Analysis of stability of rock column between cut & cover Metro Station and NATM Tunnels

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Abstract: *Planning and accommodation of underground metro stations in available land areas is an important aspect of any metro project. Designer has to adopt the innovative solution for station design due to limited space. To accommodate the station box within the available area, station may have to be constructed with the combined construction approach of NATM and cut and cover. In this approach main station box is constructed with a cut and cover method and platform tunnel is constructed with a NATM method. The sequence of construction can be simultaneous or opening of tunnel is carried out from the cut & cover shaft or TBM tunnel excavation is done before station excavation. Any underground excavation has a major influence on the nearby existing structures. This paper covers the various aspects of ground response to the interaction between strutted excavation and NATM tunnel excavation. Study of integrated excavation is carried out with varying the width of rock column between station excavation and NATM platform tunnel. The variations in the geological stratification and impact of different construction sequences are investigated.*

Key words- Earth Retaining System (ERS), secant pile, Platform NATM tunnel, Surface settlement, Underground metro, Rock column, cut and cover structures, deep excavations.

1. INTRODUCTION

India has seen a huge development in the metro rail projects in the last 3 decades. Several Underground Metro projects have been constructed and many are in the under-construction and planning phase. Planning and design of the underground metro station is a challenging job. As most of the underground stations are planned in a densely populated area to gain more public ridership. Underground metro stations are usually planned under roads, empty ground. Planning of underground station under existing road has major issue i.e., protection of buildings adjacent to the metro station. One of the underground metro stations were planned in a densely populated area in Mumbai, on narrow roads, and in the station vicinity, several dilapidated buildings were present. Hence few stations were planned to construct with a mixed method of cut and cover for station box and NATM method for Platform tunnel. Owing to the presence of buildings in the vicinity of the station footprint the possibility of a complete cut and cover station was not feasible. Hence the innovative idea of integrated NATM platform tunnel and cut & cover station excavation is adopted in many stations. This study inspires by the same case where the station box is being executed by adopting the methodology of cut and cover method and the platform is being constructed by the NATM tunneling method [1]. Connection with station box and NATM platform is made with the intermediate cross passages at regular intervals. Research study emphasis on the behavior of integrated cut and cover excavation and excavation of NATM tunnel using predictable element of soil-structure interaction analysis. The results response of ground under different parameters are presented in this paper.

Alignment of the underground metro is generally planned through a heavily built-up urban area. Many times, important Landmarks and Heritage structures are located nearby or directly above the tunnel alignment. Owing to land availability constraints, cost of private properties, inadequate available road width, and the very important presence of Heritage buildings planning, and design of metro alignment is important part of any underground metro project.

The alignment of an underground metro project is constructed with twin tunnels by Tunnel Boring Machine (TBM) connecting two stations. The underground stations or shaft are generally proposed to be constructed by adopting the cut & cover construction methodology, and NATM method of construction and ground settlements are to be limited to protect existing buildings.

Due presence of a high-water table, high rise building imposes a higher surcharge load which leads to higher settlements; however, the designer has to control it well within the acceptable limit. In high water table areas generally, excavation is done with a water-tight retaining system to prevent ground settlements due to seepage during excavations. To maintain the water table in the non-excavated area proposal of the recharge well may be required.

The purpose of this study is to carry out the assessment of rock column between cut & cover station and NATM tunnels of one Underground Metro project in Mumbai. This paper provides an analysis for safety of rock column.

- In Preliminary stage, the rock column width was 2.6m based on tender stage GIR.
- During construction stage, after preparing actual GIR, Geotechnical parameters were revised, and rock quality is considered to be poor w.r.t Tender GIR. Rock column width needed to increase for stability of supporting system during excavation.

- Following analyses are performed –

a) Rock Column width 4m between cut & cover Station and NATM Tunnel
b) Rock Column width 5m between cut & cover Station and NATM Tunnel

2. Literature review

The settlement data from TBM tunneling in varying ground condition which are representative of the Mumbai geology are analyzed and presented in this section.

In the year 1958, Martos has examined the settlement trough shape on mining excavations, which was represented by a Gaussian or Normal distribution curve.

On the later stage, Schimdt, and Peck in the year 1969 has shown that surface settlement in the above tunnels were experienced in a similar form. O'Reilly and New has developed the Gaussian mode in the year 1982, by assuming that the ground loss could be represented by a radial flow of material towards the tunnel and that the trough could be related to the ground conditions through an empirical "trough width parameter" (K). The model was guided by an analysis of case history data.

Due to the above assumptions, it was possible to develop equations for vertical and horizontal ground movements that were also presented in terms of ground strain, slope, and curvature (both at, and below, the ground surface). From there on, the equations are being widely used to access the potential impact of tunneling works during the design stage. The base equation is as mentioned below.

$$S = S_{\max} \exp\left(\frac{-x^2}{2(kz)^2}\right) = \frac{AV}{(kz)\sqrt{2\Pi}} \exp\left(\frac{-x^2}{2(kz)^2}\right)$$

Where S = ground settlement at a point; Smax = maximum ground settlement; A = cross-sectional area of tunnel; V = % of ground loss assuming the ground is incompressible i.e., V = Vs/A, where Vs is the volume loss; k = empirical constant also called as trough width parameter; and Z = depth of tunnel axis.

For an example, to determine /predict the ground movement only the following parameters were adopted /considered.

- Clough, O'Rourke and Peck adopted the excavation depth to determine ground movement as it is the only parameter.
- To predict the ground movement wherein the excavation depth is the main parameter in the formula, Bowles considered the area covered by lateral wall movement as a parameter.
- To predict the concave type and spandrel type of settlement profiles, Hsies and Ou used the excavation depth as the only parameter.
- Osman and Bolton adopted the plastic zone, which is completely related to the excavation depth and was the only parameter used in the prediction.

3. DESIGN OF TEMPORARY SUPPORT SYSTEM AND GEOLOGY

In combination of cut & cover and NATM underground metro station construction, there is access Tunnel at regular interval for connection between them. During excavation for access tunnel and Platform tunnel high stresses around the opening are to be checked and controlled. Therefore, rock column stability check is very important. This study has been performed using PLAXIS 2-D finite element analysis program.

As per requirement of Employer, all the tunnel sections shall be complied with Schedule of Dimension (SOD). The profile of Tunnel may be circular, D-Shape or horseshoe and it depends on the ground conditions. Here horse-shoe shape tunnel is considered. Cross sectional area of Tunnel is around 90.4 sqm., width is 11.2m and height is 10m. Overburden (soil mixed with rock) of 18m is considered above tunnel crown in this analysis. Actual geotechnical profile and information is collected from GIR of project. Class IV and V rock are identified at final excavation level which is 28m below ground. For parallel construction and stability of the system, all the secant pile are terminated 4m below the final excavation level.

For stability analysis, following parameters have been considered in the model –

- Co-efficient of lateral earth pressure=0.5
- The soil is modeled by using Mohr-Coulomb material model
- Using Mohr-Coulomb material model, Rock mass is modelled where the strength and deformation properties are derived using Hoek and Brown criterion based on Hoek and Torres (2002).
- Water table at ground level
- Secant pile (combination of M40 - RCC and M10 - PCC) of 1m dia, 32m depth and 170mm overlap.
- All piles are 32m depth i.e., 4m below from final excavation level.
- 5 level struts are used for supporting of secant pile, horizontal spacing 10m c/c and vertical spacing 4.5m c/c.

Table -1: Properties of Structural Element

Structural elements	Grade of Concrete	EA (kN/m)	EI (kN-m2/m)
RCC Secant Pile (1m diameter)	M40	22.14E+06	645780
Sprayed concrete for primary Tunnel lining 200mm thick	M35	5.19E+06	19720

Table 2: Geotechnical Parameters

Material Type	Unit wt (kN/m3)	Cohesion c (kPa)	Friction angle	Young's modulus E (MPa)	Poisson's Ratio
Soil	18	1	30	12	0.3
Completely weathered rock	20	27	29	423	0.3
Moderately weathered rock	25	148	55	685	0.3

Following construction stages are considered in the model:

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 strut
5. Installation of 1st level strut
6. Repeat the stage 3, 4, 5 till the last design strut is installed
7. Excavation of NATM tunnel profile

8. Installation of Primary support
9. Installation of full-strength primary tunnel lining along with wire mesh.

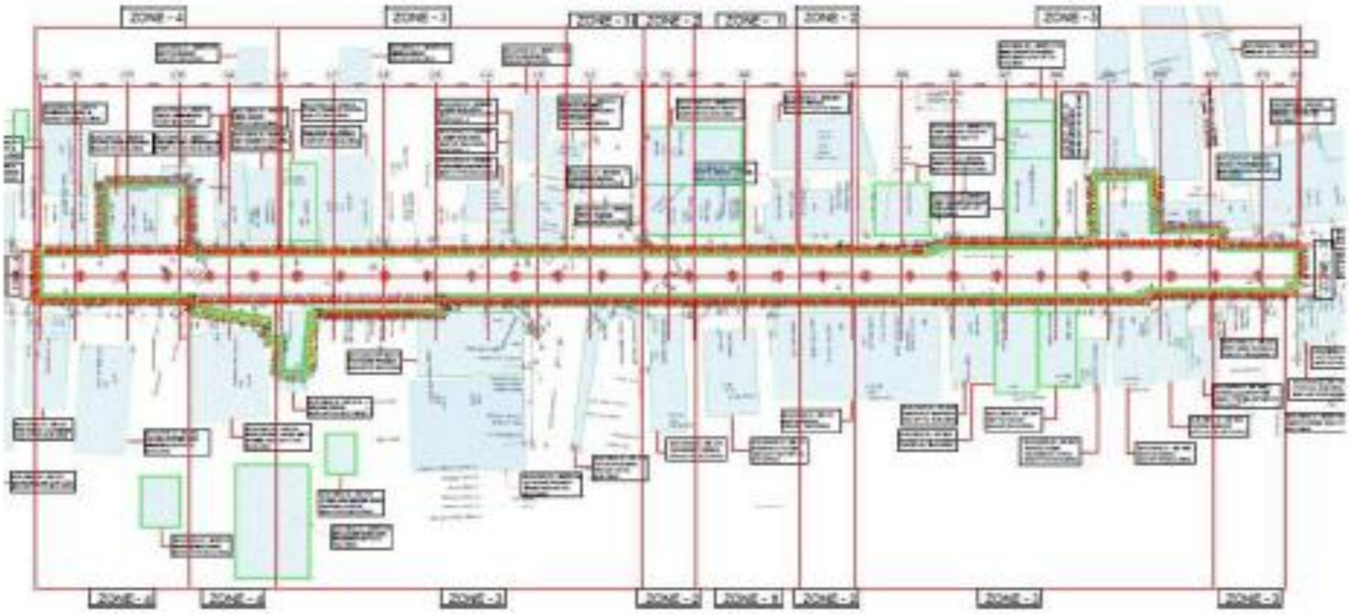


Fig -1: Road level plan of Station Box

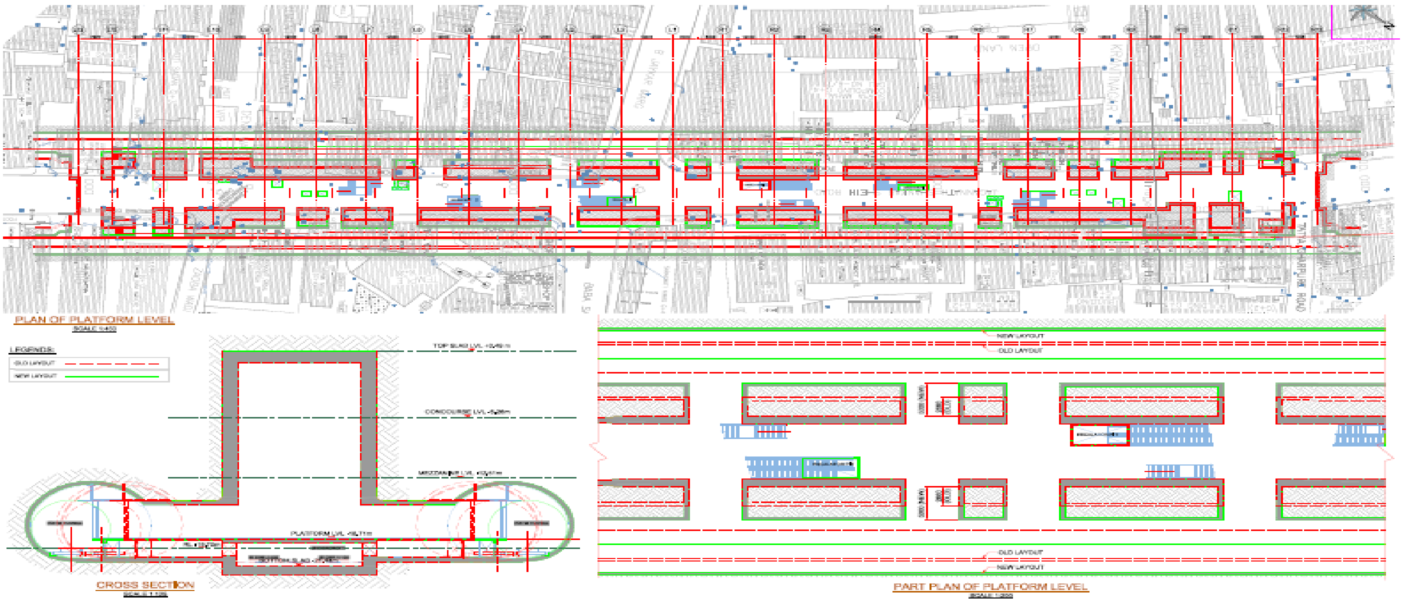


Fig -2: Undercroft level Plan of Station Box

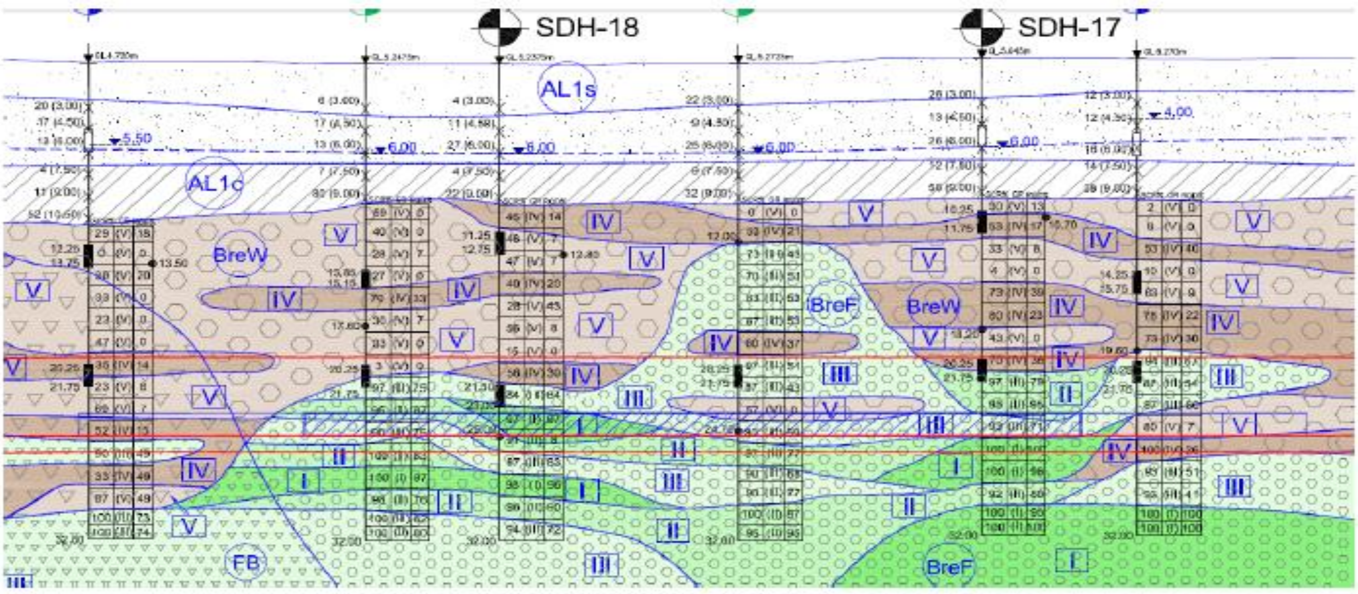


Fig -3: L- Section of Geotechnical Profile of Station Box

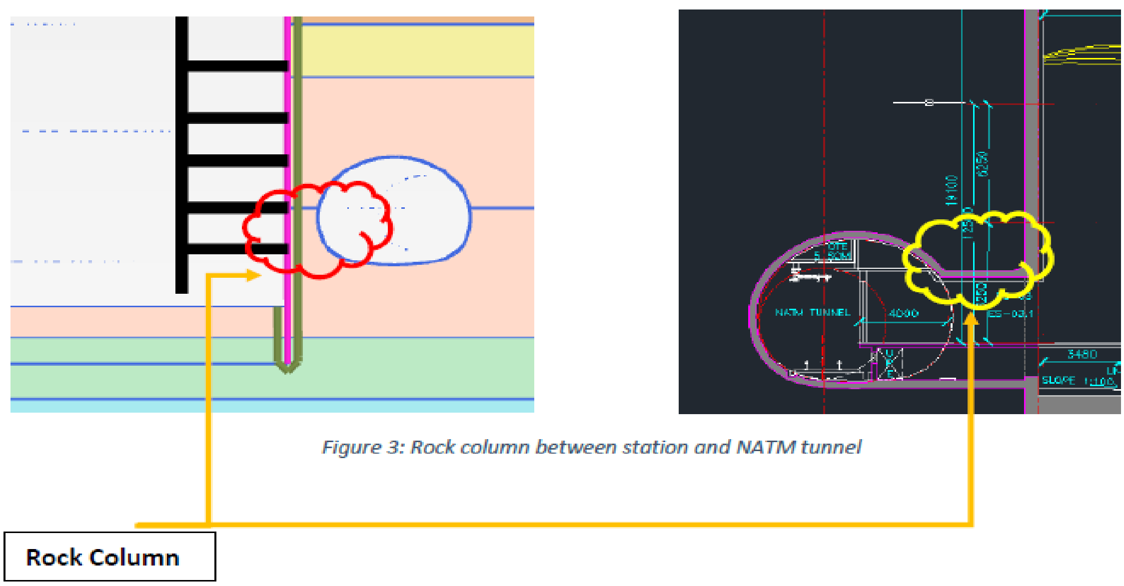


Fig -4: Rock Column width

4. METHODOLOGY

Analysis of the stability of rock column, properties of temporary support system and construction sequence are discussed here.

The geotechnical software PLAXIS 2D was used to study the soil-structure interaction between the cut & cover structure and NATM tunnel and its impact on rock column stability. The software was used to provide the factor of safety of rock and soil for the proposed construction sequence.

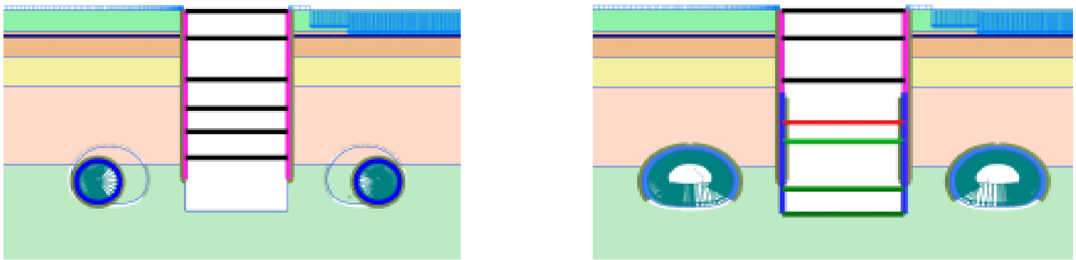


Fig -5: Construction stage PLAXIS 2-D model

5. ANALYSIS AND RESULTS

Initially rock column of 2.66m width is analyzed. The analysis was carried out for this column width, and it was observed that the rock collapses in this scenario. Hence, the width between the cut & cover station box and NATM tunnel was increased to have lower concentration of stresses in the rock column.

Following analysis were performed –

a) Rock column width of 4m between station and NATM Tunnel

PLAXIS output for Rock column stability (4m wide) considering 30% Relaxation –

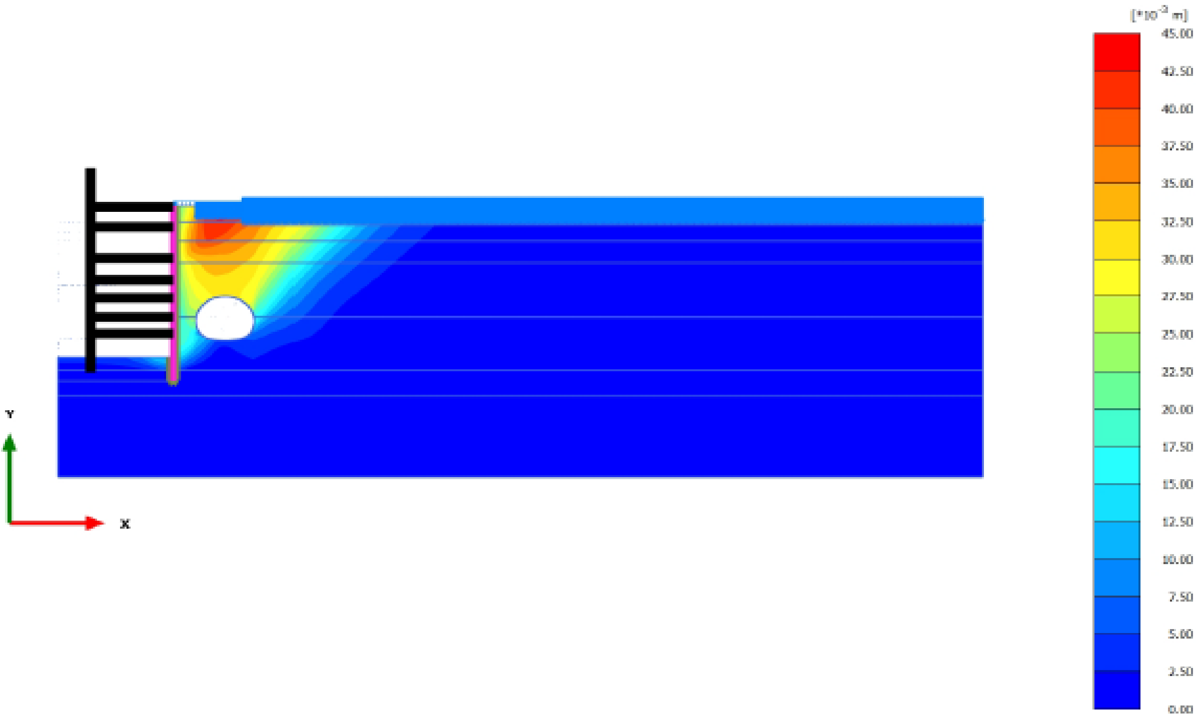


Fig -6: Total displacement after final excavation of cut & cover Box: 43mm

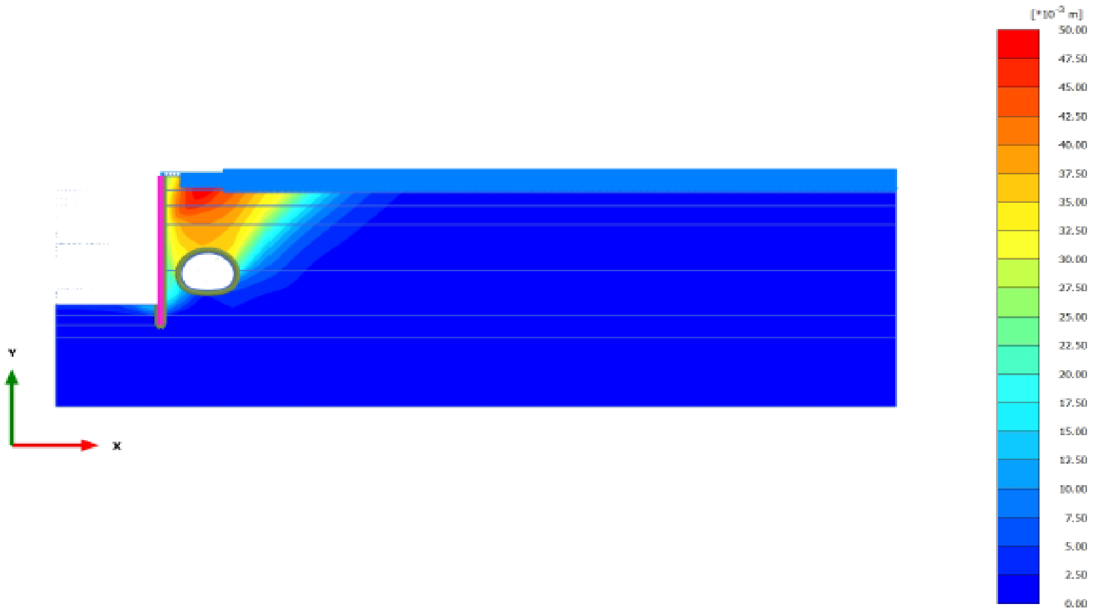
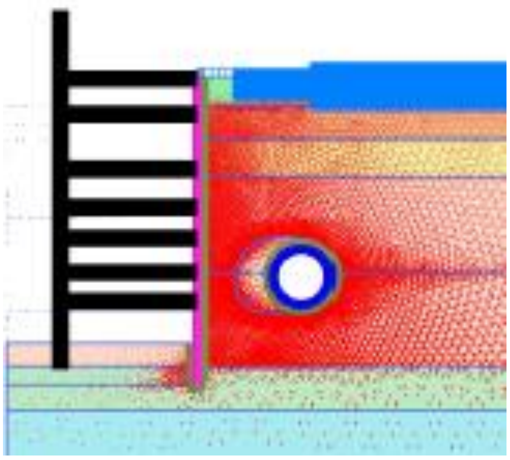


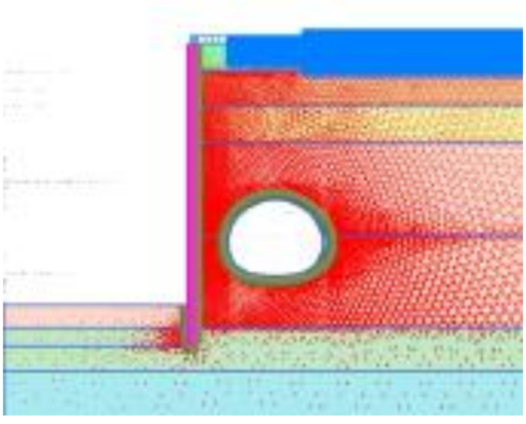
Fig -7: Maximum Total displacement near ground surface after NATM Construction: 50mm



Maximum value = 1822 kPa

Minimum value = -9982 kPa

Fig -8: Total stress after final excavation of cut & cover Box



Maximum value = 1895 kPa

Minimum value = -10.10*10^3 kPa

Fig -9: Total stress after construction of NATM lining

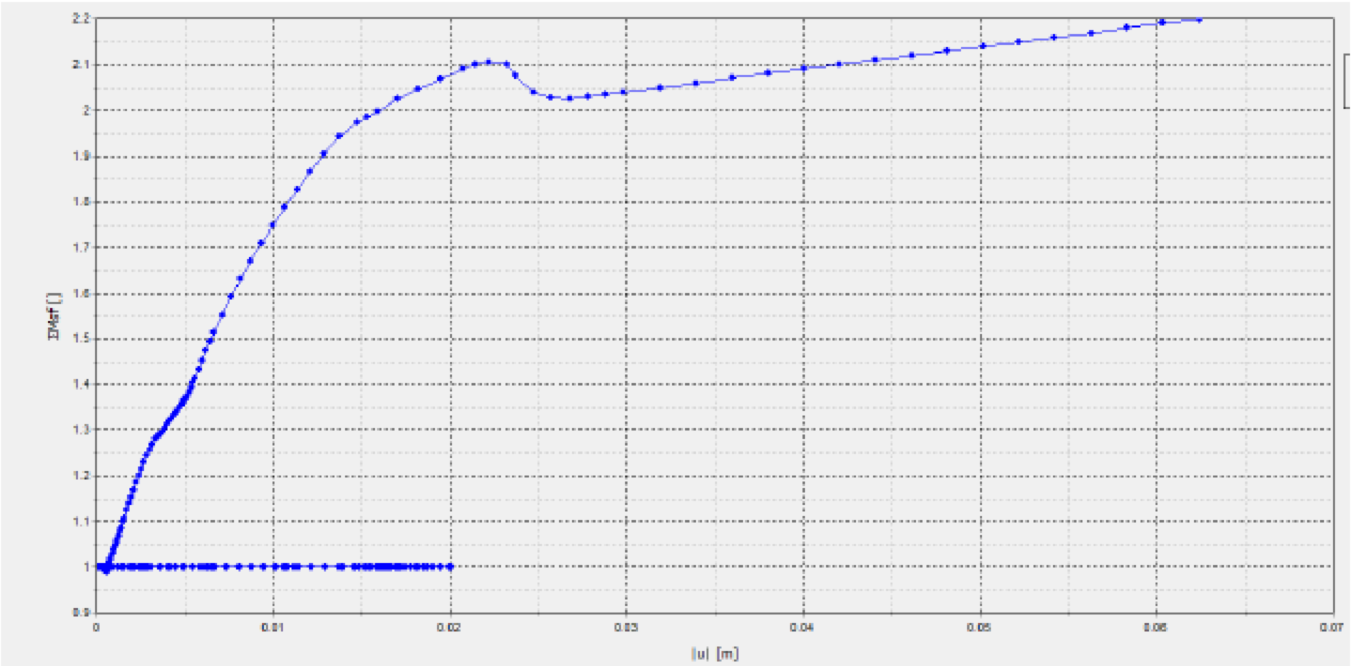


Fig -10: The factor of safety with column width 4m between station and NATM Tunnel

a) Rock column width of 5m between station and NATM Tunnel

PLAXIS output for Rock column stability (5m wide) considering 30% Relaxation –

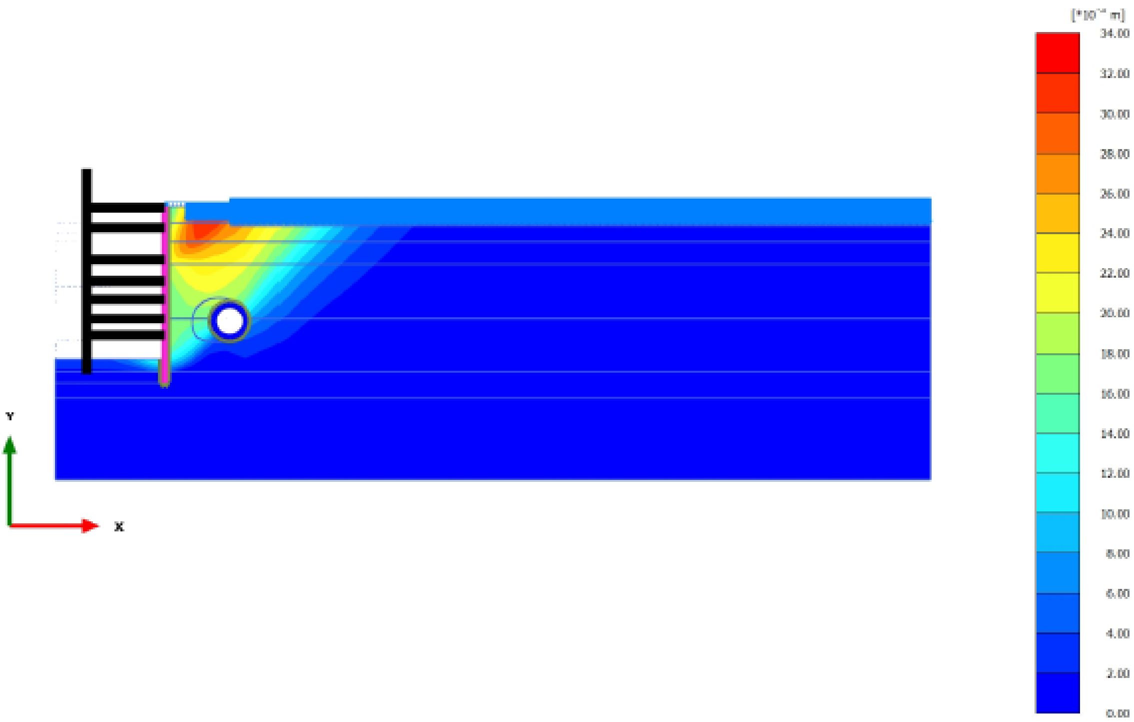


Fig -11: Maximum Total displacement near ground surface after final level excavation of cut & cover Box: 32mm

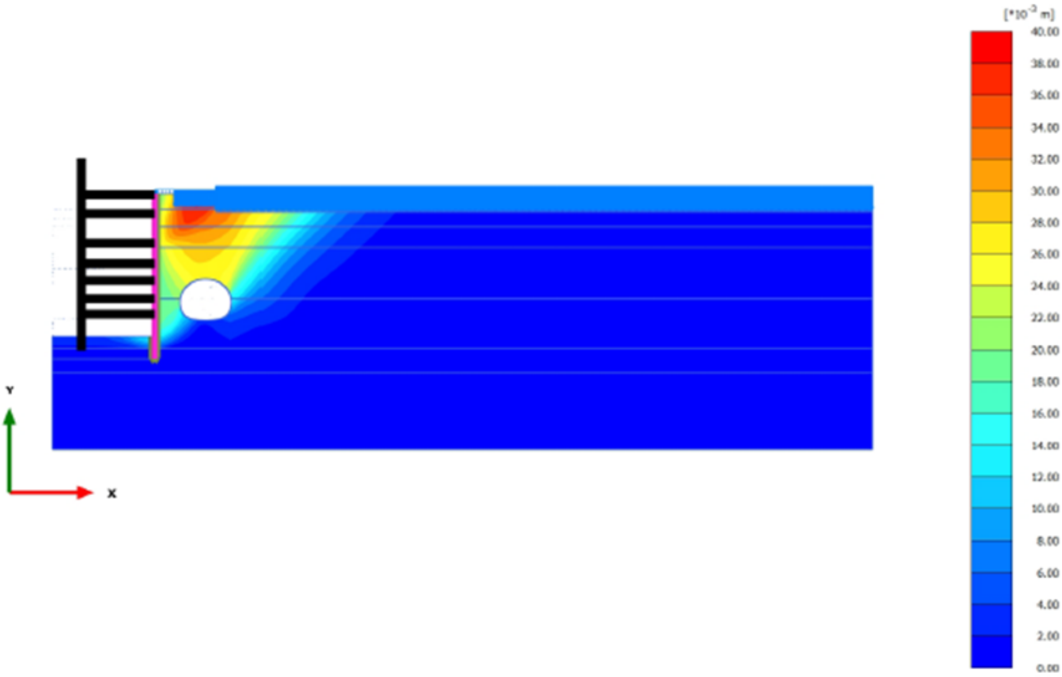
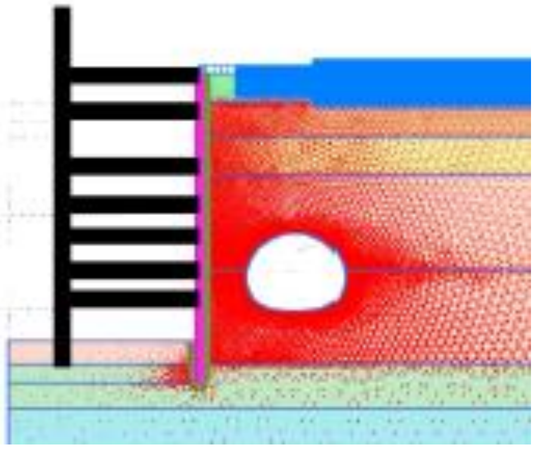


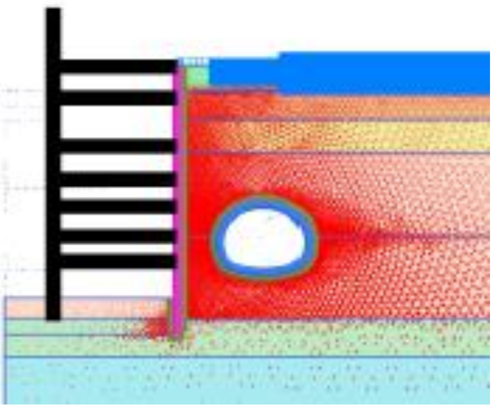
Fig -12: Maximum Total displacement near ground surface after NATM construction: 39mm



Maximum value = 1673 kPa

Minimum value = -8157 kPa

Fig -13: Total stress after final excavation of cut & cover Box



Maximum value = 1787 kPa
Minimum value = -9067 kPa

Fig -14: Total stress after construction of NATM lining

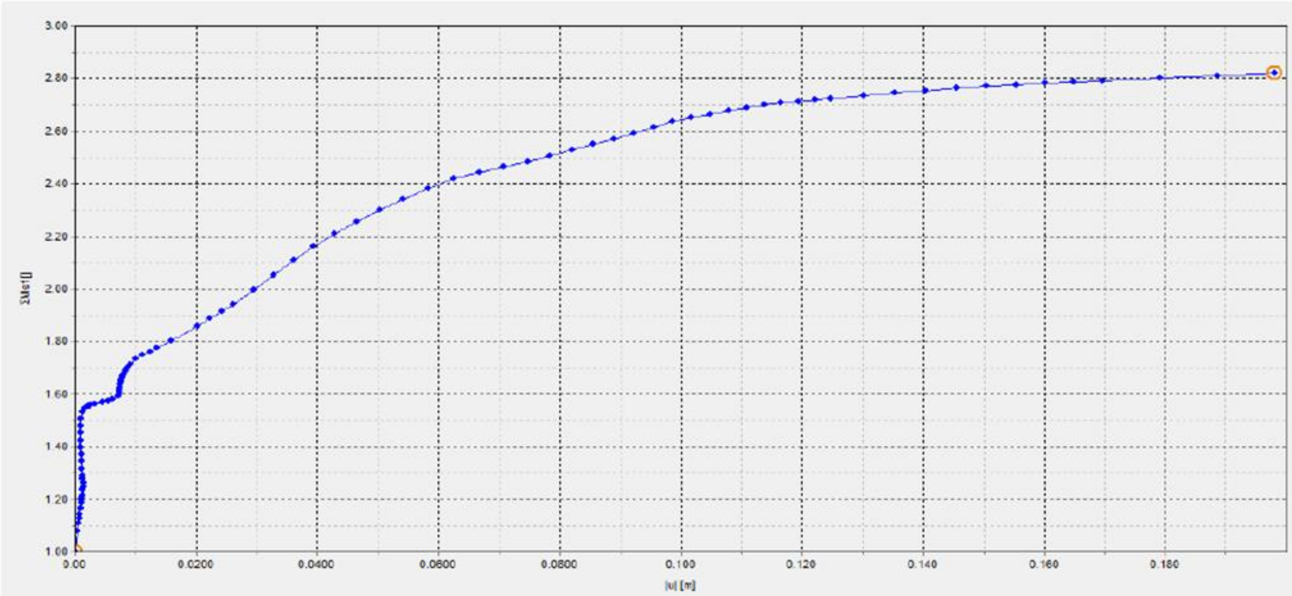


Fig -15: The factor of safety with column width 5m between station and NATM Tunnel

Table 3: Comparison of result of different rock column

Rock Column width	Total displacement after final excavation of cut & cover Box	Maximum Total displacement near ground surface after NATM Construction	**Total stress after final excavation of cut & cover Box**	Total stress after construction of NATM lining	FOS
4m Rock Column width	43mm	50mm	Maximum value = 1822 kPa Minimum value = -9982 kPa 2	Maximum value = 1895 kPa Minimum value = -10100 kPa	2.2
5m Rock Column width	32mm	39mm	Maximum value = 1673 kPa Minimum value = -8157 kPa	Maximum value = 1787 kPa Minimum value = -9067 kPa	2.8

Table 4: During construction actual displacement and stress for 5m rock column

Rock Column width	Total displacement after near ground surface final excavation of cut & cover Box	Total displacement near ground surface after NATM Construction	**Total stress after final excavation of cut & cover Box**	Total stress after construction of NATM lining
5m Rock Column width	18 mm	21 mm	Maximum value = 903 kPa Minimum value = -5272 kPa	Maximum value = 988 kPa Minimum value = -5887 kPa

6. DISCUSSION AND CONCLUSION

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

Geological stratification has major impact on tunnel design. Increase in rock column width, there is reduce of ground settlement and reduce of total stress.

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 pile on the fair 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.

It is observed that the tunnel excavation induces additional stress on the rock column and causes the rock column deformation. After excavation of tunnel, surface settlements increase immediately. The maximum surface settlements are observed immediately behind the secant pile. The width of rock column appears to have no major effect on the magnitude of maximum surface settlements. The slope of settlement trough is influence by the rock column width.

Adjacent cut & cover excavation has an influence on the behavior 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 column.

From the analysis, it is concluded that the minimum width of rock column between station and NATM tunnel shall be 5m to achieve FOS of 2.8. A sensitivity analysis was carried out for 4m wide rock column, and the analysis was not successful (i.e., FOS<2.5), confirming that the minimum width of rock column shall be 5m for these geological conditions.

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BIOGRAPHIES

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