NUMERICAL MODELLING OF BUILDING RESPONSE TO UNDERGROUND TUNNELING - A CASE STUDY OF PUNE METRO

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Abstract - *The advancement in underground construction and use of Tunnel boring machine for construction is deeply studied. The construction of underground tunnel in ground involves potential risk of damage to old age structure and may lead to collapse of structure or tunnel. Thus it is very important to predict the surface settlement before construction to minimize risk of collapse. Numerical modelling by FEM analysis of a building in Pune is studied and settlement of building is compared with in-situ settlement. This also includes the numerical modelling of building response to underground tunneling by FEM analysis w.r.t. various parameters i.e., surface settlement (Ground and building, tilting). Then, a control measures over it were proposed to eliminate this risk, which are verified by using finite element software. This works focus on studying the excavation mechanics behavior of underground tunneling and its influence on the around environment, and these conclusions are useful for providing a basis for ongoing work as well similar project construction in the future.*

Key Words: Tunnel Boring Machine (TBM), Earth Pressure Balanced(EPB), Surface settlement prediction and monitoring instruments, Building settlement marker (BSM), Ground settlement marker(GSM),etc.

1. INTRODUCTION

The Earth Pressure Balance (EPB) Shields have been developed in part to minimize surface settlement. For a correct assessment of the influence of the tunnel boring process on the buildings, and of possible damage to the buildings, a detailed prediction of the soil deformations, caused by the tunnel boring machine (TBM), is needed. Especially the gradient of the settlement trough is a main factor in the damage assessment. To obtain realistic results it is, among other things, necessary to use advanced soil models and to carefully select the corresponding model parameters. In this contribution attention will be focused on the possibilities and limitations of 3D finite element model for numerical modelling of building response to underground tunneling to on old building founded on piles. The problem of pre-existing structures arises primarily in urban environments where careful analysis of subsidence and vibrations generated by excavation systems is essential. Ground movements caused by tunnelling can have a significant impact on overlying or adjacent structures and therefore require consideration when choosing the tunnelling method. This is particularly true when tunnelling in soft ground beneath urban areas. Ground movements due to tunnelling in rock are not usually a problem except where the cover is relatively shallow, in portal areas, or where groundwater may be affected in overlying soils susceptible to settlement.

2. OBJECTIVES

The present study covers the following significant objectives with reference to process of construction of tunnels for Pune metro.

1) Case study of construction of underground tunnel for a segment of Pune Metro Rail and instrumentation and measurement of significant settlement in influence zone of tunneling.
2) Physical measurement and FEM based Numerical modelling of settlement of building located in a segment of Pune Metro.
3) Comparative study of in-situ settlement measurements and predicted settlement through FEM based Numerical modelling.
4) To predict building damage due to ground movement induced by tunneling using FEM based Numerical modelling & proposed measures to eliminate the construction risks.

3. METHODOLOGY

3.1 Instrumentation and Monitoring In Influence Zone

Monitoring is carried out at planned locations selected along the alignment of the underground metro corridor tunnel. The purpose includes monitoring of the structures under construction together with the ground, buildings and other facilities within the predicted zone of influence. The monitoring will be performed to find settlement, groundwater level, and stress. Instrument which are used for monitoring purpose are Temporary Bench mark, Piezometer, Inclinometer and Tilt meter, Extensometer and Crack meter which are used to monitor vertical movement, waterpressure, lateral movement of building, vertical deformation or heave with depth and crack width. Data sets for the soil layers and the final concrete lining in the tunnel as specified in Table No.1

Table No.1 Material properties for the soil layers

Parameter	Name	Upper sand	Clay	Stiff sand	Concrete	Unit
General						
Material model	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Linear elastic	–
Drainage type	Type	Drained	Drained	Drained	Non porous	–
Unit weight above phreatic level	γ_{unsat}	17.0	16.0	17.0	27.0	kN/m^3
Unit weight below phreatic level	γ_{sat}	20.0	18.0	20.0	–	kN/m^3
Parameters						
Young' modulus	E'	$1.3 \cdot 10^4$	$1.0 \cdot 10^4$	$7.5 \cdot 10^4$	$3.1 \cdot 10^7$	kN/m^2
Poisson's ratio	ν'	0.3	0.35	0.3	0.1	–
Cohesion	c'_{ref}	1.0	5.0	1.0	–	kN/m^2
Friction angle	ϕ'	31	25	31	–	°
Dilatancy angle	ψ	0	0	0	–	°
Interfaces						
Interface strength	–	Rigid	Rigid	Rigid	Rigid	–
Initial						
K_0 Determination	–	Automatic	Automatic	Automatic	Automatic	–

3.2Numerical Modelling By PLAXIS-3D

The increasing technology in computer software eventually leads us to the situation where structural engineers can apply PLAXIS-3D finite element calculations for ordinary design and calculation purposes. For settlement analysis due to tunneling a finite element models is often known to over- predict the settlement and to under-predict the gradient of the settlement trough. The situation considered is a Metro Rail project and a heritage building which is present in influence zone of tunneling in Pune.

The metro tunnels will be constructed near historical masonry buildings, founded on piles, as well as newer buildings, founded on prefabricated concrete piles. Thus it is very important to predetermine the settlement which will be caused when TBM will pass through that point. Along the main part of the line the tunnels will run close to or beneath the toes of the foundation piles. Both the piles and the masonry structure have little margin for deformation before damage to the construction will occur.

The full finite element analysis is divided into 20 calculation phases. In the first two phases, the piles and the building are constructed, but the corresponding deformations are not taken into account in further steps. In the following phases, the advancement of the tunnel boring process is simulated by advancing the tunnel face 3 m in every phase, starting from the back-side of the model and taking into account the previously described modelling aspects behind the tunnel face as long as they fit in the model. The first tunnel excavation step takes place in the third calculation phase. In the sixth phase the grout pressure becomes active for the first time (TBM shield is locally de-activated). In the eighth phase, when the tunnel heading has advanced to the first row of piles, the concrete lining is activated for the first time at the back-side of the model. In phase 14 the tunnel heading has advanced to the last row of piles. In the final phase 20 the tunnel heading has advanced 54 m, i.e. 18 m behind the last row of piles, such that most deformations of the buildings have occurred.

This is a realistic situation of ShivDham apartment in Pune which is built in influence zone of tunnel. It is 6.65 m diameter tunnel bored with its axis at a depth of 20 m below the ground surface (15.75 m soil above the tunnel lining). The situation of ShivDham apartment is modelled using model using PLAXIS-3D Tunnel software which is symmetric with respect to a vertical plane through the tunnel axis. The bottom of the mesh is at a depth of 30 m (5.75 m below the tunnel lining). In addition to the tunnel, a block of houses on piles is modelled adjacent to the tunnel at a distance of 10 m from the tunnel axis (5.75 m from the lining). The block of houses is 16 m long, 8 m wide and 12 m high above the ground level. The piles are found on medium gray basalt rock layer (including stiff sand layer) in which the tunnel is bored. Soil layers are as following (Figure No.1)

1. Soft upper soil -3 m
2. Upper sand layer -12 m
3. Underlying by stiff sand layer – 6m
4. Medium Gray Basalt rock layer- upto 10 m

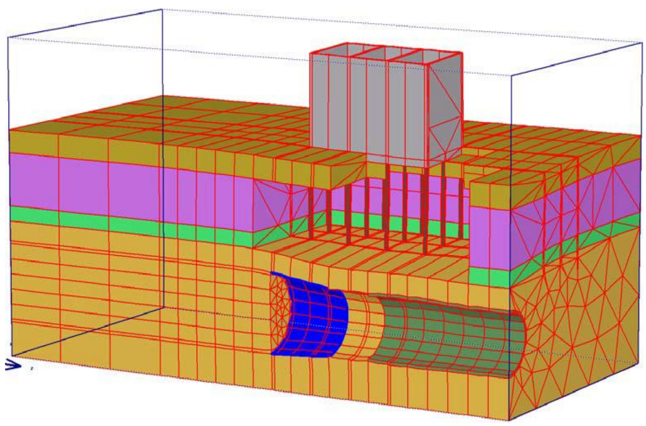


Figure No. 1 Partial view of the deformed mesh at the end of Phase 15

4. Results and Discussion

The influence of tunneling close to pile foundations on the bearing capacity of those foundations and the resulting deformations of the structure. Figure No.2 shows the tilting of the houses due to the tunneling process. At the left side the vertical settlement is 18.9 mm and at the right side the vertical settlement is 5.7 mm, which gives a gradient of 0.0012, i.e. less than 1:800. The gradient is slightly more than the gradient of the ground surface at the back-side of the model. This is due to the fact that the soil deformation and gradient at the pile tip level are higher than at the ground level. A gradient by itself is not be harmful for buildings, but what might be more harmful is the torsion that occurs when the tunnel boring process passes the block of houses. The effect of torsion reaches its maximum value when the TBM has advanced about half way the houses.

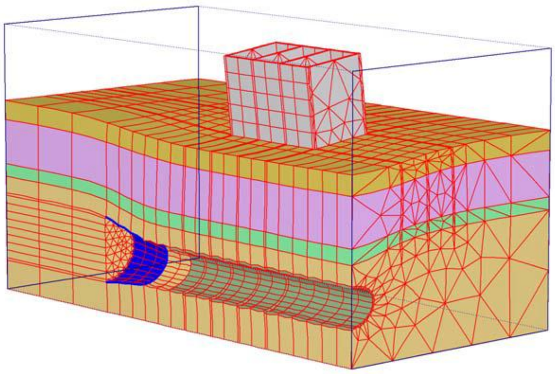


Figure No. 2 Total displacements at the end of Phase 20 (TBM well beyond houses)(deformations enlarged 100 times)

From Figure No. 3 it can be seen that the wall at the back-side has settled and is inclined whilst the front wall is still more or less undeformed. This torsion effect may lead to cracks in the masonry walls, although the amount of torsion in this example case is quite limited. It is known that the width of the settlement trough above a tunnel is generally overestimated in a finite element analysis, and, as a result, the gradient of the trough is underestimated. Similar observations have been made for the width of the settlement trough behind a sheet pile wall or a diaphragm wall.

To validate this statement an additional finite element analysis was performed for the situation as described in Section 3, taking into account small-strain stiffness effects. The analysis was performed by setting the stiffness moduli to values five times higher than used in the first analysis. It is recognized that this approach does not fully replicate the small-strain stiffness effect, since that effect is particularly pronounced at a somewhat larger distance from the tunnel. Nevertheless, the corresponding aspects can, to some extent, still be observed.

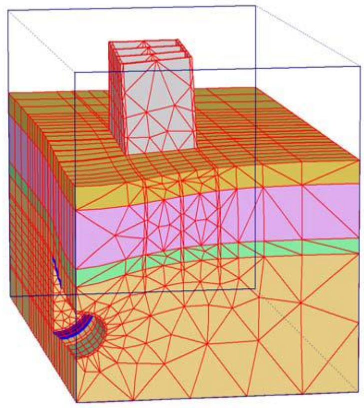
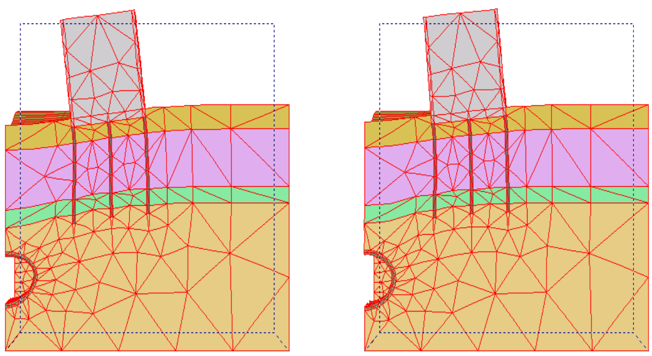


Figure No.3 Displacements at the end of Phase 10 (TBM half way houses) showing torsion of the houses (deformations enlarged 100 times)

The deformations around the tunnel are mainly strain-controlled and not stress controlled. Hence, the deformations immediately around the tunnel are not influenced by the larger soil stiffness, so a comparison of deformations is still valid. With the higher stiffnesses, the soil becomes plastic in a zone around the tunnel in an earlier stage, which effectively reduces the stiffness in this zone. As a result, the stiffness is lower around the tunnel and higher at a somewhat larger distance from the tunnel. This effect is similar (but not equal) to the small-strain stiffness effect.

Figure No.4 shows a comparison of results after Phase 20, where the model has been cut at the back-side wall of the houses. Although the deformations of the tunnel are almost the same, the settlement trough right above the tunnel in the stiff model (b) is indeed more concentrated and steeper than in the soft model (a).



a b

Figure No. 4 Total displacements at the back-side wall and beyond at the end of Phase 20(Deformations enlarged 100 times)

a. Original analysis with stiffness's

b. Modified analysis with five times higher stiffness's.

Nevertheless, the gradient of the houses in the stiff model is less than in the soft model. This is caused by the fact that in the stiff model the houses and their foundation are located just outside the zone in which most settlements occur whereas in the soft model the settlement area is wider and influences the pile foundation more than in the stiff model. Also the settlements of the ground surface are less in the stiff model than in the soft model (see Figure 4). Especially in the stiff model the inclination of the ground surface near the houses is less than at the back-side of the model. For the soft model the situation is reversed, as mentioned before.

4.1 COMPARISION OF RESULTS

Results by FEM analysis and In situ monitoring settlement of Shiv-Dham apartment is given in **Table No 2.**

Table No.2: Results by In situ monitoring settlement & settlement Results by PLAXIS-3D

Sr No.	Point ID	Insitu monitoring settlement result(mm)	Max settlement Results by FEM analysis (mm)
1	BSM 11378	-15.060	-18.9
2	BSM 11379	-13.652	-18.9
3	BSM11380	-14.560	-18.9
4	BSM 11381	-11.709	-18.9
5	BSM 11382	-11.710	-18.9
6	BSM 11383	-11.810	-18.9

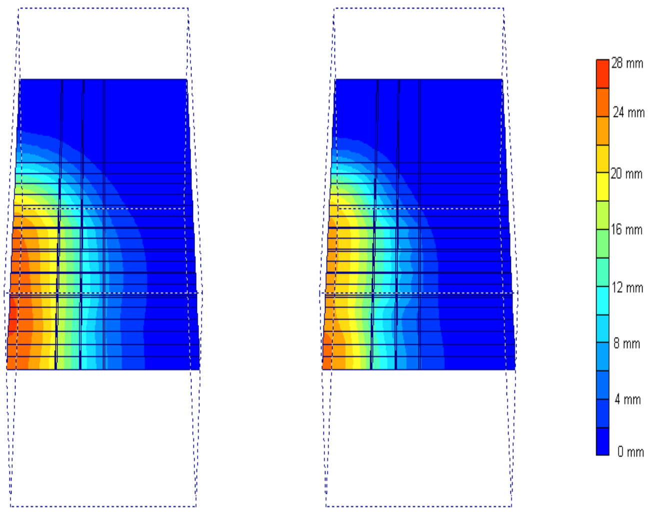


Figure No 5. Comparison of settlements at the ground surface at the end of Phase 20
a. Original analysis with stiffness's according to Table 2
b. Modified analysis with five times higher stiffness's

5. CONCLUSIONS

A 3D finite element analysis can be used quite well to simulate the tunnel boring process and to analyses the effects on adjacent structures. However, it is important to take sufficient modelling aspects into account. Regarding soil behavior, it is important to realize that the soil behaves quite stiff due to unloading and small-strain stiffness effects. In the model, the selected soil stiffness influences the width of the settlement trough and the effects of the tunnel boring process on adjacent structures.

Based on the results of analysis in this study the following conclusions can be summarized:

1. A case study of in-situ measurement of various settlement parameters using different monitoring instrument which lies in the influence zone of tunnelling is studied.
2. Numerical modelling of Shiv-Dham apartment situated on underground metro alignment in Pune ,India in done by PLAXIS-3D analysis and a comparison is made with in-situ monitoring parameters of the same building. In-situ settlement is 15.06 mm and by Numerical modelling of building maximum settlement comes out 18.9 mm which is comparable.
3. By Numerical modelling of this structure it may be concluded that settlement is over predicted.
4. The numerical techniques using the finite element methods are a powerful tool of analysis and predicting future deformations of tunnels and surrounding soil.
5. The PLAXIS 3D TUNNEL program provides an easy way for the entry of the data, good presentation of output data and flexibility to obtain the information from the output results.
6. The program supports the analysis of multi tunnels taking into account the influence of the tunnels to each others, and supports the analysis in layered soil.
7. The probable justification for the settlements difference between the methods of numerical analysis considering or neglecting construction process in the aforementioned point may be due to the change of the soil state caused by the excavation of the soil clusters in construction which consequently increase the settlement (no soil strengthening).

6. Recommendations

Building Damage Classification1 (after Burland et al, 1977 and Boscardin and Cording, 1989)				
1	**2**	**3**	**4**	**5**
Risk Category	**Description of Degree of Damage**	**Description of Typical Damage and Likely Form of Repair for Typical Masonry Building**	**Approx Crack Width**	**Max Tensile Strain %**

0	Negligible	Hairline cracks		Less than 0.05
1	Very Slight	Fine cracks easily treated during redecorations. Perhaps isolated slight fracture in building. Cracks in normal exterior brickwork visible upon close inspection	0.1 to 1	0.05 to 0.075
2	Slight	Cracks easily filled. Redecoration probably required. Several slight fractures inside building. Exterior cracks visible: some repointing may be required for weather tightness.Doors and windows may stick slightly.	1 to 5	0.075 to 0.15
3	Moderate	Cracks may require cutting out and patching. Recurrent cracks can be masked by suitable linings. Tack- pointing and possibly replacement of a small amount of exterior brickwork may be required. Doors and windows sticking. Utility services may be interrupted. Water tightness often impaired	5 to 15 a number of cracks greater than 3	0.15 to 0.3
Risk Category	**Description of Degree of Damage**	**Description of Typical Damage and Likely Form of Repair for Typical Masonry Building**	**Approx Crack Width**	**Max Tensile Strain %**
4	Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and door frames distorted. Floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams.	15 to 25 but also depend on number of cracks	Greater than 0.3
5	Very Severe	Major repair required involving partial or complete reconstruction. Beams, load bearing, walls lean badly and require shoring. Windows broken by distortion or Danger of instability.	Usually greater than 25 but depend on number of cracks	

A] Assessment of Impact on Structures

(1) Assessment of the effect of the predicted movement on all structures within the zones of influence and a certain distance beyond these influence zones must be done.
(2) Movements and distortions shall be limited as defined in clause above.
(3) Depending upon the level of risk, precautionary and protective measures should be proposed.

B] Tunnel Design Requirements

(1) The design life of final support shall be 120 years and that of non-structural components as 50 years.
(2) Minimum grades of shortcrete and concrete shall be M30 and M35 respectively.
(3) The excavation sequences for heading, benching and invert shall be designed in such a manner that the deformations inside the tunnel shall be limited to the design deformations as considered in fixing the excavation profile. The design calculations for the support system shall be carried out with standard software available in the market, e.g. UDEC, 3DEC, FLAC, PLAXIS, etc.
(4) During the tunnel excavation, the water-inflow shall be controlled. For this purpose the required ground treatment/ dewatering, as may be necessary, Should be carried out.

C] Design Loads

(1) The design method shall consider in-situ ground stresses and shall provide evidence and measurements in support of the parameters adopted in the design as part of the calculations. The ground load on the tunnel shall be based on the actual height of overburden above the tunnel lining and the coefficient of earth pressure at rest of the soil strata surrounding the tunnel and the rock loading as worked out

from the rock-mechanics engineering principles. The effect of over-consolidation of ground shall not be considered in the design of final ground support of tunnel.

(2) The design shall take into account all additional loads, stresses and strains imposed by or on adjacent EBS and assumed distortions and loads by or on the proposed NATM tunnels.

(3) Where NATM tunnels are adjacent to or beneath EBS, the design shall demonstrate that these EBS shall not be subjected to unacceptable movement, distortion or loss of support which endangers the stability of the EBS and that any resulting movements and distortions will be within prescribed limits determined by the authority for that EBS, the Engineer.

(4) Linings shall be designed to withstand all environmental loadings, distortions and other effects without detriment. In general, NATM tunnel support shall be designed to fulfil the following requirements and to resist the following loads.

a) Superimposed surface loads from traffic, existing structures over and adjacent to the NATM tunnel, and any specified future loads.

b) Appropriate ground loads (including soil load, rock load and rock wedge load), water pressure, and seismic loads.

c) Railway loads.

d) Superimposed dead and live loads from utilities, services, systems' provisions, pathways & walkways and structural elements within the tunnel etc.

e) Structural requirements for resisting buckling.

f) Long- and short-term ground yield or squeeze.

g) Unequal grouting pressures.

h) Adjacent bored/NATM tunnelling or excavation.

i) Openings in, or extensions to, the lining.

j) Long- or short-term loads induced by construction.

k) Temperature and shrinkage.

l) Accidental loading such as fire and derailment.

m) Any other loads as considered appropriate and necessary

(5) The design shall also consider the relative rates of loading /unloading in both the lateral and vertical directions, and the resultant induced tunnel deformations whether temporary or permanent.

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