

3-D NUMERICAL MODEL OF SUBSURFACE SETTLEMENT ABOVE TUNNEL LINING

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Abstract

The construction process of a bored tunnel is a complicated process. During tunnelling, loads were acting on the tunnel, hence to support the excavation process, the tunnel lining was installed. Soil stress was redistributed, the surface and subsurface soil settlement behaviour were hard to predict prior to the tunnel advance. In previous, various method was used to investigate the main parameters that effect the subsurface settlements which later can help to predict the surface settlements. In this paper, a numerical modelling was carried out to analyse the subsurface behaviour for certain soil parameters in exist of tunnel segments, grouting layer and shield layer. The subsurface measurements were conducted above the tunnel crown by 2, 4, and 6 m and it is found that the pattern of sub-surface settlement varied based on the soil properties, respectively to the surface settlement.

Keywords: 3D numerical model, soil-tunnel interaction, subsurface settlement

Introduction

Ground movement is one of the most important elements that should be studied and considered in the tunnel design. The design of urban tunnel in soft soil attempt to minimize the ground deformation whatever in a shallow or deep tunnel. To do so, numerous of researcher developed various methods to explain and predict the ground movement during tunnelling (Peck, 1969; Oteo and Moya, 1979; Sagaseta, 1987; Verruijt-Booker, 1996). The empirical method, analytical method, and numerical method was used to investigate the tunnelling induced ground movement. Those method was used either the open face or closed face shield tunnel constructions.

From analysing empirical data of many shield tunnels, Peck (1969) firstly presented the settlement trough on the surface induced by tunnelling in soft soil as a Gaussian distribution. This is also confirmed by others authors like Cording and Hansmire (1975), Mair *et al.* (1993), Ahmed and Iskander (2011). As the deviations of the Gaussian distribution in some particular cases are shown by some studies Mair *et al.* (1993); Sugai and Matsuo (1993); Peck (1969); Celestino *et al.* (2000); Jacobsz (2003); Vorster (2006) and Marshall *et al.* (2012), and show the transverse settlement taking place after construction of a tunnel, in many cases, it can be well analysed by the Gaussian distribution.

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Mair and Taylor (1997) mentioned that the components of ground movements due to tunnelling are: soil movements at the tunnelling face, ground displacements along with the shield due to the overcutting and the shape of TBM machines, ground movements at the tail behind the shield and the consolidation settlements. Figure 1 shows the two-dimensional settlement trough on the surface in greenfield conditions induced by the combination of the various component in ground movement.

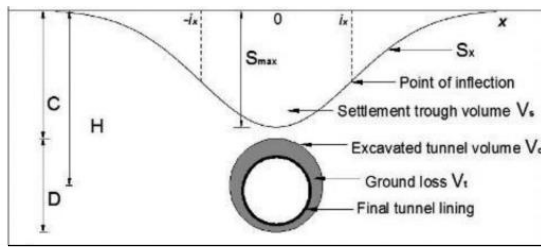


Figure 1. Gaussian curve for transverse settlement trough and ground loss VL (Peck, 1969)

In Figure 1, the volume of ground settlement per unit length through (settlement trough volume), is expressed as V_s and ground loss is expressed as V_L . The ground loss is considered as a volume of ground that is deformed due to the tunnel after construction. In undrained condition, V_s is more or semi-equal to V_L . On other hand, for tunnelling in drained condition, V_s tend to be smaller. In short, the difference is generally slight and it possibly assumed that V_s is equal to V_L (Cording and Hansmire, 1975). As the ground loss depends linearly on the tunnel theoretical volume, it is possible to consider the ground loss ratio is between the volumes of ground settlement, V_s , hence the tunnel volume per unit length can be described by Equation 1:

$$Tv(x) = \sqrt{\pi/2} \cdot v_L D^2 / 4i \cdot e^{(-x^2/2i^2)} \quad (1)$$

At a given tunnel diameter (D), two parameters control the settlement induced by tunnelling, volume loss, V_L and the trough width, i_y . The first parameter is the horizontal distance between the central tunnel axis and the inflection point of the curve, i which is determining the settlement trough width. To evaluate this parameter, Peck (1969) proposed a relation between tunnel depth and tunnel diameter. That explained the variation of i which depending on the ground condition. The second parameter is the horizontal component of the displacement that can cause damage to the buildings on the surface when tunnels are constructed in the urban area. O'Reilly and New (1982) estimated the

horizontal displacement for tunnelling in clays by considering three parameters, which they are: the relation between the ratio of the lateral distance tunnel from excavation, x and the depth of the tunnel, z_0 besides the vertical displacement induced by the tunnel, S_h .

Similarly, to Attewell and Woodman (1982), the vertical settlement in the longitudinal direction on the surface induced by tunnelling can be described based on the relation between the longitudinal coordinate, $T(y)$ the longitudinal coordinate and the trough width parameter of the longitudinal settlement i_y . Besides, Attewell and Woodman (1982) explained the horizontal displacement in the longitudinal direction by the first derivative of the settlement trough, $T(y)$ and the settlement slope can be estimated which is one of the important assessments in tunnelling design:

Mair *et al.* (1993) stated that the subsurface settlement profile also distributes as the Gaussian curve. These were based on the empirical data and centrifuge test. In details, the width of the settlement trough at the depth, z is depends on the depth of the tunnel, z_0 through a coefficient, K . Equation 2 showed that K is estimated by the analysis of observation data for the settlement above the tunnel in clay, as:

$$K = \frac{0.175 + 0.325 \left(1 - \frac{z}{z_0}\right)}{\left(1 - \frac{z}{z_0}\right)} \quad (2)$$

and:

$$\frac{T_{v,max}}{R} = \sqrt{\pi/2} \frac{V_L}{0.175 + 0.325 \left(1 - \frac{z}{z_0}\right)} \frac{R}{z_0} \quad (3)$$

where: R is the tunnel radius.

In Figure 2, the normalized maximum settlement against $a/(z_0 - z)$ is presented. The curve (A) is derived from Equation 2 with K equal to 0.5. Curve B and C are derived from equation 3 with volume loss V_L of 1.4%; R/z_0 equal to 0.1 for curve B and R/z_0 equal to 0.06 for curve C. The field data also comply with this method.

Other studies by Moh *et al.* (1996), Grant and Taylor (2000) and Jacobsz (2003) based on Mair *et al.* (1993) proposed a limited change of K in different kinds of soil in Figure 3. Ahmed and Iskander (2011) mentioned that the equation used to predict the horizontal displacement and subsurface settlement in clay proposed by Mair *et al.* (1993), can be used for sand based on analysis of the result of displacement from the soil model.

To sum up, for empirical methods, researchers have carried out numerous study on tunnel induced ground settlement to investigate the behaviour of

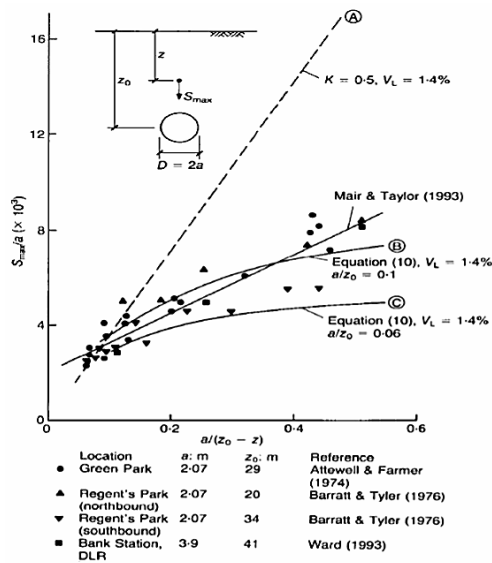


Figure 2. Subsurface settlement above the tunnel centreline (Mair *et al.*, 1993)

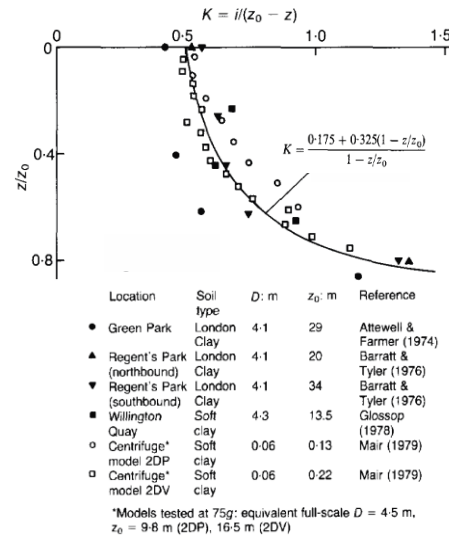


Figure 3. K for the subsurface settlement above tunnel in clay (Mair *et al.*, 1993)

surface and subsurface longitudinal settlement. However, the parameters considered was limited to tunnel diameter, D , volume loss, V_L , the trough width, i_y , and depth of the tunnel, z_0 , while a coefficient, K is taken as constant.

Next, Potts and Zdravkovic (2001) stated that numerical method is more preferable to help predict the settlement and displacement induced by tunnelling compare to the analytical and empirical method. Via numerical method, one can easily consider much more parameters in the model. Researchers also could simulate the construction procedures, complex ground condition, actual soil behaviour model, and carry out a three-dimensional multiple tunnel model. Hence, many researchers developed a three-dimensional finite element model (3D FEM) to investigate the surface settlements induced by tunnelling by using different constitutive models.

Among of these soil models, the Mohr-Coulomb model has been widely used in tunnelling modelling (Gong *et al.*, 2012; Dias and Kastner, 2013; Zhang *et al.*, 2013). Li *et al.* (2015) developed a 3D soil-fluid coupled FE model via ABAQUS (2014). 6.12 with a construction sequences details. Investigation of ground deformation due to the slurry shield tunnelling was developed and was compared with the field case study result. Their result showed that a change of grout pressure within 50 kPa, not affected the ground deformation. Next, Lambrughi *et al.* (2012) simulated the process of constructing a tunnel by using the Earth Pressure Balance machine (EPB) through a model developed

in FLAC software. The field data of a case study was used in the model. Twenty-five tunnel sections from the case study were modelled and analysed in two different geological layers: stiff clay and loamy sand. Three different soil model were used which are a linear-elastic model, Mohr-Coulomb model and modified Cam-Clay model. The result showed that the modified Cam-clay model showed the best agreement with the in-situ measurement. Jusoh *et al.* (2017) developed a 3D model to evaluate tunnel lining deformation and displacement around the tunnel by using ABAQUS software. Similarly, Mohr-Coulomb model was used. Results obtained from the numerical model were verified with a case study and show an agreement with the empirical method of Peck (1969). Agreement of numerical model results with case study findings was reported for the model of segmental tunnel lining instead of an all-at-once tunnel model.

In tunnelling, excavation advances are achieved by applying the thrust force of hydraulic jacks to the installed tunnel linings that serve as a reaction wall during TBM tunnel construction; thus, in each construction stage, the stress of the tunnel lining is affected by the thrust forces in addition to earth pressure, water pressure and a dead load of segments. While several studies on ground movements and lining forces have been performed (Zhong and Tong, 2009; Ercelebi *et al.*, 2011; Chen *et al.*, 2012; Yu *et al.*, 2012; Cho *et al.*, 2016), there is a relatively limited body of work on the relationship between the segments' thickness, jack force, and the existing of grouting layer and the

shield with subsurface settlement. Hence, there is a knowledge gap on how the axial jack forces evolve concerning construction procedure and tunnel stages.

In this paper, a soil-tunnel model was developed to investigate the behaviour of subsurface settlement in different soil formations with in presence of jack forces and relevant loads and interactions.

Numerical Model Development

A three-dimensional numerical model of soil-tunnel has been developed base on field case study of the Circle Line Stage 3 (C852) Serangoon Interchange Station, Singapore. The soil model consists of 7 soil formations with 6.5 m of tunnel diameter that excavated for 11 rings, each ring consist of 5 segments with 0.275m thickness. Figures 4 and 5 presents the soil-tunnel model.

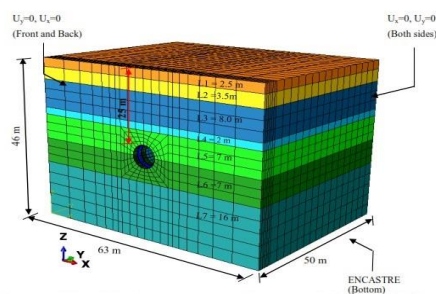


Figure 4. Soil block model with tunnel

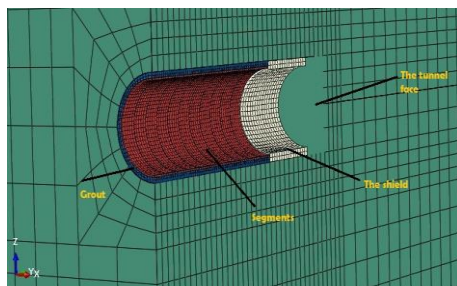


Figure 5. The tunnel model's elements as per their location in soil block

In Figure 4, the geometry of soil model was chosen as 60 m of width, 50 m of length and 46 m of height. Figure 5 presents the axisymmetric of tunnel model, the grout layer, the shield layer and the tunnel face pressure. The ground properties was addressed as the fill formation (F1), Estuarine (F2), Alluvial clay (F3), Alluvial sand (F4), Bukit Timah Granite Formation, G4 (VI) (F5), Bukit Timah

Granite Formation, G4 (V) (F6), and Bukit Timah Granite Formation, G2(III) (F7) which E is Young Modulus, p is the soil bulk density, ν is Poisson's ratio, θ is Angle of friction, and C is Cohesion which presented in Table 1. Table 1 summarize the values and parameters used in the soil ground model.

From Table 1, the first soil formation mostly is filled material consisting of unconsolidated calcareous sand and lesser quartz, ferruginous and lithic sand. The second soil formation is a transitional member consisting of unconsolidated black to blue-grey estuarine mud, muddy sand or sand, often with a higher organic content and peat layers, which is a part of the Kallang Formation. The third and fourth soil formations are Alluvium clay and sands. The fifth, sixth and seventh soil formations are granite varieties, from granite through adamellite to granodiorite; several hybrid rocks are also included within the formation. Both hornblende-rich granite and biotite-rich granite occur. Zones of norite-granite mixed rocks also exist. Hybrid granodiorite is also recognized and is named and known as the Bukit Timah Granite Formation.

Table 1. Ground properties of soil models (Mohamed *et al.*, 2007; Su, 2015; Jusoh *et al.*, 2017)

Soil layer	E (GPa)	p (kg/m ³)	ν	θ	C (kPa)
F1	0.007	1,937.5	0.333	30	10
F2	0.003	1,529.6	0.35	20	10
F3	0.003	1,937.5	0.35	22	20
F4	0.007	2,039.4	0.32	32	10
F5	0.0952	2,039.4	0.333	30	28
F6	0.0864	2,039.4	0.3	35	30
F7	3.5	2,345.3	0.32	35	30

Table 2. The tunnel model properties

	E (GPa)	δ (kg/m ³)	ν
Shield	22.5	-	0.125
Segments	38	2,500	0.2
Grout	2.6	2,400	0.286

(Lambrugh *et al.*, 2012)

Next, Table 2 presented the properties of lining, grout and shield used to model the tunnel elements properties with E is Young Modulus, δ is the density, ν is Poisson's ratio. The grouting properties by Lambrugh *et al.* (2012) is used for this study due to the similarities of stratigraphic profile between the Madrid Metro tunnel and the Singapore MRT tunnel.

More details of soil-tunnel model development and the model verification was presented by

El-Sayed *et al.* (2019). Note that, after succeeding validated the initial model with existing case study, the model then continue use similar numerical development process but the soil model now focusing a single soil formation of Table 1 of each modelling in order to investigate the effect of soil types with jack forces in the tunnel excavati on and to investigate how the subsurface settlement behaved in different soil formation.

Results and Discussions

In this section, results of the ground behaviour at tunnel periphery in different ground formations are presented (Figures 6-12), respectively. The sub surface behaviour were measured at three different locations of 2, 4, and 6 m from tunnel crown along the longitudinal cross section. These are radial displacements from tunnel periphery in term of the settlement value that plotted as longitudinal settlement. It is plotted as a ratio between the settlement and the tunnel diameter against the tunnel length. In addition, the longitudinal surface settlement for the ground surface also plotted in the graph as comparison.

In general, one can see that a similar pattern of sub surface settlement can be seen in different soil formations from F1 to F7. Initially, the sub surface settlement give some small ground movement at early phase of excavation due to increasing in the soil volume with the tunnel installation. Then, the settlement increases due to distortion of soil equilibrium and increment of volume loss around the tunnel periphery as the result of excavation. The soil-tunnel interaction tried to reach a new equilibrium thus it slowly decrease the movement again until an abrupt changes of sub surface settlement occurred approaching towards the end of tunnel excavation. Note that this vertical settlement not only possess at the tunnel crown but also around the tunnel periphery. The soil redistribute their soil stresses hence also lead to a horizontal displacement at the tunnel side. From Figures 6-12 also, one can see the comparison of subsurface settlement pattern to the surface settlement pattern.

From Figures 6-8, a similar range of subsurface settlement depicted for 2, 4, and 6 m above the tunnel crown. Ground formation of F1-Fill and F2-Estuarine shows similar range of subsurface settlement due to the similarity magnitude of the soil parameter for both formations. While, for F3-Clay, it possess soft soil formation of clay; the subsurface displacement did occurs much earlier with higher magnitude of settlement, about 30 mm compare to the F1 and F2 which only reach the maximum of 20 to 25 mm, respectively.

In addition, one can see the soil reaction of the ground surface, the maximum settlement depicted for F1-fill and F2-estuarine show an immediate large magnitude as the subsurface settlement easily

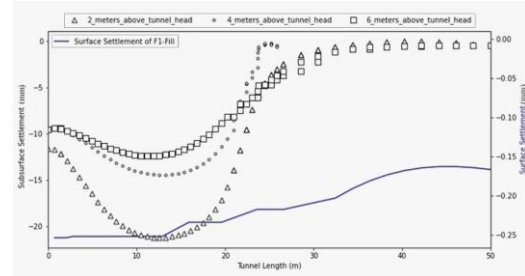


Figure 6. Surface and subsurface settlement of F1-fill soil above the tunnel axis

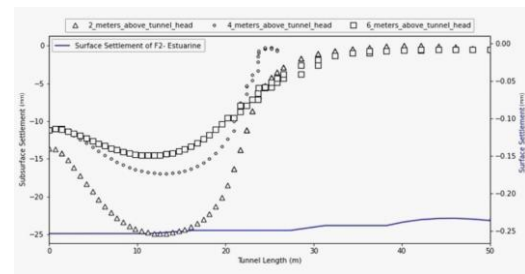


Figure 7. Surface and subsurface settlement of F2- Estuarine soil above the tunnel

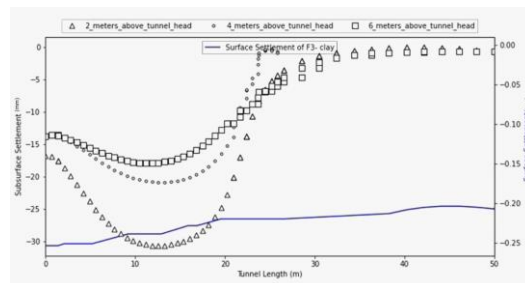


Figure 8. Surface and subsurface settlement of F2- Estuarine soil above the tunnel

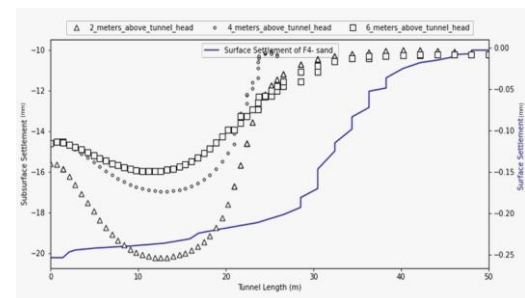


Figure 9. Surface and subsurface settlement of F4-Sand soil above the tunnel axis

redistributed to the ground surface. Oppositely, F3-clay soil formation only gives slightly small maximum magnitude of ground surface settlement even though a high subsurface settlement depicted near the tunnel periphery. Clayey soil takes slower pace in redistribution of stress thus lead to small ground settlement at the surface.

In Figures 9-12, the formations of F4-Sand, F5-Granite, F6-Granite and F7-Granite shown a similar range of subsurface magnitude along the tunnel excavation length. An obvious sudden jump could be seen in the 2 m subsurface settlement above the tunnel crown when compared to both 4 m and 6 m soil behaviour. In term of magnitude, the formation of F7 lead to least surface and subsurface settlement as they have a very strong ground formation. In addition, F4 lead to high magnitude subsurface settlement similar to what have been depicted to clay formation (F3). However, when compare to a clay formation, the sand formation still presenting a sudden jump soil surface settlement which leads to an important benchmark behaviour for this kind of soil. Clay soil previously only give an almost flat bed settlement reading towards the end of tunnel construction.

Next, Figure 13 presents a comparison of soft ground formation of fill formation (F1), Estuarine (F2), Alluvial clay (F3), Alluvial sand (F4) that have a soil density in the range of 1.5 to 2 Mg/m³, cohesion of 10 to 20 kPa and angle of friction of 20° to 32°. From this figure, one can see the F3-clay depicts the higher subsurface settlement and least settlement can be seen for both F1-fill formation and F4-alluvial sand formation. The F4-sand formations depicts a surface settlement with sudden jump which agreeable to the general soil reaction at field. As the modelling are limited to a Mohr Coulomb model, other soil factor such as soil dilation cannot be investigate in this results.

Figure 14 presents the comparison of subsurface settlement of granite formations of F5, F6, and F7 with high Young Modulus of 0.09 to 3.5 GPa. F7-Granite has the highest modules and density values among the seven soil formations, this reflected on the subsurface displacement and surface settlement magnitude which is the lowest among the other formations.

Figure 15 presents the critical subsurface settlement at 2 m above the tunnel crown axis. As one can see, the nearer the measurement of the subsurface to the tunnel crown, the higher the settlement or ground movement depicted. From the results, one could see that the settlement was stating small at first few rings but the increase to almost 2 times of initial settlement then possess the decrement of settlement when approaching towards the end of the tunnel excavation.

It can be concluded that from different soil formations, subsurface settlements near to the tunnel periphery (i.e., 2 m above the tunnel crown)

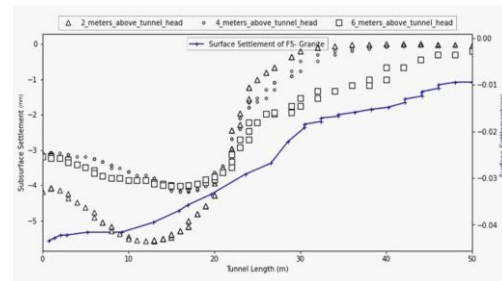


Figure 10. Surface and subsurface settlement of F5-Granite soil above the tunnel axis

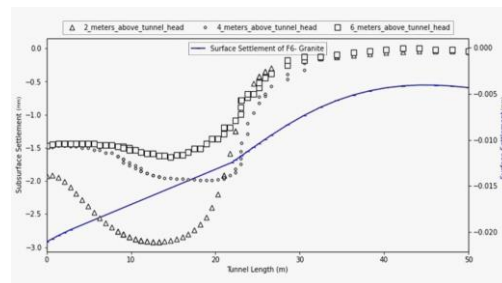


Figure 11. Surface and subsurface settlement of F6-Granite soil above the tunnel axis

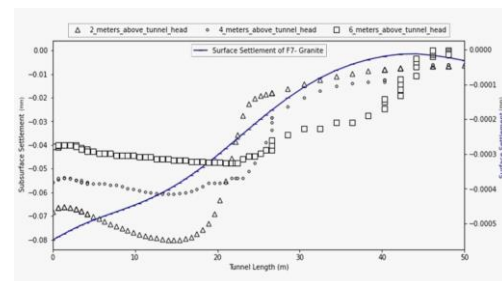


Figure 12. Surface and subsurface settlement of F7-Granite soil above the tunnel axis

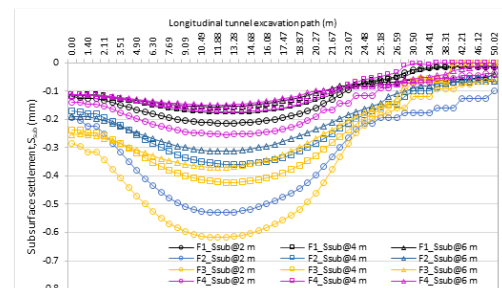


Figure 13. Subsurface settlement of low density soil formation above the tunnel

led to more settlement especially for a low soil density compared to the high soil density for a similar tunnel condition. One also could see, how much the initial tunnel progression lead to a heave rather in soft ground than immediately reaching a stable longitudinal settlement in stable ground formation.

Next, to sum up the result of surface and subsurface settlement, Tables 3 and 4 presents the identified magnitude and location of maximum surface and maximum subsurface displacement along the excavation path in different soil formations.

From Table 3, the ratio of maximum subsurface settlement at 2 m of tunnel crown to the maximum depicted of surface settlement can be as 0.002% in low-density soil and depicts the range of 0.01% to 1% for high soil density. Therefore, if one knows the surface settlement, one can predict how much the subsurface settlement occurred inside the ground.

From Table 4, one could see that the maximum surface settlement, S_{max} for all formations had occurred at the head of shield. The magnitude of settlement does indicate that the surface settlement is the summation of the subsurface displacement.

Conclusions

A soil-tunnel model was developed in ABAQUS to investigate the behaviour of subsurface settlement for the different soil formations, in related to specific tunnel properties such as segments thickness. The subsurface settlement for soil models is analysed with the existence of tunnel lining, grout layer and shield. The subsurface settlement were presented of 2, 4, and 6 m from tunnel crown shows the displacement occurred as long the lining and the grout is react to the soil or ground to reach equilibrium, in which, the unification for all subsurface behaviour led to the soil surface settlement. Despite the magnitude of sub surface settlement for the different soil formations, the behaviour of sub surface settlement for the different soils is almost similar in pattern. It is also concluded that based on the subsurface settlements near to the tunnel periphery (i.e., 2 m above the tunnel crown), this subsurface settlements led to higher settlement magnitude for lower density soil when compare to the higher density soil in a similar tunnel condition. When comparing to the surface settlement, a ratio of subsurface settlement to the surface settlement has been proposed for different soil types but the findings is limited based on a simple soil model simulation, i.e., Mohr Coulomb model.

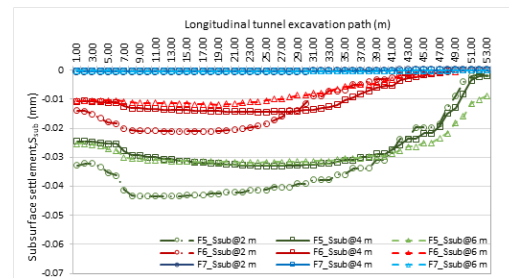


Figure 14. Subsurface settlement of high density ground formation above the tunnel axis.

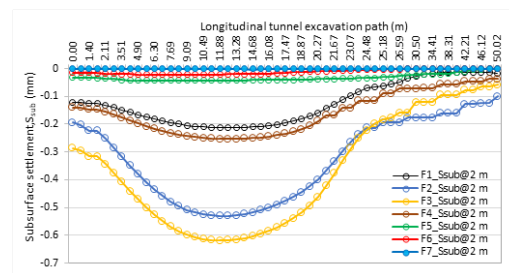


Figure 15. Critical subsurface settlement at 2m above the tunnel axis

Table 3. Summary of maximum settlements of ground surface settlement, S_{max} and the subsurface displacement, S_{sub} of 2, 4, and 6 m

Soil layer	Maximum settlement measured			
	$S_{sub@2\text{ m}}$ (mm)	$S_{sub@4\text{ m}}$ (mm)	$S_{sub@6\text{ m}}$ (mm)	S_{max} (mm)
F1	0.0021	0.0018	0.0015	102.01
F2	0.0028	0.0019	0.0016	190
F3	0.0026	0.0018	0.0016	238
F4	0.0026	0.0018	0.0015	99
F5	0.0027	0.0021	0.002	16
F6	0.0026	0.0018	0.0015	8
F7	0.0024	0.0018	0.0014	0.23

Table 4. Summary of maximum settlements of ground surface settlement, S_{max} and the subsurface displacement, S_{sub} of 2, 4, and 6 m

Soil layer	Location of maximum settlement measured			
	$S_{sub@2\text{ m}}$ (m)	$S_{sub@4\text{ m}}$ (m)	$S_{sub@6\text{ m}}$ (m)	S_{max} (m)
F1	18.2	15.4	12.6	21
F2	18.2	15.4	12.6	21.8
F3	16.8	14	11.2	21.8
F4	18	14.6	11.8	21.2
F5	18.2	14.7	11.7	21.2
F6	18.5	15.3	11.86	21.4
F7	19.1	15.8	11.9	21.2

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