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Behavioural Study of Braced Excavation Integrated with NATM Tunnel for Metro Station Platform

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ABSTRACT

The limited availability of land necessitates the design and construction of station box using multiple construction techniques such cut & cover and new Austrian tunneling method (NATM). The integrated construction sequence using cut & cover excavation followed by NATM tunnel will have a combined effect on the ground movements and settlements of the nearby structures. This paper emphasizes on the ground response for such integrated excavation and its impact on rock pillar, secant pile walls system and NATM lining. For this study, various soil/rock configuration and rock pillar widths have been modeled using Finite Element Method of analysis (FEM).

Keywords: Earth retaining system (ERS); Cut & cover (C&C); Secant pile; NATM tunnel; Surface settlement; Underground metro; Rock pillar; Finite element method (FEM)

1. INTRODUCTION

In recent times, several metro projects have been undertaken by the government of India. Many underground metros are operating across India; few are under construction and many more are under planning stage. One of the major constraints for any underground metro project is the availability of land for station construction. Stations are planned to attract maximum ridership, provide connections to business district, integrate with existing transportation modes and catalyze future prospect of development. This makes metro alignment to travel through the densely populated areas, having scarcity of open land for station construction. Generally, the existing roads with few land parcels available around are considered for locating the metro stations. This on other hand allows alignment to follow existing roads as far as possible. But, the roads in such a densely populated areas have buildings alongside it. In such case, it is important to plan the metro station within the available land area without disturbing the comfort of nearby residence. The congested city areas do not have sufficient road width to accommodate the entire station box structure. Underground stations under narrow roads requires complex construction sequence involving cut & cover and NATM construction methods. At such locations, the cut & cover box is excavated using earth retaining system. This box structure is then used as an access shaft for the construction of the adjacent platform tunnels using NATM technique.

Behaviour of closely spaced tunnels has been analyzed by several authors in the past. The interaction between ground settlement trough with respect to geometry of tunnels has been studied using numerical modeling (Soliman et al.,1993; Kawata and Ohtsuka, 1993; Perri, 1994; Saitoh et al., 1994; Shahrour and Mroueh, 1997; Yamaguchi et al., 1998; Karakus et al., 2007; Liu et al., 2009). Kim et al. (1998) performed tests using scale models and suggested that the interaction of tunnels is mostly influenced by their geometry. These studies also revealed that increase in rock pillar width (rock-barrier between the twin tunnels) results in reducing the surface settlement, and eventually leads to a more stable ground surface at the location of the tunnel. Chakeri et al. (2010) conducted a similar study on NATM tunnel excavations to investigate the ground behaviour and observed considerable deformation in existing line-4 tunnel as excavation was being done below this tunnel. It was also noticed the effect of different construction sequence on the surface settlement.

This paper focuses on an effect of the width of rock pillar formed between cut & cover excavation and adjacent tunnel on integrated excavation. The effects of rock cover above tunnel crown on ground settlements was also studied. The commercially available finite element analysis program PLAXIS-2D was used in this study.

2. STABILITY ANALYSIS OF EXCAVATION

Cut and cover metro station with platform tunnel generally having cross passage to access the tunnel platform at regular intervals, which makes it a 3-dimensional problem for analysis. Excavation of cross passages between the cut & cover box and platform tunnel shall induce the higher stresses around the opening. However, as access cross-passage is generally planned at a wider distance, it has a localized impact on the rock pillar stability. An interpretation of 2-D analysis is more reliable and quicker 2-D analysis is adopted for the study.

Finite element analysis is used to study the behaviour of combined excavation of cut & cover and tunnel excavations. The model geometry is discretized using mesh of 15-noded triangular elements. Extension of the model i.e., boundary is considered more than twice the depth of excavation to ensure no any influence due to boundary conditions.

Modified horse-shoe shaped tunnel with cross-sectional area of about 90.1m^2 is proposed to accommodate the Schedule of Dimensions (SOD) requirements for systems and platform. The tunnel measures 11.2m in width and 10m in height. A 10m overburden (of soil mixed rock mass) above the tunnel crown is considered in the analysis which is nearly equal to the tunnel equivalent diameter (D) of 10.75m. The overburden on the tunnel crown comprises of soil and completely weathered rock. The extent of completely weathered rock is considered till the tunnel axis. In order to avoid influence of secant piles on a rock pillar, piles are terminated at 1m before the axis of the tunnel and invert of the tunnel lies below the piles. Earth retaining system of secant piles and struts is modelled in order to support the weak and permeable strata during cut & cover box excavation.

Tables 1 and 2 summarize the properties of structural members considered in the analysis along with strength and stiffness parameters for soil and rock. For modelling purposes following considerations have been made:

- For soil and rock, coefficient of the lateral earth pressure (K_o) is considered as 0.5,

- Soil is modelled using Mohr-Coulomb material model,
- Rock mass is modelled using Mohr-Coulomb material model wherein the strength and deformation properties are derived using Hoek and Brown criterion,
- Water table is considered at ground level,
- Secant piles (comprising soft and hard concrete piles) of 1m diameter with 150mm overlap are modelled with 1.7m center to center spacing,
- Piles are terminated in moderately weathered rock, with one-meter socketing, and piles are laterally supported with struts, and
- Rock slopes below the secant pile toe are supported using sprayed concrete lining and rock bolts.

Table 1 - Properties of structural element

Structural elements	Grade	EA (kN/m)	EI (kN-m^2/m)
Sprayed concrete to stabilize rock slope below secant pile toe 100mm thick	M35	2.95x10^6	2465
Sprayed concrete for tunnel lining 200mm thick	M35	5.91x10^6	19720
Secant pile (1m diameter)	M40	14.6x10^6	203500

Table 2 - Ground Parameters

Material type	Unit weight γ_{sat} (kN/m^3)	Cohesion c (kPa)	Friction angle Φ’ (°)	Young’s modulus E (MPa)	Poisson ’s Ratio ν′
Soil	18	1	30	12	0.3
Completely weathered rock	20	35	37	89	0.3
Moderately weathered rock	25	148	55	685	0.2

In NATM, sprayed concrete along with wire-mesh generally forms the primary and immediate support for a tunnel. The weep holes in the sprayed concrete linings do not allow to build a water pressure in the supported rock mass. Therefore, sprayed concrete linings are not subjected to water pressure. As it is shallow tunnel, gravity loading has been considered for analysis. Excavation for tunnel is modeled in Plaxis 2-D as a plane strain condition using convergence confinement method (Panet, 1995). Relaxation of the rock mass due to tunnel excavation and before installation of sprayed concrete lining support is modeled using Eq. 1.

$$P_{fict} = a.p_o \frac{b}{x+b} \qquad \text{(Panet, 1995 and Oreste, 2001)} \qquad (1)$$

where

a = 0.75,
p_o = in-situ stress,
b = 0.845,
x = distance of the support from the face (1.5m round length), and
R = radius of tunnel (6m), and hence $P_{fict} = 0.62\, p_o$.

Thus, internal pressure is equal to 62 % of the lithostatic stress giving 38% ground relaxation with 1.5 meter of round length.

The finite element modeling of platform tunnel excavation is carried out as explained below:

Excavation of the platform tunnel is modelled using the convergence-confinement method, and the initial stress release factor (1-β) considered as 40%. This stress release factor corresponds to the ratio of the stress release before the lining installation. Stress release factor of (1-β) = 70% is considered for the installation of green concrete and (1-β) = 100% considered to activate effect of completed sprayed concrete lining construction.

Following are the stages considered in the modelling:

1. In-situ stage,
2. Installation of secant piles,
3. Lowering of water table inside the cut & cover box 1m below - 1st level of strut,
4. Excavation of soil up to 1m below -1st level of strut,
5. Installation of 1st level strut,
6. Repeat stage 3, 4 and 5 till the last designed strut is installed,
7. Excavation below the toe of piles till the final excavation level reached,
8. Installation of rock bolts and sprayed concrete at the excavated rock face,
9. Excavation of NATM tunnel profile,
10. Installation of primary lining (green concrete) and rock bolt, and
11. Installation of full-strength primary tunnel lining along with wire mesh (hardened concrete).

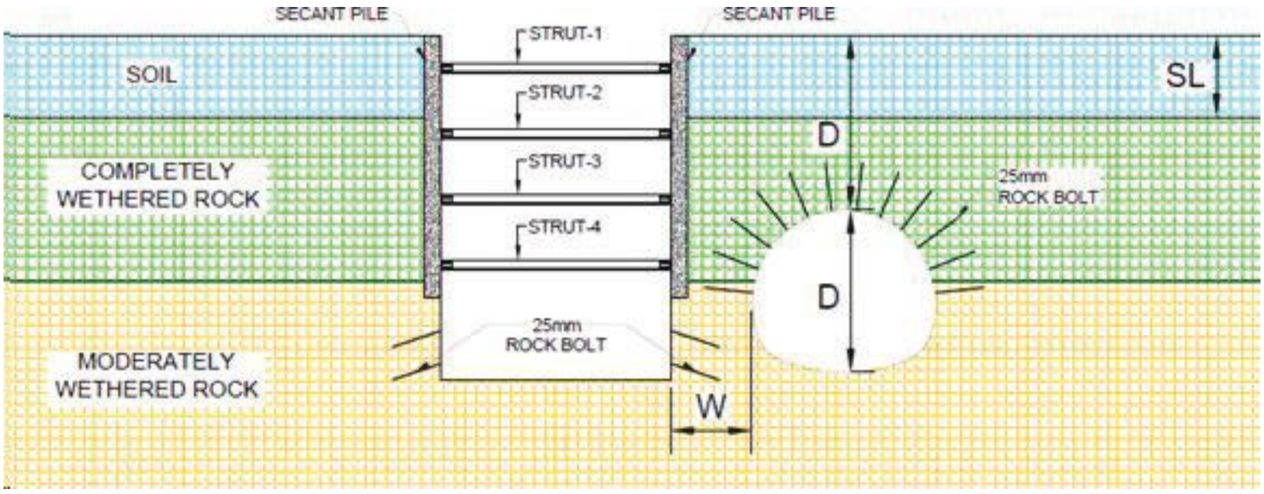

Fig. 1 - Geometry of excavation

3. EVALUATION OF NUMERCAL ANALYSIS

The following two scenarios are analyzed:

- Variation in thickness of overburden soil
- Variation in rock pillar width

3.1 Variation in Thickness of Overburden

The influence of varying geological stratification on the behaviour of rock pillar, tunnel lining and surface settlement is studied. Analyses were performed for 3 different thickness of soil overburden represented in the form of SL/D ratio, where SL and D denote soil depth, and diameter of the tunnel. Values of SL/D considered for analysis are 0.3, 0.5 and 0.7 (Fig. 2). The comparison of analysis results for different SL/D ratios along with its effect on rock pillar displacement, tunnel lining displacement and ground settlements are presented in Figs. 2, 3 and 4 respectively.

Figure 2 shows that maximum rock pillar displacement along x-axis is about 4.2mm for all values of SL/D. Rock pillar displacement has increased by 40% after the tunnel excavation. After tunnel excavation, displacement in rock pillar was observed to be nearly same for all S/D values. It indicates that there was minor effect of stresses due to sufficient width of the pillar and shallow rock cover above the excavated tunnel.

Figure 3 indicates that maximum deformation in the tunnels took place at the crown position i.e., at 0º or 360º for all SL/D values. For SL/D = 0.3, maximum lining deformation of 12.8 mm was observed. Deformations increased by 15% & 40% for the ratios of SL/D = 0.5 and 0.7 respectively.

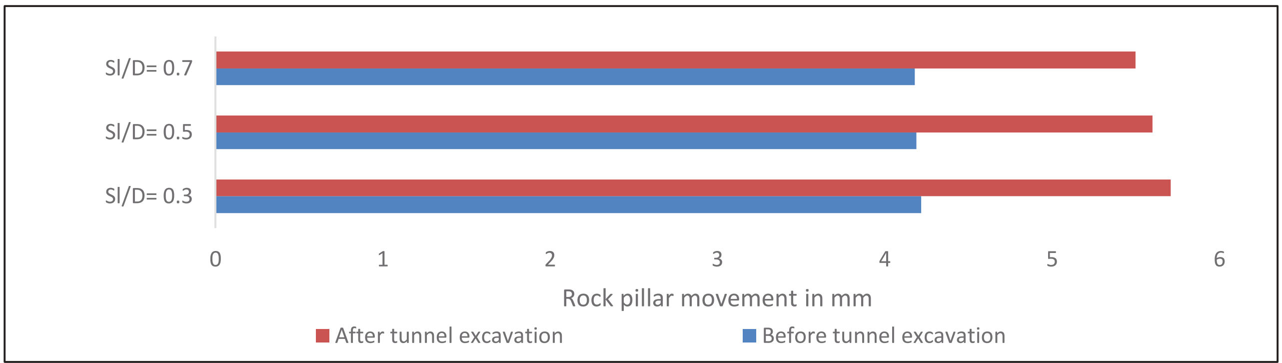

Fig. 2 - Horizontal displacements in rock pillar with varying soil depth

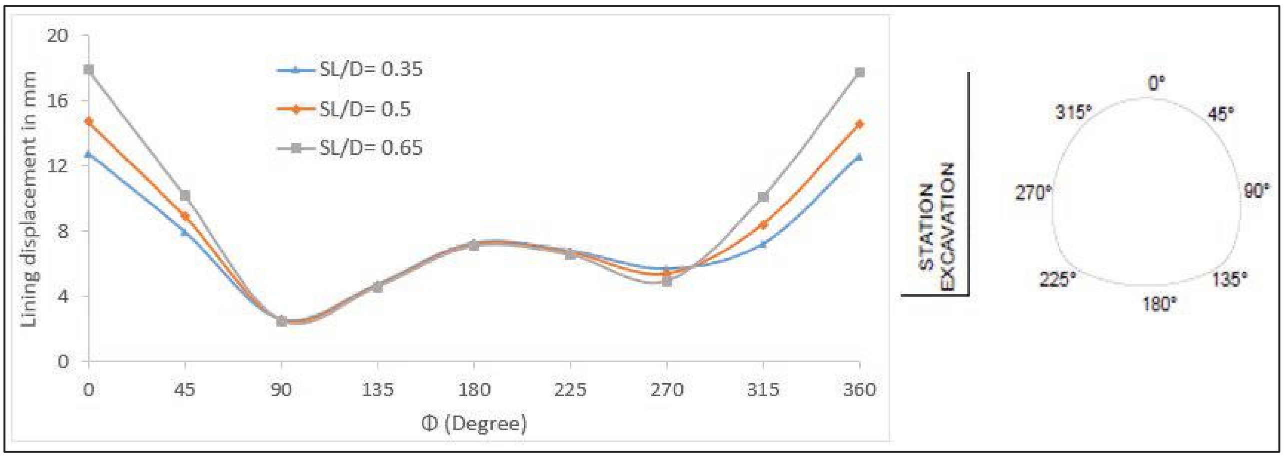

Fig. 3 - Comparison of tunnel lining displacement with varying soil depth

Impact of different SL/D ratios on surface settlement are presented in Fig. 4. For SL/D more than or equal to 0.5, it is observed that ground settlement at the face of the secant pile is significantly higher. As we move away from piles, and towards the tunnel crown effect of different SL/D ratios on ground settlements is lesser. Settlement of ground at the tunnel crown i.e., at a distance of 10m from the face of the pile for SL/D= 0.3 is observed as 15mm. For SL/D ratio of 0.5 and 0.7, ground settlements are increased by 35% and 80% respectively.

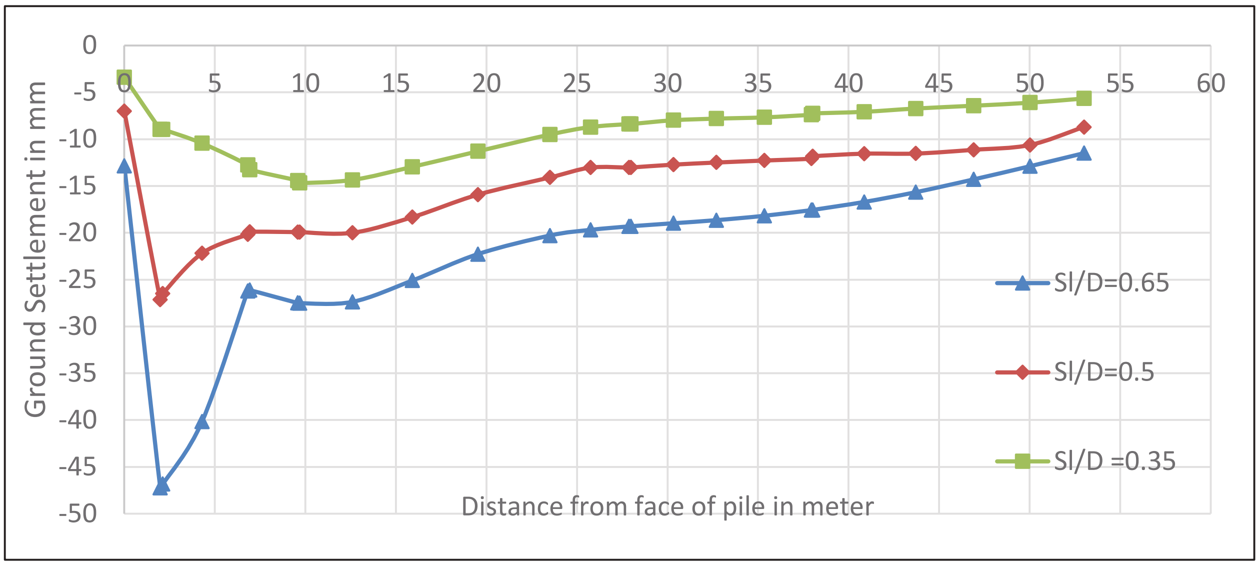

Fig. 4 - Comparison of surface settlement with varying soil depth

3.2 Variation in Rock Pillar Width

The W/D ratio i.e., the width of rock pillar (W) to diameter of the tunnel (D) ratio of 0.35, 0.5, 0.7, 1.0, 1.5, and 2.0 are chosen in this. For various W/D ratios corresponding horizontal movement in rock pillar, total displacement in tunnel lining, secant piles, and ground settlements are studied. The results are presented in Figs. 5 to 9.

From Fig. 5 it is observed that rock pillar horizontally deforms more as the rock pillar width reduces. Maximum rock pillar movement of 2mm was observed between prior to tunnel profile excavation, and immediately after the cut & cover box excavation reached to the final level. For W/D = 0.35 rock pillar movement is increased by 150% reaching 5mm. As the W/D ratio is increasing rock pillar movement is reducing for W/D = 1 slight increase in rock pillar movement is recorded.

The rock pillar deformation starts to increase as the tunnel exaction progresses. For W/D ratio of 0.35, displacement of 5mm was observed. The displacement further reduces to 3.75mm and 2.8mm for W/D= 0.5 and 0.7 respectively.

As the W/D ratio increases the rock displacements reduces. It is further observed that for W/D ratio of 1 change in rock pillar displacement is insignificant.

In Figure 6, comparison of tunnel lining deformation for various W/D ratios is presented. For comparison purposes a base case scenario with tunnel excavation in undisturbed ground is considered. It is observed that tunnel deformations are more in crown, compared to the invert lining.

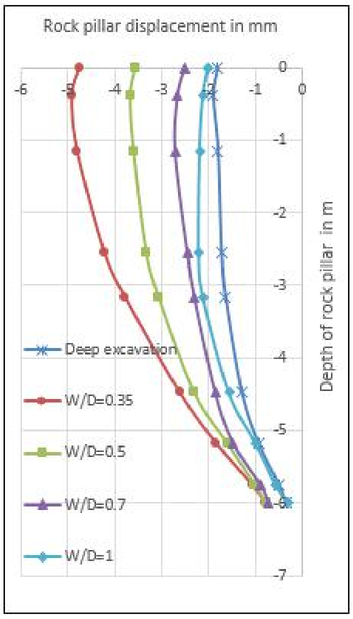

Fig. 5 - Horizontal displacement in rock pillar with a various width of a rock pillar

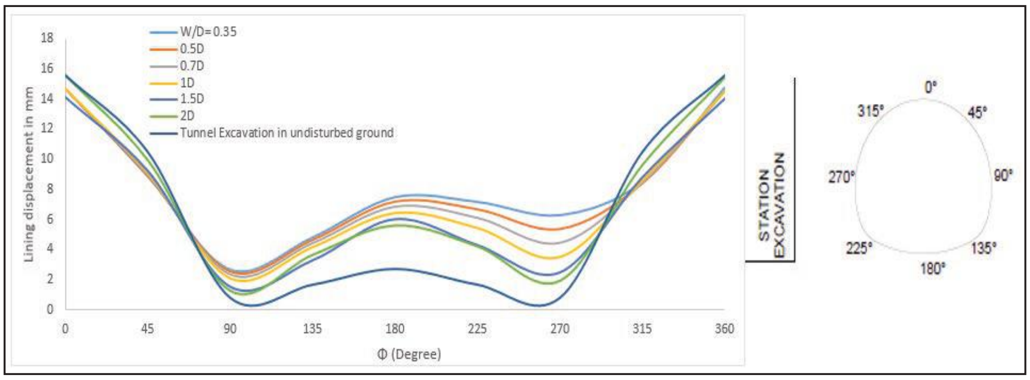

Fig. 6 - Comparison of lining deformation with a various widths of a rock pillar

As the tunnel excavated adjacent to the deep excavation tunnel wall tends to deform into the cut & cover excavation. Higher impact of rock pillar width on the lining deformation at angle of 180- 270˚ is recorded. For the case of W/D = 0.35 lining deformation is reached to the 7.2 mm at 270˚. Whereas as W/D ratio increases lining deformation is reducing substantially and for W/D ratio of 1.5 and 2 variations in tunnel lining deformation is constant around 2mm.

For W/D ratios due to unbalanced load effect, the deformation to the face of tunnel lining towards the deep excavation side has more effect that the other side. For W/D = 0.35 lining deformation for face towards the C & C box excavation (270º) reached to 7.2mm, whereas, for W/D ratio 0.5, 0.7 and 1 lining deformation at 270º rotation are reduced by 7%, 15%, and 25% respectively. For W/D = 1.5 & 2 lining deformation is constant about 4.25 mm i.e., 40% reduction in lining deformation with compared to W/D ratio of 0.35.

3.2.1 Impact on secant pile due to adjacent tunnel excavation

As explained earlier owing to permeable nature of sprayed concrete lining excavation of tunnel may lead to the temporary water drawdown in the vicinity until the permanent lining is installed. This tends to reduce the active pressure behind the secant pile row near the tunnel. Also, due to the excavation and relaxation of ground around the tunnel surface settlement increases. The combined effect of drawdown and ground relaxation further reduces the active earth pressure on the secant pile row near the tunnel. Whereas, the secant pile row farther from tunnel is not subjected to ground relaxation and water drawdown effects. These ground condition produce an unbalance pressure on the earth retaining system. The effect of these unbalanced loads on secant pile system, along with tunnel lining, rock pillar and ground movements are discussed here.

In the case of strutted excavation, the unbalanced load is shared through non-uniform deformation of secant piles. In such case, the piles away from tunnel excavation show higher deformations owing to relatively higher active earth pressure. The piles near to tunnel excavation show lower deformations due to relatively lower active earth pressure.

In the final stage of cut & cover box excavation, 18mm of pile movement was recorded on the top section of piles from both side of excavation. However, with the excavation of tunnel the movements in pile system near to the tunnel side is reduced to 2mm and the movement of 35mm is observed for the secant piles away from tunnel.

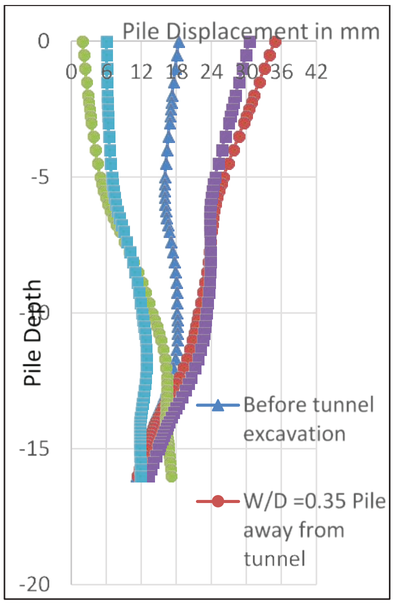

Fig. 7 - Comparison of secant pile displacement for W/D 0.35 and 2

The plot of pile displacement with tunnel excavation for W/D ratio of 0.35 and 2 along with the base case of pile displacement prior to tunnel excavation is presented in Fig. 7. The Fig. 7 indicates 18mm deformation at pile top before tunnel excavation. After tunnel excavation, piles facing the tunnel is moving towards the soil reducing the 95% pile top displacement reducing to 1mm, whereas displacement in pile away from the tunnel is increased by same i.e., 95%. For W/D = 2 changes in pile displacement is 65% in both the sides of piles.

The settlement of 17 mm was noticed immediately after excavation of cut & cover box, which further increased by 30 % and become 22.5mm after the excavation stages for tunnel are modelled in Plaxis (Fig. 8).

In order to further evaluate the ground settlement, the tunnel excavation was modelled by varying W/D ratios. The influence of W/D ratio on ground settlements is presented in Fig. 9. As tunnel is excavated, ground settlements increased by 62% to 28.2 mm when compared with the 17.3mm settlement observed at the end of cut & cover excavation stage. It is observed that with reduction in W/D ratio from 2 to 0.3, the movements of piles near the tunnel excavation are reduced. The reduction in pile deflection also resulted in reduced ground settlements. Impact of tunnel excavation on ground settlement above the tunnel crown is insignificant However, settlement extent has significantly increased with increase in W/D ratio.

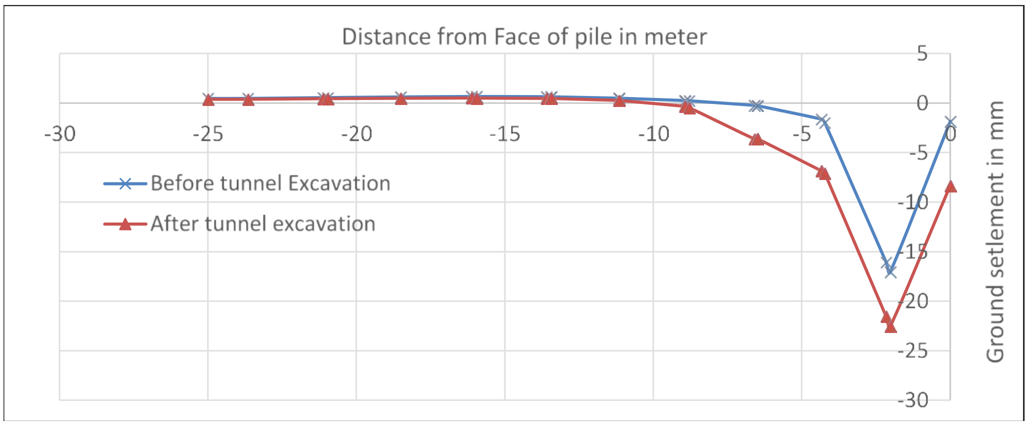

Fig 8 - Comparison of surface settlement for W/D=0.35 on other side of tunnel after tunnel excavation

4. DISCUSSION AND CONCLUSIONS

Two-dimensional FEM modelling is used to understand the complex soil-structure interaction involving cut & cover excavation with an adjacent tunnel. It is observed that the excavation of tunnel adjacent to the cut & cover box excavation influences the ground behaviour along with the behaviour of earth retaining system.

The geological stratification has major impact on tunnel design. Increase in soil depth above the tunnel crown leads to larger deflection in the tunnel lining at crown. On other hand the geological stratification does have only marginal effect on rock pillar deformation.

Excavation of tunnel will cause a short-term loss of ground water due to which the unbalanced load path is imposed on earth retaining system of supporting cut & cover excavation. The unbalanced loading conditions increases the displacement of secant piles on the far side of tunnel excavation. The loss of ground water can be controlled by installing a grout curtain around the tunnel profile before the start of excavation along with recharge wells.

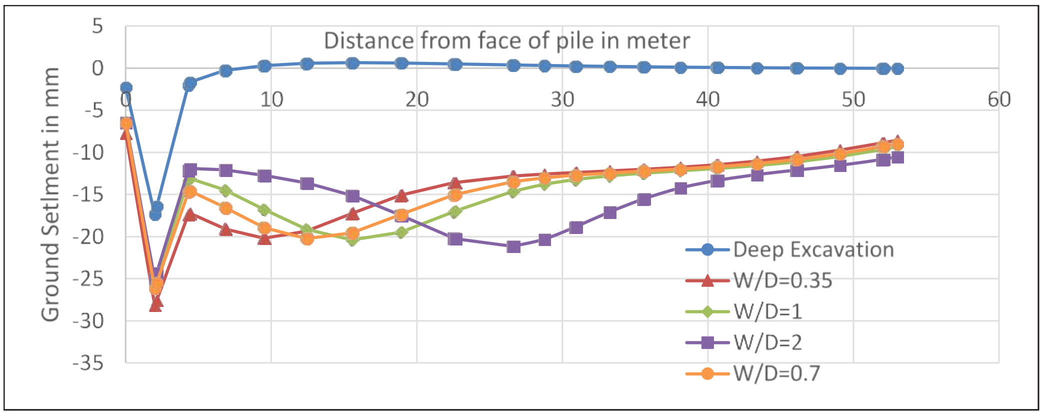

Fig. 9 - Comparison of surface settlement with various width of a rock pillar

It is observed that tunnel excavation induces additional stresses on the rock pillar and causes the deformation of the rock pillar. The surface settlements increase immediately after the excavation of tunnel. The maximum surface settlements are observed immediately behind the secant pile. The width of rock pillar appears to have no major effect on the magnitude of maximum surface settlements. The shape of settlement trough is influenced by the rock pillar width.

Adjacent cut & cover excavation has influence on the behaviour of tunnel excavation. Tunnel lining was subjected to higher deformation at the face wall adjacent to the open excavation and deformation increased with reduction in width of the rock pillar.

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