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Effect of Overburden Pressure and Soil Parameters on Tunnel Induced Ground Settlement

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Abstract. With continuous improvement of urban transportation systems, the requirement of tunnel has increased day by day due to the scarcity of surface space and restricted movements. Mechanized excavation by Tunnel Boring Machine is being extensively used in metro, railway and road tunnels due to comparatively less hazards and relatively faster excavation speed. Therefore, it is essential to have an innovative, cost-effective and safe design of tunnel with appropriate consideration of design methodology and site constraints like existing buildings and other structures. In the design of tunnel, it is very important to have a proper estimation of ground settlement which is induced due to tunneling. The variation in ground settlement due to varying characteristics of subsurface deposits and tunnel depth, which cause variation of overburden pressure, needs to be addressed properly for tunnel design. Therefore, with this in view, a parametric study has been made for a 6.3m diameter circular tunnel structure having different depths of 9.7m, 10.6m, 12.8m and 13.6m, encountering varying soil layers of clayey silt, sandy silt and silty sand. A set of numerical models have been developed to compare the results obtained from analytical method as well as field data recorded at project site. The results of the study reveal that ground settlement gradually decreases with increase of overburden pressure, and thereby, depth of tunnel. It is observed that about 9–29% reduction in ground settlement value occurs, when overburden pressure as well as depth of tunnel increases by 10-41%. Also, with change of soil layer from silty sand to clayey silt, the ground settlement reduces significantly from 14% to 25%, even when the depth of tunnel remains the same. The findings of the present study may be helpful to the researchers and practicing engineers in the design of tunnels under different subsoil conditions.

Keywords: Ground Settlement, Soil Parameters, Tunnel Depth, Overburden.

1 Introduction

The underground tunneling is gaining popularity day by day in improving the surface space congestion problem of urban transportation network. Every developing city is planning to construct underground structures, tunnels for metros, subways and other utilities. The construction of underground tunnel usually leads some disturbance on surface of soil, particularly settlement. Surface settlements due to underground tunneling are generally caused by stress relief and subsiding caused by support movement during excavation. Therefore, underground tunnel design requires a proper estimation of ground settlement for safe and economically efficient construction of underground tunnel structure. The purpose of the present study is to review the current approaches of evaluating, measuring and preventing of surface settlement as well as to develop a correlation between tunnel induced ground settlement with overburden pressure and soil parameters. However, it is not to be denied that every project has its own uniqueness and it should be evaluated on a case-by-case basis by experts, as well as available literature.

A cost-effective and safe design of tunnel structure should be in such a way that its impact on the adjacent structures should be as minimum as possible during construction and service. The main objective of calculating settlement by predictive methods is to propose a reasonable estimate of ground settlement. Peck and Schmidt (1969) assumed a geometric form of settlement profile, specifically the shape of settlement trough above tunnel which is represented by normal distribution curve (error function curve) [1]. This concept is well accepted as the very basic form of surface settlement profile. Settlement trough above tunnel could be estimated by error function curve shown in Figure.1.

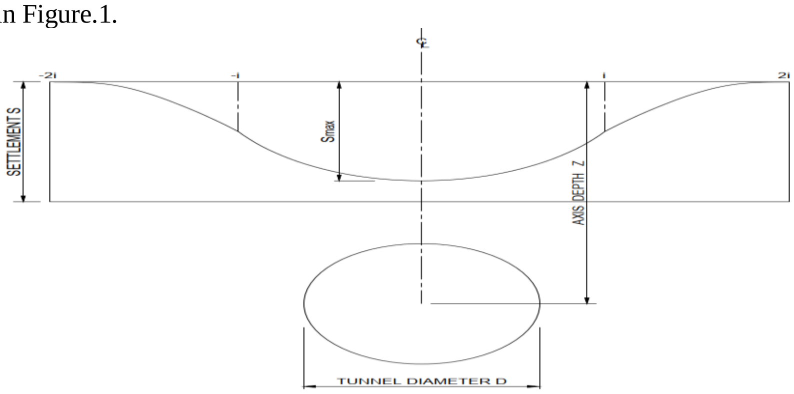

Fig. 1. Normal distribution curve (error function curve) to represent the cross-section of settlement trough.

A more generalized form of normal distribution curve (error function curve) in three-dimensional space was derived by Attewell and Woodman (1982). However, New and Reilly (1991) discovered that the flexibility of Finite Element model assists to understand the movements in much better way. Ground movement and ground settlement depend on several factors which include (i) geological and geotechnical conditions, (ii) tunnel depth and size, (iii) excavation methodology and (iv) the quality of work. It is known that a shallow-depth tunnel tends to have relatively greater effect on ground than the deeper one [2]. The ground settlement varies with the variation of subsurface deposits and various depths of tunnel. Present paper covers a parametric study on 6.3m outer diameter typical circular tunnel structure having different depths of 9.7m, 10.6m, 12.8m and 13.6m, encountering varying soil layers of clayey silt, sandy silt and silty sand. With different tunnel depths, the effects of various overburden pressures and difference in soil parameters on ground settlement has been logged to develop a correlation between ground settlement with tunnel depth and soil parameter. Also, a set of numerical models in Finite Element Method (FEM) have been developed to compare the results obtained from analytical method as well as field data recorded at project site.

2 Methodology

2.1 An overview

Present paper discusses different approaches in predicting surface settlement associated with tunnel construction. In addition, this paper deals with different analytical methods, empirical and numerical method to analyse the problem of tunnel induced ground settlement. From various literatures, it has been observed that patterns of a settlement can be drawn with the help of different approaches mentioned below:
A. Analytical solution which includes: i) Elasticity solution and ii) Sagaseta's solution
B. Empirical solutions and
C. Numerical solutions.

A. Analytical Solutions. Analytical solution exists for a point-load acting below the surface of an elastic half-plane (Poulos and Davis, 1974). The strains and stresses due to the withdrawal of material inside a cavity is estimated with the stresses at infinity [3].
Elasticity Solution . Chow (1994) used elasticity solution to estimate settlement on shallow tunneling where the effect of tunnel face is ignored, and tunnel is assumed to have infinite length. The surface settlement of tunnel, S is calculated as settlement relative to a distance point on surface (Augard, 1997):

$$S = (\gamma D^2 z^2) / \{8G(x^2 + z^2)\} \qquad (1)$$

where, D is tunnel's diameter, γ is soil's unit weight, G is shear modulus of soil, x is horizontal distance from the center of tunnel, and z is the depth measured from center of tunnel. Elastic solution is also relevant for hard rock conditions.

Sagaseta's Method . Sagaseta (1987) suggested a method to eliminate stresses from the equations and to work in the terms of strain where the boundary condition is only in the term of displacement.

B. Empirical Solutions . The empirical solutions have been performed by several authors, such as Attewell and Woodman (1982), New and O'Reilly (1982, 1991), etc. to predict the ground settlement induced by bored tunnels for "green-field" site conditions. Peck (1969) described ground settlement based on data from more than twenty case histories.

In general practice, empirical solutions are most commonly used. These solutions are in many cases combined with analytical solutions or finite element computations, later calibrated with data from different case histories.

C. Numerical Solutions. Numerical solutions, mainly the finite element method (FEM), offer a flexible tool for predicting surface settlement. Finite element method could be performed in both two-dimensional plane (2D) and three-dimensional space (3D). New and Reilly (1991) estimated that the flexibility of FE models can assist understanding the movements of the particular site by extending conventional design methods [1]. In short, the numerical solution (like FEM) is being used as a more reliable and powerful tool in computer technology. Numerical methods are not only applied for predicting ground settlement but for the entire design procedure of tunnel, including excavation sequence, soil - tunnel lining interaction, consolidation etc.

2.2 Mathematical background

The net volume of ground settlement trough is approximately equivalent to the volume loss (V_L) of tunnel in the most of ground conditions. Volume loss (V_L) is generally expressed as a percentage (V_L%) of gross area of a finished tunnel. The magnitude of volume loss V_L is estimated based on case history data, site conditions and engineering appraisals. In shield and EPB TBM tunneling method, V_L generally lies in between 1% - 2% in cohesive soil and 0.5% - 1% in non-cohesive soil. The maximum surface settlement over axis of tunnel S_{max} is expressed as:

$$S_{max} = 0.313\, V_L(\%)\, D^2 / i \qquad (2)$$

As per normal distribution curve (error function curve), theoretical surface settlement is express as:

$$S = S_{max} \exp(- x^2 / 2i^2) \qquad (3)$$

Where D is the equivalent excavation diameter of tunnel, x is transverse distance from tunnel centre, and i is the width of the settlement trough which is the distance to the inflection point of the curve. Further, i can be calculated as function of KZ_0, where Z_0 is tunnel axis depth and K is dimensional constant which depends on soil type. Referring from various literature and study, K value for loose to medium silty fine sand is generally considered as 0.3. K value of 0.35, and 0.4 are generally considered for medium to dense silty sand and very stiff sandy clayey silt respectively.

2.3 Numerical analysis and computational method

A series of parametric studies for different ground conditions along with different depth of tunnel are carried out by developing the numerical model (FEM) compared to empirical/analytical solutions. The geotechnical software Phase2 (version: 8.009) and MIDAS GTX NX have been adopted which use finite element method to calculate deformations and stresses. For all analyses, two-dimensional models have been applied using the Mohr-Coulomb criteria for ground and the elasticity theory for materials.

3 Model of the study

A typical 6.3m diameter circular tunnel section of Delhi Metro Rail Corporation (DMRC) Dwarka-Najafgarh corridor has been considered for this study and analysis. The present section of tunnel is located at Najafgarh area which has been constructed in DMRC Phase-III work. The double tube running tunnel has been excavated and supported by an Earth Pressure Balanced Tunnel Boring Machine (EPB-TBM). Ground conditions can be characterised according to one main stretch along the alignment, which coincides with the tunnel stretch within project area. Geotechnical parameters which has been considered for present study are presented in Table-1. Model view of geotechnical profile from geotechnical software Phase2 (version: 8.009), tunnel cross section along with tunnel depth of 9.7m is shown in Figure.2.

Table 1. Depth wise Geotechnical parameters for tunnel stretch within project area

Soil Type	Depth m	SPT Value (Avg.)	C’ (Avg.) kPa	Φ’ (Avg.) deg	Y (Avg.) kN/m3	E’ (Avg.) kPa	ν’ (Avg.)
Filling Material	0 – 1.5	10	-	26	18.0	10500	0.3
Loose to Medium silty sand	1.5 – 7.5	15	-	28	19.0	21500	0.3
Medium to dense silty sand	7.5 – 10	36	-	30	19.0	36000	0.3
Very Stiff Sandy clayey Silt	10 – 21	48	12	33	19.0	33600	0.3
Very Dense Silty Sand	21 – 30	50	-	35	20.0	50000	0.3

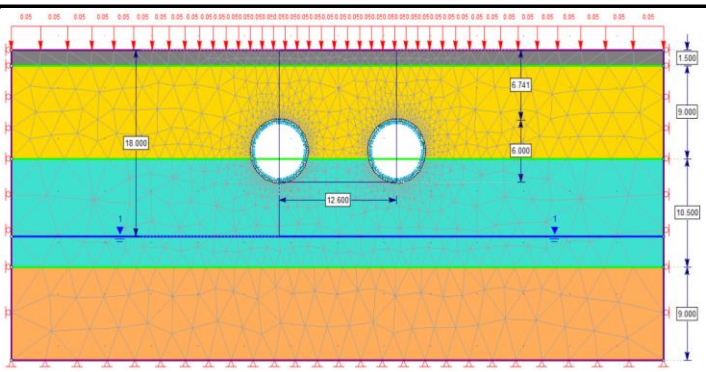

Fig. 2. Model view of geotechnical profile, tunnel cross section along with tunnel depth of 9.7m.

Tunnel depth of project area is not uniform, it varies from 9.7m to 13.6m depth below ground at different length-section of the project. Therefore, surface settlement would vary due to change in tunnel depth as well as change in ground condition. An analytical method (elasticity solution) and empirical method have been proposed for estimating ground settlement at a depth of 9.7m, 10.6m, 12.8m and 13.6m. A two-dimensional numerical model (FEM) has been further developed with geotechnical software Phase2 for predicting ground settlement for tunnel depth of 9.7m.

4 Presentation of Results

Surface settlement predicted by analytical method / elasticity solution with Eq. (1) for tunnel depth of 9.7m, 10.6m, 12.8m and 13.6m are shown in Figure.3. Surface settlement predicted by empirical method with Eq. (2) and Eq. (3) for tunnel depth of 9.7m, 10.6m, 12.8m and 13.6m are shown in Figure.4. Ground Settlement from geotechnical software Phase2 (version: 8.009) for tunnel depth of 9.7m is shown in Figure.5.

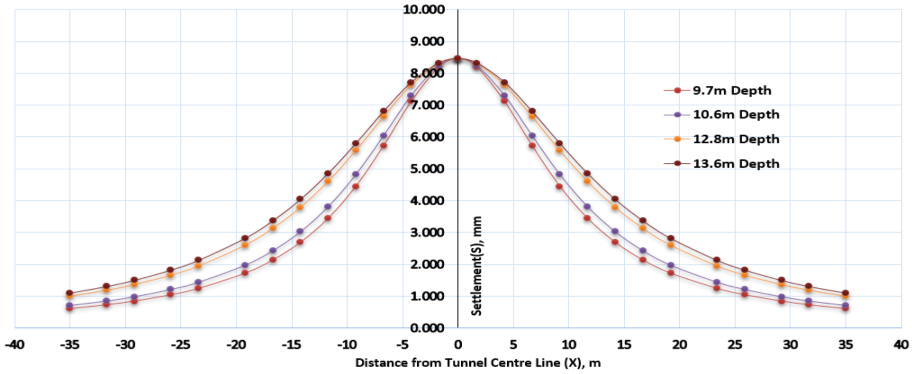

Fig. 3. Comparison of surface settlement predicted by analytical method (elasticity solution) for different tunnel depth.

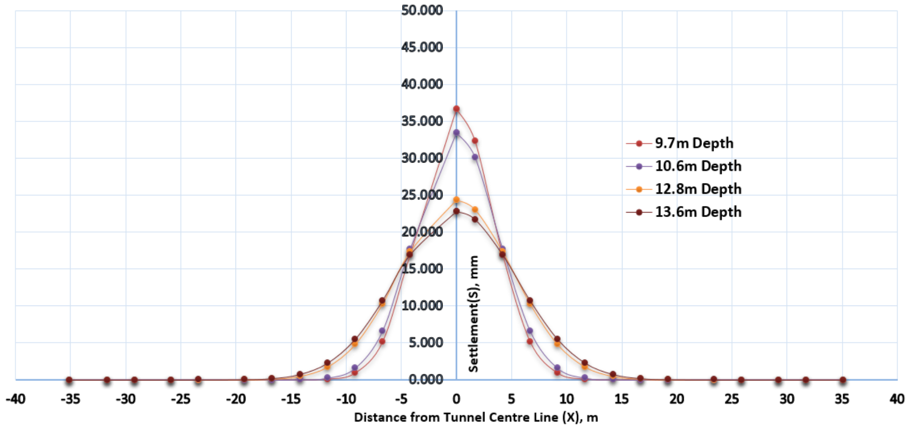

Fig.4. Comparison of surface settlement predicted by empirical method for different tunnel depth.

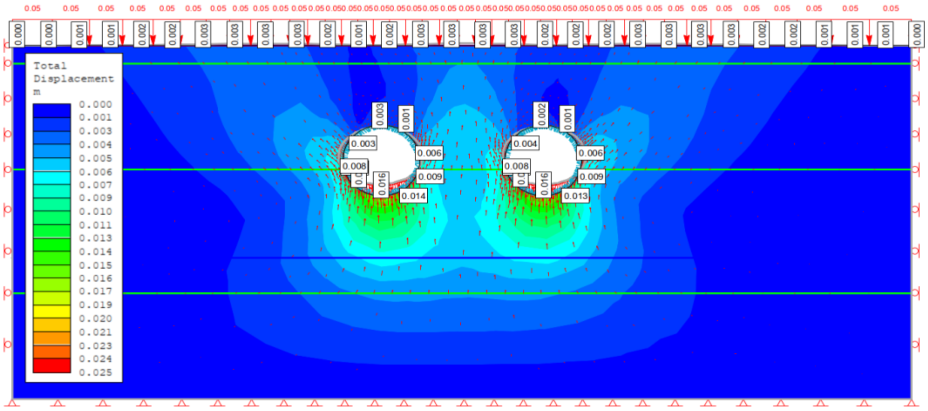

Fig. 5. Ground Settlement from numerical model (FEM) for tunnel depth of 9.7m.

The ground settlement results obtained from predictive method has been further cross checked with realistic ground settlement data recorded at project site at Dwarka-Najafgarh corridor. Similarity in settlement behavior has been observed between results from predictive settlement method with realistic ground settlement data recorded at project site. Ground settlement at project site during execution and post construction have been recorded and monitored by ground settlement marker. Ground settlement data recorded at project site for the similar location with similar depth of tunnel (9.7m from ground) is shown in Figure.6.

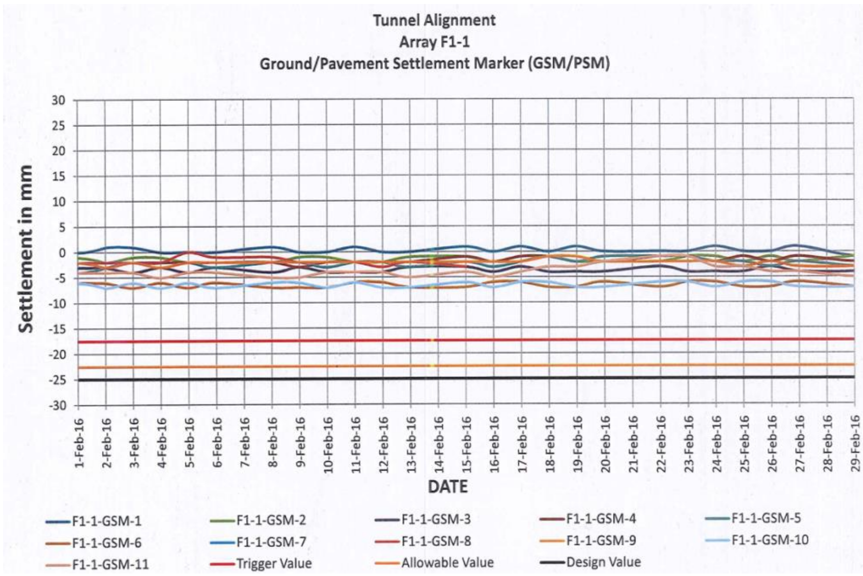

Fig. 6. Ground settlement data recorded at project site.

The present parametric study was initially conceptualized by comparing the ground settlement values obtained from different predictive methods along with realistic data recorded at project site for similar depth of tunnel on similar ground condition. This study has been further elaborated for different tunnel depths (9.7m, 10.6m, 12.8m and 13.6m) with varying soil parameter mostly from loose silty fine sand to medium dense silty sand and very stiff sandy clayey silt at different stretch of tunnel alignment of the study area at Najafgarh, Delhi. The entire investigation part of parametric study has been conducted in 12 different cases for 4 different tunnel depths (9.7m, 10.6m, 12.8m and 13.6m) with 3 different ground conditions (loose to medium silty fine sand, medium to dense silty sand and very stiff sandy clayey silt). In the present investigation, along with conventional analytical and empirical method, a set of numerical models has been further developed by FEM to identify non-linear behavior of tunnel depth, surrounding soil with ground settlement. Ground settlement value obtained from empirical method for 12 different situations of 4 different tunnel depths with 3 different ground conditions have tabulated in the Table-2.

Table 2. Surface Settlement above tunnel for different depth of tunnel at different ground conditions.

Depth of Tunnel from Ground	Surface Settlement above tunnel at different ground conditions, mm		
	loose to medium silty fine sand	medium to dense silty sand	very stiff sandy clayey silt
9.7m	42.83	36.71	32.12
10.6m	39.00	33.43	29.25
12.8m	32.47	27.83	24.35
13.6m	30.38	26.04	22.78

5 Discussions on Results

Based on analyses done in the present study an attempt has been made in this section to address the variation of ground settlement with varying ground conditions and tunnel depths and also results obtained from different methods have been compared.

5.1 Surface Settlement for different tunnel depths with same ground condition

Ground settlement for 4 different tunnel depths (9.7m, 10.6m, 12.8m and 13.6m) have been plotted for 3 different ground conditions (loose to medium silty fine sand, medium to dense silty sand and very stiff sandy clayey silt). Ground settlement for 4 different tunnel depths with ground condition of *loose to medium silty fine sand* is shown in Figure.7, *medium to dense silty sand* is shown in Figure.8, and *very stiff sandy clayey silt* is shown in Figure.9.

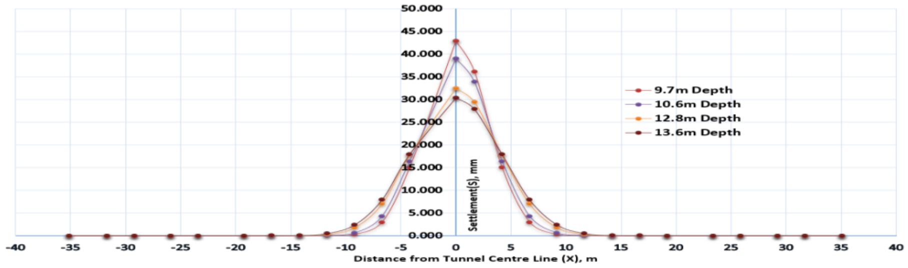

Fig. 7. Comparison of Ground settlement for different tunnel depths at loose to medium silty fine sand.

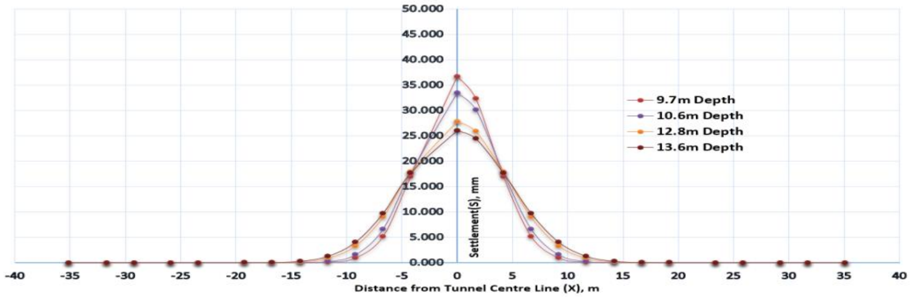

Fig. 8. Comparison of Ground settlement for different tunnel depths at medium to dense silty sand.

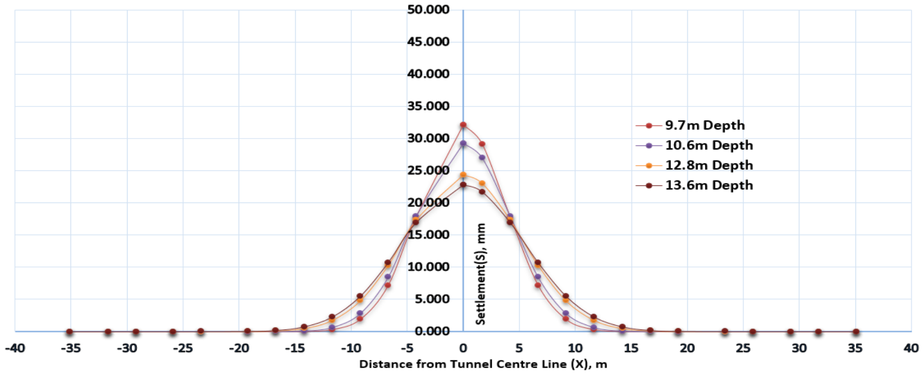

Fig 9. Comparison of Ground settlement for different tunnel depths at very stiff sandy clayey silt.

The results from above shown figures, it is clear that ground settlement gradually decreases with increase in overburden pressure, and thereby, depth of tunnel. It is observed from above shown figure that ground settlement value decreases by 9%, 24% and 29% when overburden pressure as well as depth of tunnel increases by 10%, 32% and 41% respectively, even when ground condition remains the same.

5.2 Surface Settlement for same tunnel depth with different ground conditions

Ground settlement for 3 different ground conditions (loose to medium silty fine sand, medium to dense silty sand and very stiff sandy clayey silt) have been further plotted for 4 different tunnel depths (9.7m, 10.6m, 12.8m and 13.6m). Ground settlements with 3 different ground conditions for 9.7m tunnel depth is shown in Figure.10, 10.6m tunnel depth in Figure.11, 12.8m tunnel depth in Figure.12 and 13.6m tunnel depth in Figure.13. Apart from above empirical/analytical method, a set of numerical models (FEM) analysis has been further performed for 9.7m tunnel depth with 2 different ground conditions i.e. silty fine sand and sandy clayey silt.

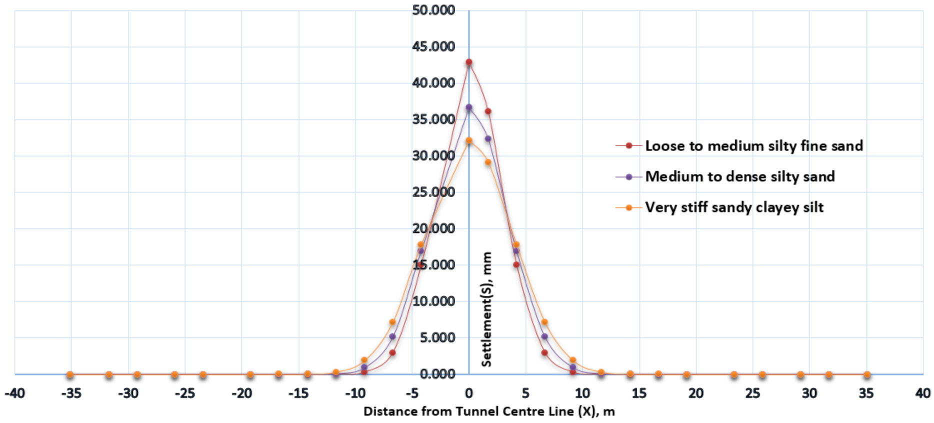

Fig.10. Comparison of Ground settlement for 9.7m tunnel depth at 3 different ground condtions.

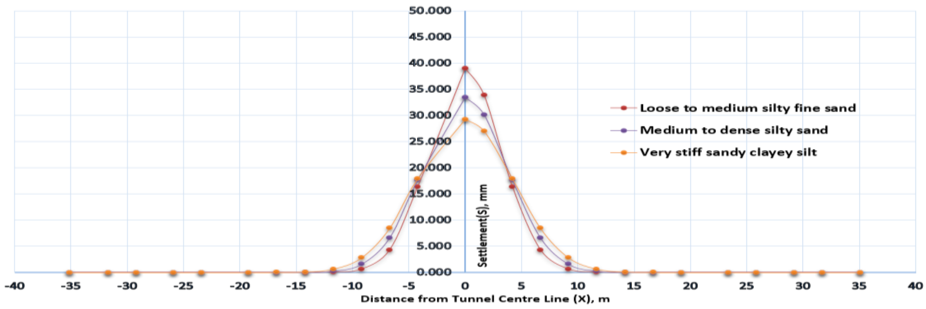

Fig. 11. Comparison of Ground settlement for 10.6m tunnel depth at 3 different ground conditions.

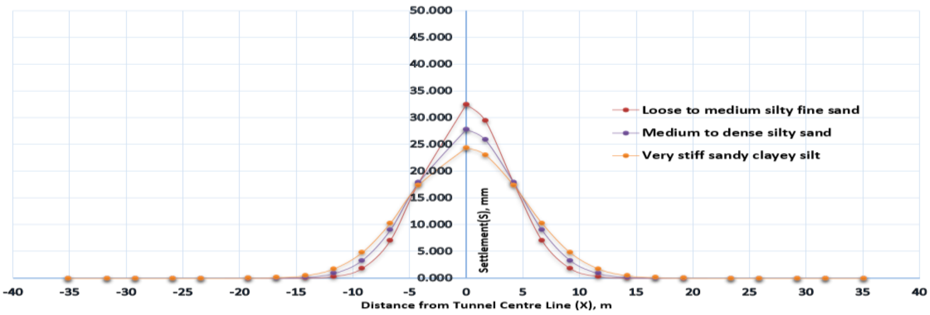

Fig .12. Comparison of Ground settlement for 12.8m tunnel depth at 3 different ground conditions.

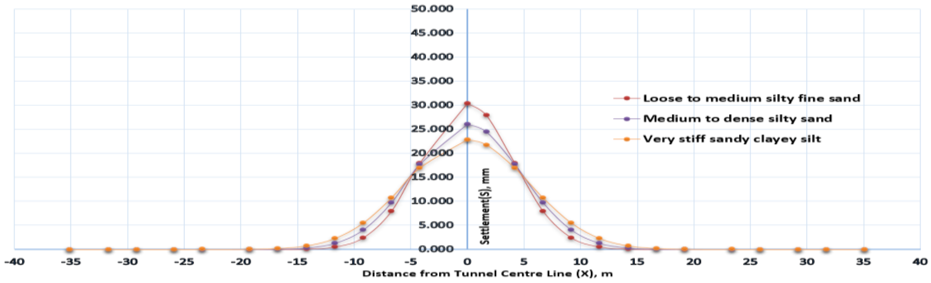

Fig. 13: Comparison of Ground settlement for 13.6m tunnel depth at 3 different ground conditions.

The results from above shown figures, it is clear that ground settlement gradually decreases with change of soil layer from silty sand to clayey silt. It is observed that ground settlement value decreases by 14% when ground condition is changed from the state of loose to medium silty fine sand to the state of medium to dense silty sand even at same depth of tunnel. Ground settlement value decreases by 25% when ground condition is changed from the state of medium to dense silty sand to the state of very stiff sandy clayey silt, even when ground condition remains the same.

Comparison of Ground settlement obtained from MIDAS GTX NX for 9.7m tunnel depth at ground conditions of silty fine sand and sandy clayey silt is shown in Figure.14.

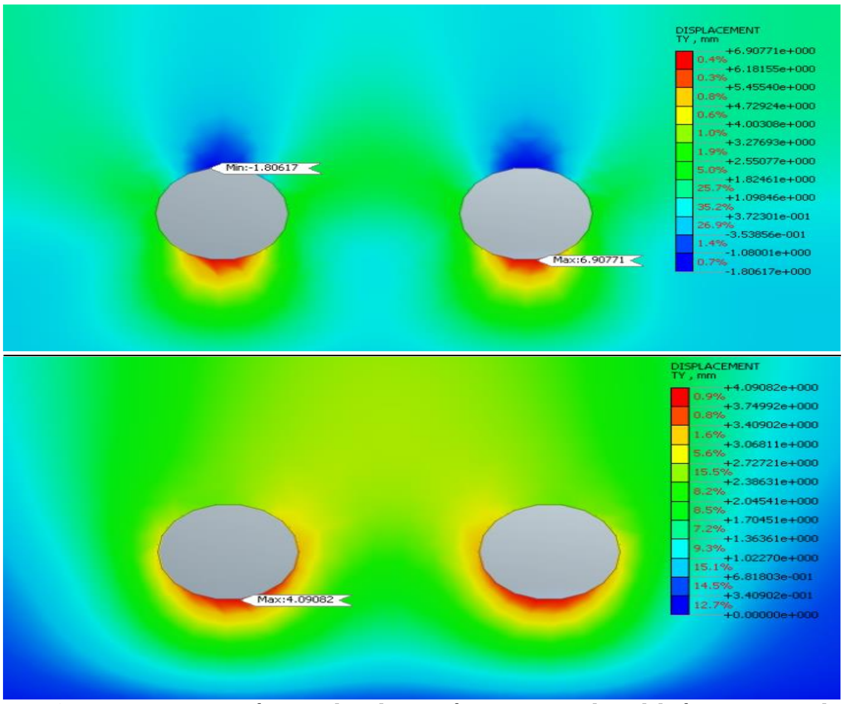

Fig.14. Comparison of Ground settlement from numerical models for 9.7m tunnel depth at ground conditions of silty fine sand (top) and sandy clayey silt (bottom).

From above shown figure of numerical model is clear that surface settlement value decreases when ground condition is changed from silty sand to the sandy clayey silt, even when ground condition remains the same.

5.3 Comparison of different methods

After comparing ground settlement results from different predictive methods i.e. analytical method (ref: figure-3), empirical method (ref: figure-4) and FEM method (ref: figure-5) with actual settlement data recorded at project site (ref: figure-6), it is clear that surface settlement obtained from numerical models (FEM) gives more reliable results among all predictive method for obtaining surface settlement.

6 Conclusions

In the present study, the behaviour of surface settlement above a tunnel placed on varying soil parameters at different depth have been studied by using analytical/empirical method and FE-based computer program. A series of parametric studies have been further carried out to find out the interaction between soil and tunnel as well as to develop a relationship between tunnel induced surface settlement with overburden pressure and soil parameters. The conclusions drawn from the current study and analysis are as follows:

1. Ground settlement results obtained from numerical models (FEM) is very close to actual ground settlement data recorded at project site. Hence, it can be concluded that numerical models (FEM) gives more reliable results among all others predictive methods for obtaining surface settlement. Analytical and empirical methods are suitable for preliminary estimations or assumptions.
2. The ground settlement varies with the variation of subsurface deposits and various depths of tunnel. A shallow depth tunnel tends to have relatively greater effect on ground than the deeper one. Ground settlement decreases with change of soil layer from silty sand to clayey silt.
3. Ground settlement gradually decreases with increase in overburden pressure i.e. depth of tunnel. Ground settlement value reduces by 9-29% when overburden pressure as well as depth of tunnel increase by 10-41% even with same ground condition. Ground settlement value decreases by 9%, 24% and 29% when overburden pressure as well as depth of tunnel increase by 10%, 32% and 41% respectively, even when ground conditions remain the same.
4. With change of ground conditions from silty sand to clayey silt, the ground settlement reduces significantly by 14% to 25%, even when depth of tunnel remains the same. When ground conditions are changed from the state of loose to medium silty fine sand to the state of medium to dense silty sand, ground settlement value reduces by 14% even at same depth of tunnel. When ground conditions are changed from the state of medium to dense silty sand

to the state of very stiff sandy clayey silt, ground settlement value further reduces by 11%, even when depth of tunnel remains the same.

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References

1. Sven Moller: Tunnel induced settlements and structural forces in linings. 2006 Mitteilung 54 des Instituts fur Geotechnik Herausgeber P.A. Vermeer.
2. Eric Leca, Animateur Barry New, General Reporter: Settlements induced by tunneling in Soft Ground. Tunnelling and Underground Space Technology 22 (2007) 119–149, ITA/AITES Report 2006.
3. Mohammed Y. Fattah, Kais T. Shlash and Nahla M. Salim: Settlement Trough due to Tunneling in Cohesive Ground. Indian Geotechnical Journal, 41(2), 2011, 64-75.
4. Delhi Metro Railway Corporation, Technical Specification: DMRC Out line Design Specification for Underground Structure.
5. Takahiro Aoyagi: Representing Settlement for Soft Ground Tunnelling. Massachusetts institute of Technology, May 2005.
6. Nguyen Duc Toan: TBM and Lining - Essential Interfaces. Politecnico di Torino, Turin, Italy, October 2006.