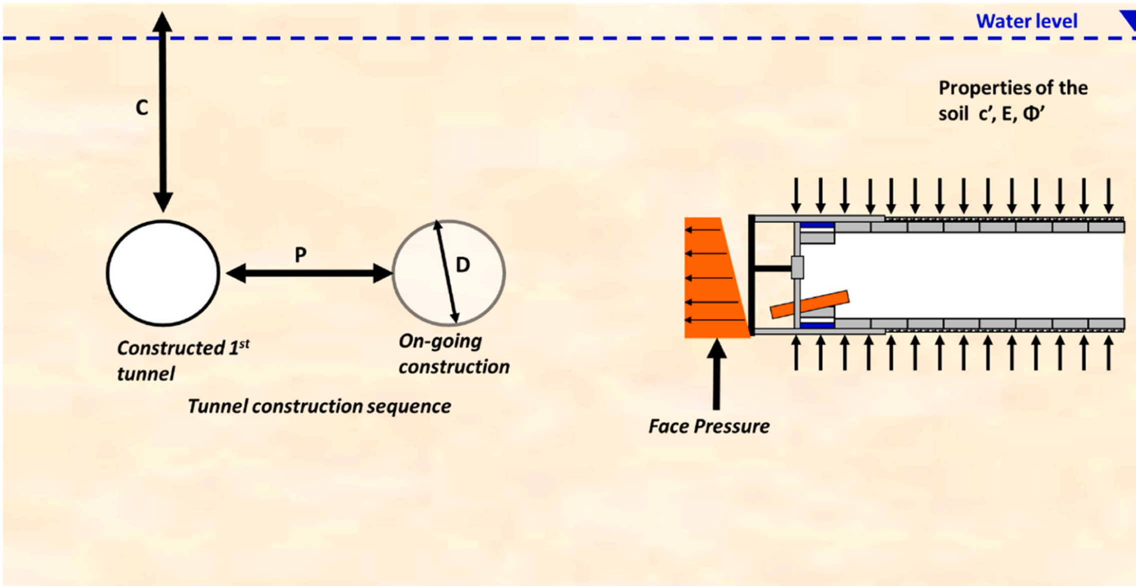


Fig. 12. Summary of the parameters affecting the SS due to twin tunnels.

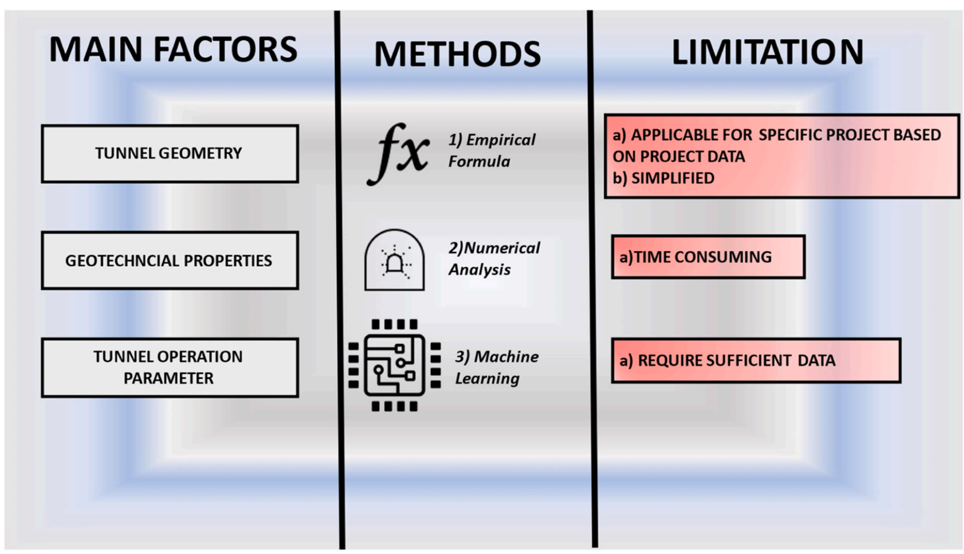


Fig. 13. Factors and method to determine the SS due to tunnelling.

regulate face pressure during excavation. This involves installing pressure sensors at the tunnel face,capable of displaying the allowable minimum and maximum face pressure values, facilitating precise adjustments to excavation rates and face pressure.

Hence, to limit SS, the tunnel geometry can be adjusted accordingly such as controlling the depth and the distance between the tunnels. Whereas the ground with low effective strength parameters and soil stiffness can be considered ground treatment such as compaction grouting and deep soil mixing to improve the geotechnical properties of the ground to reduce the settlement. Tunnel operation parameter with the proper control of operating face pressure and optimum value could control the SS during the tunnel excavation. In summary, it is evident that twin tunnel has more factor than the single tunnel such as pillar width that affect the SS due to tunnelling. No interaction between twin tunnel can be seen when the distance between the tunnel is more than 3D. Thus, the SS is solely affected by the single tunnel when the distance between tunnel centre-to-centre is more than 3D. Other than this parameter, single and twin tunnel have the similarities of the factors affecting SS. Each of the factors has the impact to the SS and these factors have impact to one another.

The impact of SS during tunnel construction can be broadly categorized into three main factors: tunnel geometry, soil properties, and operational parameters. Each of these factors contributes differently to SS, and the interaction can vary depending on project specifics and site conditions. The interaction between soil properties and tunnel geometry is particularly significant. In softer or more compressible soils, larger tunnel diameters or deeper excavations can cause higher settlement. Conversely, in stiffer or less compressible soils, tunnel geometry may have a lesser impact on settlement.

Furthermore, the relationship between tunnel operational parameters and soil properties, as well as tunnel geometry also play important roles. For instance, these parameters influence the optimal face pressure value during tunneling, as shown in Eq. 6. Proper management of face pressure and accurate identification of soil materials are essential for minimising the SS induced by tunnelling.

Considering the complexity of interactions among these factors,

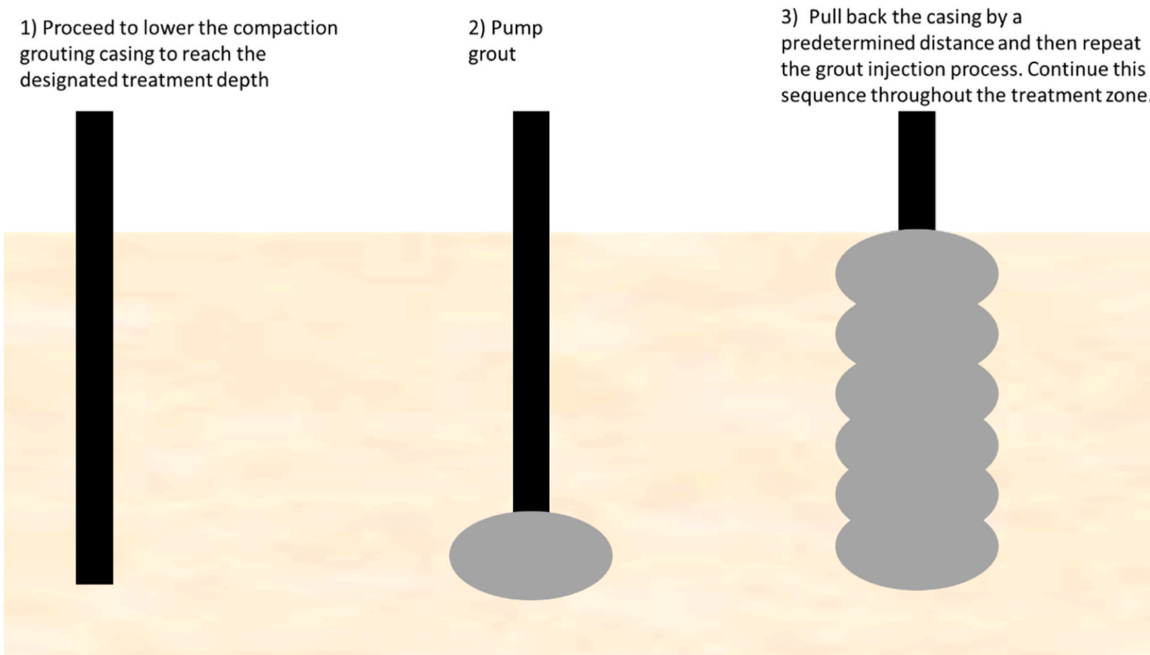


Fig. 14. Simplified process of compaction grouting.

employing machine learning (ML) techniques for predicting SS due to twin tunneling is highly recommended. ML excels in handling complex, high-dimensional data, making it suitable for analyzing multiple factors affecting SS simultaneously. This approach enables the identification and quantification of the individual impact of each factor on SS.

ML models can help to address this issue by analyzing large amounts of data and identifying patterns and relationships between the different factors and impact on SS. In addition, ML models can be trained using both historical and real-time data, which can enable more accurate and precise predictions of SS. By including multiple factors as input variables in the ML model, researchers can control for the impact of different factors and analyze individual contribution to SS. Furthermore, researchers can conduct sensitivity analyses by varying the values of different input variables while keeping others constant, which can help to identify the most important factors affecting SS.

Tunnelling for Practical Works

Practicing engineers can effectively mitigate surface settlement risks and ensure the safety of surrounding structures through various methods. Firstly, conducting thorough site and subsurface investigations, including laboratory testing, aids in comprehending geological conditions, soil properties, and existing structures near the tunneling project. Additionally, performing detailed risk assessments assists in identifying and prioritizing potential factors contributing to surface settlement risks. Engineers evaluate the likelihood and consequences of different scenarios, considering tunnel geometry, soil properties, and operational parameters, and devise a risk management plan to address identified risks. Implementing a comprehensive monitoring and instrumentation program is crucial. Instruments such as ground settlement markers, inclinometers, tiltmeters and building settlement marker can be utilized to continuously monitor ground movements, inclination of wall and building settlement during tunneling. These instruments can be categorized into three levels of monitoring - Alert, Action, and Alarm - allowing engineers to take necessary actions promptly when monitored readings reach specific thresholds.

In common practice, ground settlement markers are measured from rods with plates using the total stations. However, in congested urban areas, satellite monitoring through INSAR (Interferometric Synthetic Aperture Radar) can be considered for monitoring as it provides coverage for a wide range of ground movements. Although satellite monitoring and ground settlement marker does not offer real-time data, it is crucial to establish different threshold guidelines for each measurement time to under the ground movement during the tunnelling. These thresholds, named Alert, Action, and Alarm, prompt engineers to take necessary actions when ground settlement thresholds are reached. At the Alert threshold, engineers must increase monitoring frequency and remain vigilant. If the measurement reaches the Action threshold, immediate actions such as ground strength properties improvement or adjustment of face pressure are required to further reduce settlement. Finally, if settlement reaches the Alarm stage, tunnelling works in that area must cease, and a thorough investigation should be conducted to identify the root cause. Leveraging ample data from past projects, ML algorithms can analyze historical monitoring data to recognize patterns signaling potential SS risks.

Congested urban areas are often characterized by a dense network of existing infrastructure, including buildings, roads, pipelines, and utilities. Uncontrolled SS from tunneling activities can jeopardize the structural integrity of these assets, leading to costly repairs, disruptions to services, and safety hazards for residents and commuters. Li et al. [52] and Farrell [32] have shown the use of grouting is applicable for reducing the settlement at the urban area

Conclusions and Future Studies

In summary, from the review the geometry of tunnels play a crucial role in determining the magnitude and distribution of SS. This study highlights the significance of parameters such as tunnel diameter, depth, and center-to-center distance (d) in influencing SS outcomes. Specifically, closer tunnel spacing in twin tunnel scenarios increases the likelihood of interaction between tunnels, leading to elevated SS risks. Besides, large diameter contributes to higher volume loss. The geotechnical characteristics of the surrounding soil, including effective cohesion, friction angle, and stiffness have influence on SS. Understanding soil properties is essential for predicting and mitigating SS risks effectively. Tunnelling operation parameters, such as face pressure, grouting pressure, and excavation methods impact SS outcomes. Proper management of face pressure, for instance, is crucial for controlling settlement during excavation. Real-time monitoring and precise control of operational parameters are essential for minimizing SS risks during tunnelling activities.

Despite comprehensive review for the tunnelling affecting the SS, the studies did not cover various type of soils and other tunnelling operation parameters such as jack force thrust and penetration rate. As there are limited information for the study shows for the relationship of SS with the jack force thrust and penetration rate. Besides, ground water level is also another component is not included because limited information of actual ground water level is available for the tunnelling project due to the cost of installation of Standpipe monitoring throughout the alignment. In addition, this review is only suitable for singe and twin tunnelling instead of stacked tunnel or others arrangement of tunnel. To address the identified limitations and further advance the understanding of SS induced by tunneling, more factors can be taken into the consideration provided that the more data and publication with the remaining factors.

Besides, the development of Theory-Guided Machine Learning (TGML), combining the strengths of traditional theoretical models and data-driven ML techniques can be considered to enhance prediction accuracy and interpretability. Additionally, comprehensive field studies and validation efforts are needed to refine and validate empirical formulas and numerical models under diverse site conditions. Furthermore, exploring innovative monitoring technologies and control strategies for tunnelling operations could provide valuable insights into SS mitigation measures.

In summary, this study review the available publications on the factor affecting SS induced by tunneling operations and highlighting the importance factors that consider tunnel geometry, soil properties and tunnel operational parameters.

CRediT authorship contribution statement

Chia Yu Huat: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Panagiotis G. Asteris:** Conceptualization, Validation, Writing – review & editing. **Hossein Motaghedi:** Supervision, Writing – original draft, Writing – review & editing. **Sai Hin Lai:** Supervision, Writing – original draft, Writing – review & editing. **Danial Jahed Armaghani:** Conceptualization, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing. **Pouyan Fakharian:** Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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