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Prediction of transverse settlement trough considering the combined effects of excavation and groundwater depression

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Abstract. There are two primary causes of the ground movement due to tunnelling in urban areas; firstly the lost ground and secondly the groundwater depression during construction. The groundwater depression was usually not considered as a cause of settlement in previous research works. The main purpose of this study is to analyze the combined effect of these two phenomena on the transverse settlement trough. Centrifuge model tests and numerical analysis were primarily selected as the methodology. The characteristics of settlement trough were analyzed by performing centrifuge model tests where acceleration reached up to 80g condition. Two different types of tunnel models of 180 mm diameter were prepared in order to match the prototype of a large tunnel of 14.4 m diameter. A volume loss model was made to simulate the excavation procedure at different volume loss and a drainage tunnel model was made to simulate the reduction in pore pressure distribution. Numerical analysis was performed using FLAC 2D program in order to analyze the effects of various groundwater depression values on the settlement trough. Unconfined fluid flow condition was selected to develop the phreatic surface and groundwater level on the surface. The settlement troughs obtained in the results were investigated according to the combined effect of excavation and groundwater depression. Subsequently, a new curve is suggested to consider elastic settlement in the modified Gaussian curve. The results show that the effects of groundwater depression are considerable as the settlement trough gets deeper and wider compared to the trough obtained only due to excavation. The relationships of maximum settlement and infection point with the reduced pore pressure at tunnel centerline are also suggested.

Keywords: volume loss; excavation; groundwater depression; settlement trough; centrifuge model test

1. Introduction

According to the UN technical report, around 70% of the world population will be living in the urban areas by 2050 and the urban population will have doubled in the next century (UN 2007, 2013, Broere 2016). The cost of managing the traffic congestion in OECD countries is up to 2.0% of their accumulative GDP (Godard 2008). One of the solutions to solve these problems face by the people and to meet the needs of the community is the utilizations of underground space. In urban areas, the major problem faced during the tunnel design is the ground settlement.

There are two main reasons of ground settlement due to tunnelling; first reason is the lost ground and secondly the groundwater depression (FHWA 2009). The main reason is the lost ground inevitably caused by the loss of existing ground due to excavation depending upon the tunnelling methods and the construction quality. Face loss occurs due to the difference between ground stresses and the stabilization pressure on the TBM face. It causes the longitudinal ground movement due to stress relief. Shield loss occurs when the gap between the overcut ground and the shield causes the ground to move radially into the gap. Tail loss and lining deformation are among the major reasons of ground settlement in TBM tunnelling. It occurs when proper backfilling is not performed in the gap located between the segmental lining and the ground. It also includes the lining deformation due to the ground load. Long term loss occurs when the ground and the support deterioration cause the loss of stiffness and also when the ground consolidation occurs due to drainage, especially in clays, during the service life of tunnel. The long term settlement, differential settlement, and land subsidence occurred in very soft clayey layer and aquifers of high groundwater table in Shanghai region (Shen *et al*. 2014). Groundwater depression occurs during the construction and drainage stages. It can also happen before construction due to artificial lowering of groundwater. Groundwater depression causes an increase in the effective stresses in the ground due to the change in pore pressure, resulting in elastic (immediate) settlement. Due to the decrease in pore pressure, the effected ground gets loosened and its strength is also reduced accordingly. This phenomenon produces layers or lenses of compressible soils and weathered rocky materials. Most of the settlement in cohesive soils occurs due to consolidation. The settlement due to excavation can cause damage to the adjacent structures (Ding *et al*. 2017, Zheng *et al*. 2017).

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2. Characteristics of ground settlement due to tunnelling

In lifecycle modelling of corrosion damaged RC Peck

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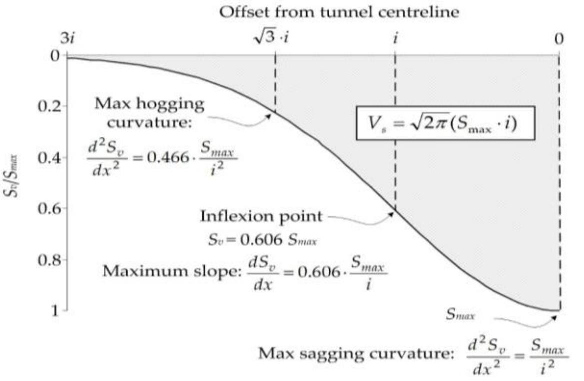


Fig. 1 Settlement trough expressed by Gaussian curve (Alec 2009)

(1969) suggested that the settlement trough shape due to tunnelling generally matches well with the Gaussian curve. The settlement $S_v(x)$ can be obtained by using Eq. (1). The detailed characteristics of Gaussian curve are shown in Fig. 1.

$$S_v(x) = S_{\max} \cdot \exp\left(\frac{-x^2}{2i^2}\right) \tag{1}$$

where S_v is vertical settlement, S_{max} is the maximum vertical settlement at the tunnel centerline, x is the horizontal distance from the tunnel centerline, i is the horizontal distance from the tunnel centerline to the inflection point of the surface settlement trough.

The volume of the settlement trough (V_s) can be obtained by the integration given in Eq. (2). The volume loss (ground loss) can be expressed as the ratio of V_s to the notional excavated volume of the tunnel, as shown in Eq. (3).

$$V_s = \int_{-\infty}^{\infty} S_v(x)dx = \sqrt{2\pi}(S_{\max} \cdot i) \tag{2}$$

$$V_L(\%) = \frac{4V_s}{\pi D^2} \cdot 100 \tag{3}$$

where V_s is the volume of the settlement trough (per unit length of tunnel), D is the tunnel diameter.

Clough and Schmidt (1981) proposed the settlement trough width at low cover to diameter ratio, as given in Eq. (4).

$$i = R \cdot \left(\frac{z_t}{D}\right)^{0.8} \tag{4}$$

where R is tunnel radius, z_t is the tunnel axis depth (C+D/2), C is the overburden of tunnel.

O'Reilly and New (1982) proposed that the settlement trough width is not related to the tunnel diameter, and also suggested the relationship between i and z_t, as shown in Eq. (5). The inflection point moves away from the tunnel centerline with an increase in the value of K, and vice-versa. They also proposed the relationships between i and z_t according to the ground conditions, as given in Eq. (6).

$$i = K \cdot z_t \tag{5}$$

$$i = 0.28z_t - 0.12 \tag{6}$$

where K is the trough width parameter depending on the type of ground.

Some researchers have reported that the Gaussian curve does not always provide a good fit to the settlement trough data (Celestino *et al*. 2000, Jacobsz *et al*. 2004, Vorster *et al*. 2005). Vorster *et al*. (2005) suggested a modified Gaussian curve with three degrees of freedom to obtain a better fit for soil settlement, as shown in Eqs. (7) and (8). An additional parameter, α, controls the vertical location of the inflection point. The Gaussian curve can be obtained by using α =0.5 in the modified Gaussian curve. An increase in the value of α makes the trough shape narrow. The optimum values of i and α can be obtained by analyzing the field measurement data or experimental data using a least-squares regression method. The volume of the settlement trough (modified Gaussian curve, Eqs. (9) and Eq. (10) can be obtained using the value of T^* given in Eq. (11). It is concluded hereby that modified Gaussian curve provides a better fit than the previous studies.

$$S_v(x) = \frac{n}{(n-1) + \exp\left[\alpha \cdot \left(\frac{x}{i}\right)^2\right]} \cdot S_{\max} \tag{7}$$

$$n = e^{\alpha} \cdot \frac{2\alpha - 1}{2\alpha + 1} + 1 \tag{8}$$

where n is the shape function parameter controlling the width of the trough, α is parameter to ensure that i remains the distance to the inflection point.

$$V_s = \int_{-\infty}^{\infty} S_v(x)dx = T \cdot i \cdot S_{\max} \tag{9}$$

$$T = \frac{-n \cdot \sqrt{\pi} Li_{0.5}(1-n)}{(n-1) \cdot \sqrt{\alpha}} \tag{10}$$

$$T^* = \exp(1.699 + 0.522\alpha - 1.472\sqrt{\alpha}) \tag{11}$$

where $Li_s(\xi) \equiv \sum_{k=1}^{\infty} \frac{\xi^k}{\xi^s}$, T is new function of n and α. T^* can also be used instead of T.

3. Centrifuge model tests using two types of tunnel models

3.1 Principle of centrifuge model test

The main principle of centrifugal modeling is to apply the centrifugal acceleration, as given in Eq. (12), to a 1/N scaled model in order to recreate the stress conditions in prototype. The vertical stresses in the model and the prototype are expressed in the Eqs. (13) and (14), respectively.

$$Ng = \omega^2 R_e \tag{12}$$

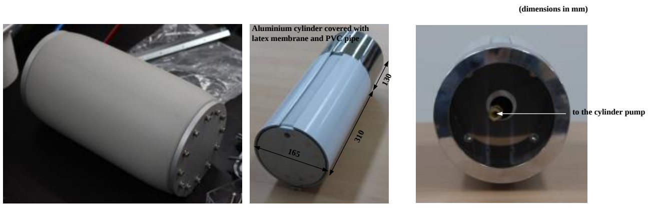
$$\sigma_{vm} = \rho \cdot N \cdot g \cdot h_m = \rho \cdot \omega^2 \cdot R_e \cdot h_m \quad (13)$$

$$\sigma_{vp} = \rho \cdot g \cdot h_p \quad (14)$$

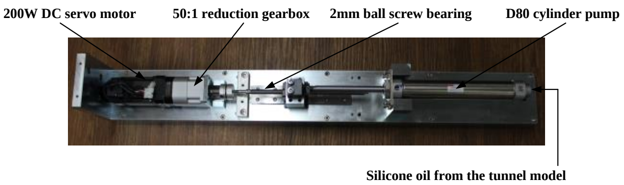
where N is the centrifuge acceleration scale, ω (= $2\pi \cdot rpm/60$) is the angular velocity of the machine, R_e is the effective nominal radius, σ_{vm} is the vertical stress in model, h_m is the height of model, g is Earth gravity (i.e., 1g=9.81 m/s^2), ρ is the density of soil, σ_{vp} is the vertical stress in prototype, h_p is the height of prototype.

Model tests were conducted using K-water geotechnical centrifuge machine developed in 2013 which is one of the largest in Korea as shown in Fig. 2. The prepared model weighed about 20.4 kN and it used to take 16-18 minutes for the machine to reach up to 80g condition. The machine usually accelerates at 100-105 rpm to achieve an angular velocity of 10.47-10.99 rad/s.

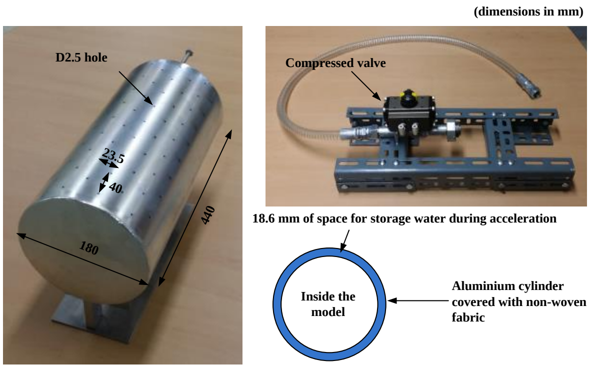
Fig. 2 Various views of centrifuge machine in K-water



(a) Volume loss tunnel model



(b) Volume control system



(c) Drainage tunnel model

Fig. 3 Design of volume loss tunnel and drainage tunnel models

3.2 Two types of tunnel models

The purpose of the tests was to analyze the ground movement due to ground lost and groundwater depression. As it was difficult to analyze the effect of ground lost and groundwater depression simultaneously in the simulations, two different tunnel models were developed to simulate the two phenomena separately. Two types of tunnel models were developed in this study. Tunnel volume loss model (tunnel model 1) simulates the tunnel excavation procedure involving the controlling of extracted volume of silicone oil as shown in Fig. 3(a). The operational principle is based on the movement of 2 mm ball screw bearing towards the servo motor after every single revolution. After that, 10,053.09 mm^3 of silicone oil is extracted from the tunnel model as shown in Fig. 3(b). Volume loss value resulting due to real construction procedure gives an idea about the quality of construction.

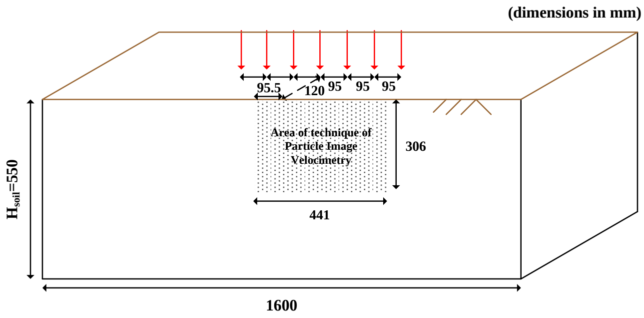
The target volume loss was obtained by reducing the diameter of tunnel model while centrifugal acceleration. Tunnel model 1 was fabricated using aluminum cylinder, latex membrane, silicone oil, and PVC pipe as shown in Fig 3(a). Maximum diameter of tunnel model was 180 mm. When N times g-level was applied on the model, it behaved as N times 180 mm in the prototype.

Drainage tunnel model (tunnel model 2) was developed to simulate the groundwater drainage during the tunnel construction. Tunnel model 2 was fabricated using aluminum cylinder, non-woven fabric, compressed valve, and plastic pipe reinforced with wire as shown in Fig. 3(c). The diameter of tunnel model 2 was 180 mm just like tunnel model 1. A total of 27 holes of 2.5 mm diameter were drilled in the model; the transverse and longitudinal spacing of drilled holes were 23.5 mm and 40 mm, respectively. The holes were drilled in one-fourth of the tunnel model at 45° on both sides around the periphery of the crown.

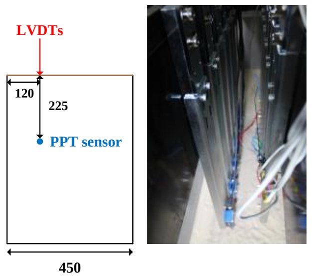
3.3 Test scenarios and measuring systems

The purpose of test scenario 1 was to analyze the surface and subsurface settlement according to volume loss of the tunnel at C/D=1.73. Tunnel model 1 was used and in situ stresses were developed by accelerating the model at 80g condition. The diameter of the tunnel model was selected as 180 mm in order to substitute it for the prototype diameter of 14.4 m. Tunnel model 1 was prepared to be located at the depth of 312.5 mm from the surface in order to substitute the overburden (C) of 25 m in the prototype. Thus, the value of C/D was achieved to be 1.73. In this test, dry Jumunjin sand was used without the presence of groundwater conditions.

The purpose of test scenario 2 was to analyze the surface settlement according to the groundwater depression, unlike the previous test. Tunnel model 2 was used without the application of volume loss in this test. The ground conditions were same as in previous tests, however, the groundwater level was at 100 mm from the surface in order to facilitate the drainage of water in the strong box through the drainage holes. The groundwater level in the model was selected to substitute the groundwater level of 8 m from the surface in the prototype. Unsteady flow (unconfined fluid flow) condition was developed as water was not injected



(a) Front view



(b) Side view

Fig. 4 Configuration of the measurement system

from the boundary during the drainage of water from tunnel model.

A total of seven linear variable differential transformers (LVDTs, MHR500MC-006) were used to measure the surface settlement by tunnelling. The transverse distance between the sensors was kept as 95 mm and all the sensors were installed at 120 mm distance from the Perspex wall, as shown in Fig. 4(a). These measuring range of LVDTs ranged from ±0.13 mm to ±50.80 mm and non-linearity was 0.25%. A total of two pore pressure transducers (PPTs) were used to measure the reduced pore pressure according to the drainage in tunnel model 2. The reduction in pore pressure was measured during the experiments due to the limitation of difficulties faced in measuring the groundwater level directly in the experiments. These sensors were positioned at the same distance from the Perspex wall as the LVDTs were, but at a depth of 225 mm from the surface of sand used in the model, as shown in Fig. 4(b).

4. Analysis of the settlement trough based on the experimental results

The value of volume loss (%) is a function of maximum settlement, inflection point, and shape parameters; it can be obtained by the volume of settlement trough. Surface settlements were analyzed according to different parameters such as the volume loss and consideration of groundwater depression with the help of two types of experimental results. The curve fitting of measurement data was performed using non-linear least squares method by Matlab (R2014b).

4.1 Analysis of surface settlement trough

In test scenario 1, surface settlement troughs based on

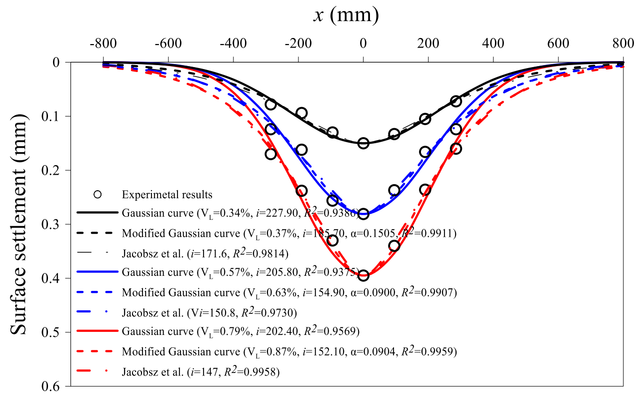


Fig. 5 Surface settlement trough based on test scenario 1 (LVDTs)

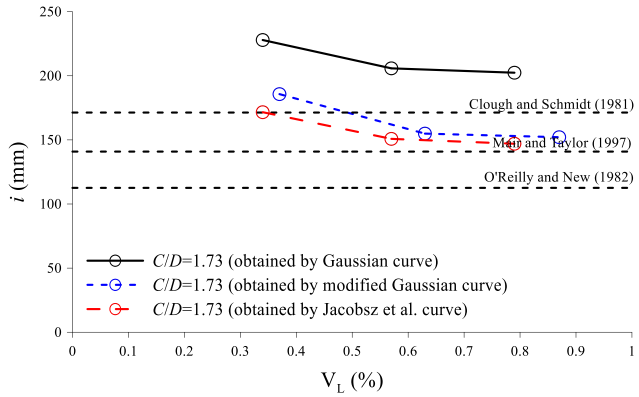
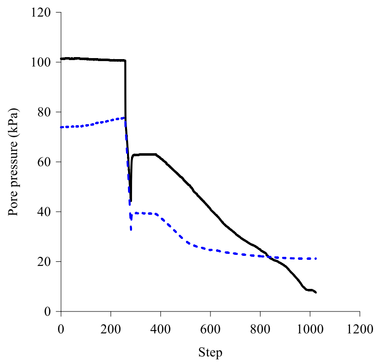


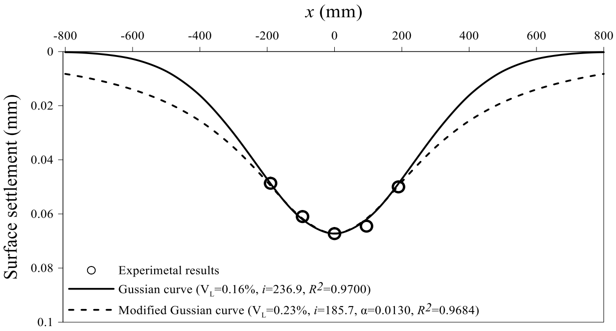
Fig. 6 Comparison of the inflection points with the previous studies

seven LVDTs results were analyzed. The maximum settlements in test scenarios 1-1, 1-2, and 1-3 were obtained as 0.150, 0.281, and 0.395 mm, respectively. Accordingly, the maximum settlements in the prototype were obtained as 12, 22.48, and 31.60 mm, respectively. In the settlement trough of test scenario 1-1, the inflection points obtained by Gaussian curve and modified Gaussian curve were 227.90 and 185.70 mm, respectively. The volume loss calculated through were 0.34% and 0.37%, respectively, as shown in Fig. 5 (black lines). In the settlement trough of test scenario 1-2, the inflection points obtained by Gaussian curve and modified Gaussian curve were 205.80 and 154.90 mm, respectively and the volume loss was calculated as 0.57% and 0.63% as shown in Fig. 5 (blue lines). In the settlement trough of test scenario 1-3, the inflection points obtained by Gaussian curve and modified Gaussian curve were 202.40 and 152.10 mm, respectively. The volume loss values were calculated to be 0.79% and 0.87%, respectively, as shown in Fig. 5 (red lines). The results obtained through modified Gaussian curve were better than those obtained by Gaussian curve and Jacobsz's curve. The inflection point obtained by modified Gaussian curve was much closer than the one obtained by Gaussian curve, however, the smaller value of α obtained in the results caused more volume loss.

The inflection points obtained by modified Gaussian curve and Jacobsz's curve at C/D=1.73 ranged within those presented by R. J. Mair and R. N. Taylor (1997) as well as Clough and Schmidt (1981), as shown in Fig. 6. The value

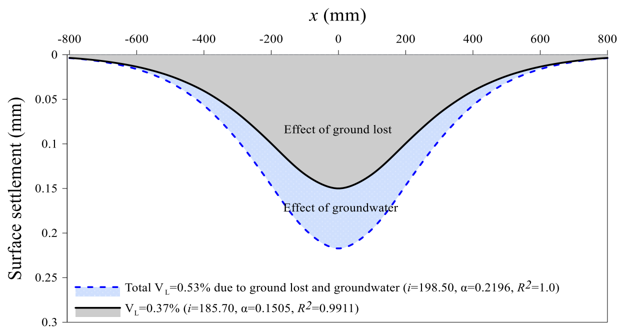


(a) Decrease in pore pressure during the test

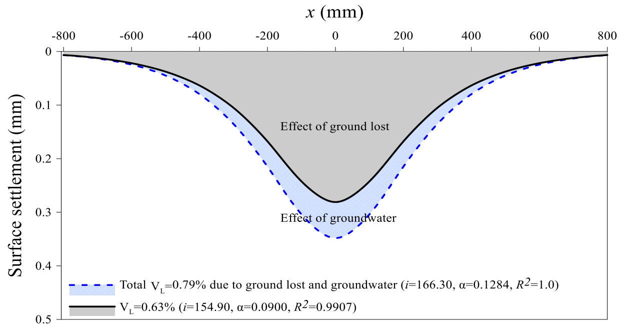


(b) Surface settlement based on test scenario 2 (LVDTs)

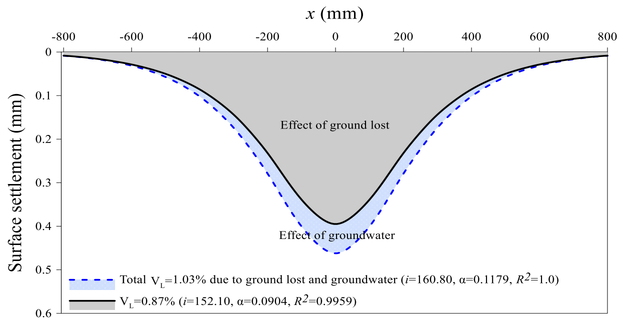
Fig. 7 Decrease in pore pressure and its effect on surface settlement



(a) Test scenario 1-1 + 2



(b) Test scenario 1-2 + 2



(c) Test scenario 1-3 + 2

Fig. 8 Results obtained by applying superposition method in test scenarios 1 and 2

of inflection point tends to decrease with the increase in volume loss.

4.2 Effect of groundwater depression on surface settlement trough 2005

When the compressed valve was opened after reaching 80g condition, water started flowing out of the model. The change in pore pressure, measured by two separate PPT sensors, due to groundwater depression was 37.92 and 38.23 kPa respectively, as shown in Fig. 7(a). In test scenario 2, the surface settlement trough obtained from five LVDTs measurements were analyzed. The maximum surface settlement at the centerline was 0.0672 mm equivalent to 5.4 mm of that in the prototype. The volume loss due to groundwater depression was calculated to be 0.16%, as shown in Fig. 7(b).

The effects on surface settlement due to tunnel excavation and groundwater depression were quantitatively analyzed in this section by using superposition method (Suwansawat and Einstein 2007). The superposition method was chosen for analysis mainly for its consideration of immediate settlement (elastic behavior of soil) due to groundwater depression and its ability to match with the Gaussian curve and other existing curves due to the maximum settlement value obtained at the centerline. The settlement trough was analyzed according to the effects of tunnelling (excavation and groundwater depression) by obtaining the arithmetic sum of the surface settlement based on test scenarios 1 and surface settlement based on test scenarios 2, as shown in Fig. 8(a)-8(c). The settlement trough parameters such as inflection point, α, and R^2 value were obtained as shown in Fig. 8. The results based on modified Gaussian curve show that the effects of groundwater depression relatively increase when the volume loss only due to excavation is less. The increment in the value of inflection point decreases from 12.8 mm to 8.7 mm when the volume loss increases from 0.37 to 0.87%. Resultantly, the maximum settlement, trough width, and total volume loss increase due to the consideration of the effects of groundwater depression. The inflection points decreases when the volume loss increases in the settlement trough due to excavation, whereas, the inflection point increases when the total volume loss increases in the settlement trough due to groundwater depression. The main difference of this study from the previous studies is the analysis of surface settlement trough considering the groundwater depression.

5. Prediction of settlement trough due to combined effect of excavation and groundwater depression

5.1 Application of new suggested curve and numerical modeling

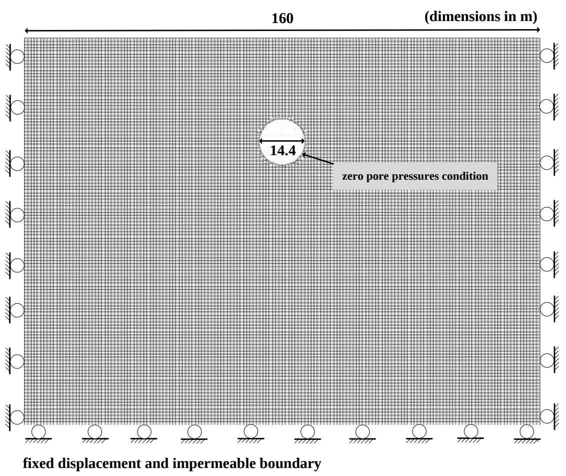


Fig. 9 Two dimensional tunnel model in plane-strain condition

Table 1 Physical properties and constitutive model of sand and water

Contents	Unit	Sand	Water
Density	kg/m^3	1,600	1,000
Bulk modulus	MPa	16.7	2,000
Shear modulus	MPa	10	-
Elastic modulus	MPa	25	-
Poisson's ratio	-	0.2504	-
Cohesion	Pa	0	-
Friction angle	Degree	34	-
Dilation angle	Degree	0	-
Permeability	m^2/Pa-sec	1.02×10^{-10}	-
Porosity	-	0.3	-
Constitutive model	-	Mohr-Coulomb model	-

The surface settlement due to excavation extended up to 2.5-3*i* from the centerline and faded down to zero at the surface, whereas in the case of decrease in pore pressure, some elastic settlement was observed even at a considerable distance from the centerline. Thus, the settlement trough obtained in the case of decrease in pore pressure did not match well with the settlement curves presented in the previous research work in which decrease in pore pressure was not considered. Due to this reason, a new parameter, u was added to the modified Gaussian curve, as seen in Eq. (15), in order to obtain a suitable curve for settlement trough due to groundwater depression. Here, u represents the elastic settlement at a distance farther from the tunnel centerline.

$$S_v(x)=\frac{n}{(n-1)+\exp\left[\alpha\cdot\left(\frac{x}{i}\right)^2\right]}\cdot(S_{\max}-u)+u \qquad (15)$$

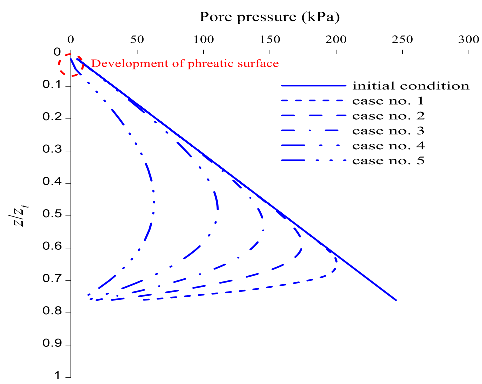
In this study, two dimensional analyses were performed in plane-strain condition as shown in Fig. 9. The size of tunnel diameter in all cases was used as 14.4 m. In order to minimize the interference of boundary conditions for accomplishing the fluid flow analysis, the distance between the model boundary and the tunnel wall and invert was kept to be more than 5.0*D*. In order to analyze the settlement only to due to groundwater depression, the tunnel periphery was fixed in both *x* and *y* directions and unsteady flow condition was developed. The physical properties of sand and groundwater used in the numerical analysis are given in Table 1.

Table 2 Different cases and their details used for numerical analysis

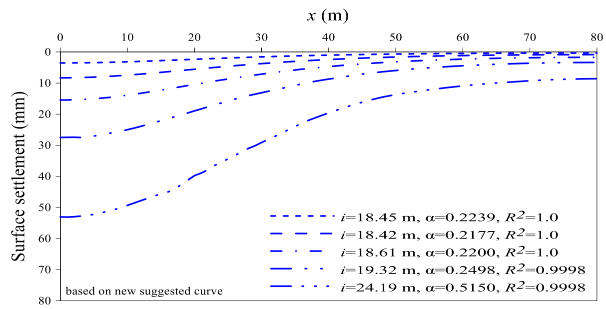
Case no.	*C*/*D* ratio	Groundwater level	$\Sigma\Delta p$ * (kPa)	$\Sigma\Delta p/\Sigma p$**
1			362.8	0.12
2			615.6	0.20
3	1.73	Up to surface (25 m)	926.4	0.30
4			1365.4	0.44
5			2130.2	0.68

* $\Sigma\Delta p$ is sum of reduced pore pressure with respect to depth at the centerline

** $\Sigma\Delta p/\Sigma p$ is ratio of the summations of reduced pore pressure to total pore pressure with respect to depth



(a) Variation in pore pressure distribution with depth at tunnel centerline



(b) Surface settlement trough according to the decrease in pore pressure

Fig. 10 Pore pressure distribution and its effect on surface settlement (*C*/*D*=1.73)

5.2 Numerical simulation for groundwater depression

The overburden values of 25 m was considered in the numerical simulations and the groundwater level was simulated to be up to the surface in all cases. Numerical simulation for a total of 5 cases was performed with five different magnitudes of groundwater depression, as shown in Table 2. The pore pressure distribution and its effect on the surface settlement trough was analyzed according to the decrease in pore pressure at *C*/*D* ratio condition of 1.73, as shown in Fig. 10. In the case of *C*/*D*=1.73 condition, the maximum settlement largely increased from 3.539 mm to 53.04 mm and the inflection points obtained by the new suggested curve increased after initial decrement. The reason behind an increase in the settlement trough after initial decrement was that despite the settlement trough seems to be narrow in shape, the elastic settlement getting farther from the centerline resulted in changing the trend of the inflection points.

5.3 Prediction of settlement considering the combined effect of excavation and groundwater depression

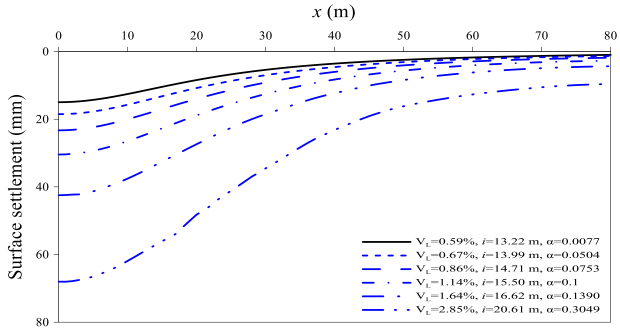
In order to consider the combined effect of excavation and groundwater depression, the settlement trough obtained from volume loss (0.5, 1.0, and 2.0%) and the results from section 5.2 were superpositioned for analyzing the surface settlement, as shown in Table 3.

In the case of *C*/*D*=1.73 condition, the characteristics of surface settlement trough were analyzed by using superposition method in order to obtain five surface settlement troughs according to the change in groundwater depression, each at three different volume loss values (0.5, 1.0, and 2.0%). Fig. 11(a) shows the settlement troughs based on the combined effect of 0.5% volume loss and groundwater depression resulting in an increase in the magnitude of reduced pore pressure that caused the maximum settlement to increase from 14.98 mm to 68.02 mm and the inflection point to continuously increase from 13.22 m to 20.61 m. There was no trend observed for change in inflection points due to groundwater depression, but there was a uniform increase in inflection points when the excavation was also considered besides groundwater depression. The volume loss obtained only due to excavation was 0.59% and the combined effect of excavation and groundwater depression caused up to 2.85% volume loss. Fig. 11(b) shows the settlement troughs based on the combined effect of 1.0% volume loss and groundwater depression resulting in an increase in the magnitude of reduced pore pressure that caused the maximum settlement to increase from 33.39 mm to 86.43 mm and the inflection point to continuously increase from 11.18 m to 16.67 m. The volume loss obtained only due to excavation was 1.19% and the combined effect of excavation and groundwater depression caused up to 3.38% volume loss. Fig. 11(c) shows the settlement troughs based on the combined effect of 2.0% volume loss and groundwater depression resulting in an increase in the magnitude of reduced pore pressure that caused the maximum settlement to increase from 81.6 mm to 134.64 mm and the inflection point to continuously increase from 10.50 m to 13.08 m. The volume loss obtained only due to excavation was 1.99% and the combined effect of excavation and groundwater depression caused up to 4.37% volume loss.

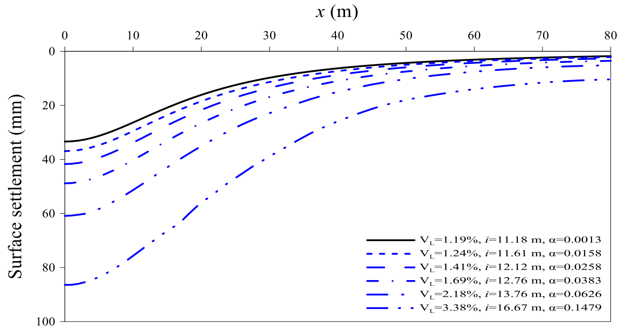
The variation of sum of pore pressure with depth along the tunnel centerline was used to express the quantitative relationships between inflection points and pore pressure.

Table 3 Parameters used for combined cases in application of superposition method

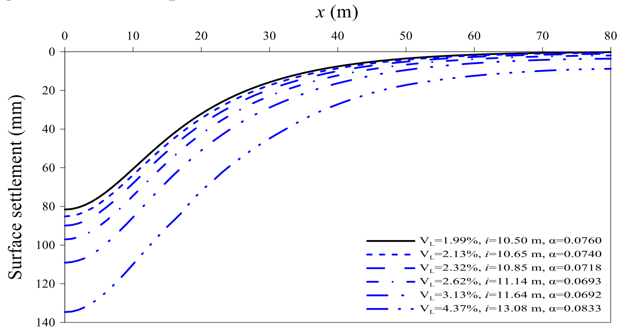
Combined case no.	C/D ratio	Groundwater level	Volume loss (%)	$\Sigma\Delta p$ (kPa)				
1	1.73	Surface (25m)	0.5	362.8	615.6	926.4	1365.4	2130.2
2			1.0	362.8	615.6	926.4	1365.4	2130.2
3			2.0	362.8	615.6	926.4	1365.4	2130.2



(a) Effect of increase in 0.5% volume loss due to groundwater depression



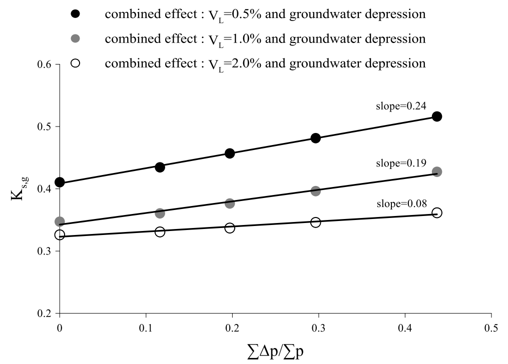
(b) Effect of increase in 1.0% volume loss due to groundwater depression



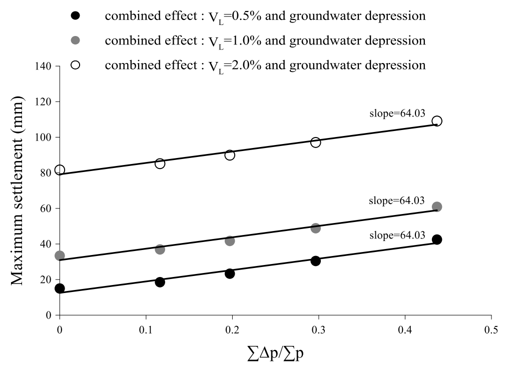
(c) Effect of increase in 2.0% volume loss due to groundwater depression

Fig. 11 Surface of increase due to combined effect of excavation and groundwater depression (*C*/*D*=1.73)

The relationship between $K_{s,g}$ and $\Sigma\Delta p/\Sigma p$ was found out to be linear, as shown in the Fig. 12 (a), making it possible in suggesting Eqs. (16), (17), and (18) based on the sum of K_s and a parameter related to groundwater condition. The maximum settlement was also found out to be increasing continuously without being affected by the volume loss, as shown in Fig. 12(b). Although the inflection point did not



(a) $K_{s,g}$ values at varying reduced pore pressure



(b) Maximum settlement at varying reduced pore pressure

Fig. 12 Linear relationships between $\Sigma\Delta p/\Sigma p$ and parameters related to the trough (C/D=1.73)

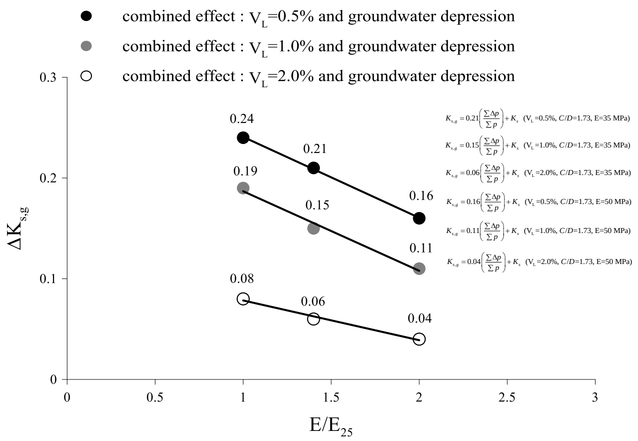


Fig. 13 Relationships between slope of $K_{s,g}$ and E/E_{25} at C/D=1.73

increase considerably at 2.0% volume loss but the continuous increase in maximum settlement caused the total volume loss to reach up to 4.37%.

$$K_{s,g} = 0.24\left(\frac{\sum \Delta p}{\sum p}\right) + K_s \quad (\mathrm{V_L}=0.5\%) \tag{16}$$

$$K_{s,g} = 0.19\left(\frac{\sum \Delta p}{\sum p}\right) + K_s \quad (\mathrm{V_L}=1.0\%) \tag{17}$$

$$K_{s,g} = 0.08\left(\frac{\sum \Delta p}{\sum p}\right) + K_s \quad (\mathrm{V_L}=2.0\%) \tag{18}$$

where $K_{s,g}$ is the trough width parameter at surface due to combined effect of excavation and groundwater depression, $S_{max,g}$ is increased maximum settlement considering groundwater depression.

The elastic settlement due to groundwater depression largely depends on the ground conditions specially elastic modulus. The initially used value of elastic modulus (25 MPa) was increased by 1.4 and 2.0 times resulting in three elastic modulus cases; 25 MPa, 35 MPa, and 50 MPa in C/D=1.73 condition. The slopes of $K_{s,g}$ show a linearly decreasing trend with an increase in ratio E/E_{25}, as shown in Fig. 13. In case of C/D=1.73 condition, although the slope of $K_{s,g}$ at $\mathrm{V_L}$=0.5% decreased up to a maximum of 0.16, but when 50% decrease in pore pressure was considered, the increase in inflection point was obtained as 2.58 m as compared to that in case of considering excavation only. The relationships between $K_{s,g}$ and $\Sigma\Delta p/\Sigma p$ according to the elastic modulus are also given in Fig. 13.

6. Conclusions

• The settlement troughs due to groundwater depression match well with the existing curves. However, the cases where large groundwater depression is considered, smaller values of the coefficient of determination (R^2) were achieved due to the elastic settlement at a distance farther from the tunnel centerline. Therefore, an additional parameter was suggested in the modified Gaussian curve (Vorster *et al*. 2005). Using the new suggested curve, high R^2 values of settlement trough due to groundwater depression can be obtained as well as the existing concept of inflection point can also be maintained considering the effect of groundwater depression.

• It is difficult to obtain the trend of inflection point due to the individual effect of groundwater depression, whereas, the combined inflection point ($i_{s,g}$) shows linearly increasing trend according to the groundwater depression. This trend remains same even when various settlement troughs due to excavation according to different values of volume loss are applied. The linear empirical relationships between trough parameters ($K_{s,g}$ and $S_{max,g}$) and the ratio of summations of reduced pore pressure to total pore pressure with respect to depth were also suggested. The effects of elastic modulus of ground on the suggested empirical relationships were analyzed and additional equations were proposed.

Acknowledgements

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References

Alec, M.M. (2009), "Tunnelling in sand and its effect on pipelines and piles", Ph.D. Dissertation, University of Cambridge, Cambridge, U.K.

Broere, W. (2016), "Urban underground space: Solving the problems of today's cities", *Tunn. Undergr. Sp. Technol.*, **55**, 245-248.

Celestino, T.B., Gomes, R.A.M.P., and Bortolucci, A.A. (2000), "Errors in ground distortions due to settlement trough adjustment", *Tunn. Undergr. Sp. Technol.*, **15**(1), 97-100.

Clough, G.W. and Schmidt, B. (1981), *Design and Performance of Rxcavations and Tunnels in Soft Clay*.

Ding, Z., Wei, X.J. and Wei, G. (2017), "Prediction methods on tunnel-excavation induced surface settlement around adjacent building", *Geomech. Eng.*, **12**(2), 185-195.

Godard, J. (2008), "Should we/can we avoid underground urban mass transit systems?", *Proceedings of the ITA-AITES World Tunnel Congress 2008*, Agra, India, September.

Hung, C.J., Monsees, J., Munfah, N. and Wisniewski, J. (2009), *Technical Manual for Design and Construction of Road Tunnels-Civil Elements,* US Department of Transportation, Federal Highway Administration, National Highway Institute, New York, U.S.A.

Jacobsz, S.W., Standing, J.R., Mair, R.J., Hagiwara, T. and Sugiyama, T. (2004), "Centrifuge modelling of tunnelling near driven piles", *Soil. Found.*, **44**(1), 49-56.

O'Reilly, M.P. and New, B.M. (1982), "Settlements above tunnels in the United Kingdom-their magnitude and prediction", *Tunnelling' 82*, London, December.

Peck, R.B. (1969), "Deep excavations and tunnelling in soft ground", *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City, Mexico, August.

Shen, S.L., Wu, H.N., Cui, Y.J. and Yin, Z.Y. (2014), "Long-term settlement behavior of metro tunnels in the soft deposits of Shanghai", *Tunn. Undergr. Sp. Technol.*, **40**, 309-323.

Suwansawat, S. and Einstein, H.H. (2007), "Describing settlement troughs over twin tunnels using superposition technique", *J. Geotech. Geoenviron. Eng.*, **133**(4), 445-468.

U.N. (2007), *World Population Prospects: The 2007 Revision*, Technical Report, Department of Economic and Social Affairs, Population Division, United Nations.

U.N. (2013), *World Population Prospects: The 2012 Revision*, Technical Report ESA/P/WP.228, Department of Economic and Social Affairs, Population Division, United Nations.

Vorster, T.E., Klar, A., Soga, K. and Mair, R.J. (2005), "Estimating the effects of tunneling on existing pipelines", *J. Geotech. Geoenviron. Eng.*, **131**(11), 1399-1410.

Zheng, G., Du, Y., Cheng, X., Diao, Y., Deng, X. and Wang, F. (2017), "Characteristics and prediction methods for tunnel deformations induced by excavations", *Geomech. Eng.*, **12**(3), 361-397.

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