TBM- Ground Interaction Modelling

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Vineetha K, Boominathan A, Subhadeep Banerjee
Department of Civil Engineering, Indian Institute of Technology Madras, Chennai, India, boomi@iitm.ac.in

ABSTRACT: Extensive underground tunneling is being carried out today all over India using Tunnel Boring Machine (TBM) due to the significantly reduced construction time. However, field monitoring studies report ground movements and damages to buildings under which the TBM advanced through. This necessitates critical research on TBM- ground interaction to predict variations in the in-situ ground condition, optimize the TBM performance and avoid any damage to the adjacent structures. The present study focuses on a closed- face pressurized tunneling concept where all the relevant components of a mechanized tunneling process like application of face pressure, cutter head torque, tail grout pressure, back- up trailer weight and shield- skin friction, soil removal, shiel d removal, lining installation and grout hardening are numerically modelled, for a shallow tunnel of 8.0 m diameter. Tunneling is carried out in stiff clay at a depth of 19.0 m from the ground surface. Ground response in terms of deformation and pore pressure is monitored at critical locations for each excavation. As the tunneling progressed, changes in these parameters could be very well established in the numerical analysis.

RÉSUMÉ : Tunnel souterrain étendu est menée aujourd'hui dans toute l'Inde en utilisant tunnel boring machine (TBM) en raison de la réduction significative du temps de construction. Cependant, les études de suivi sur le rapport, les mouvements de terrain et de dommages aux immeubles en vertu de laquelle le TBM avancé à travers. Cela nécessite d'importants travaux de recherche sur l'interaction sol-TBM pour prédire les variations de l'état du sol in situ, d'optimiser les performances et éviter les TBM d'endommager la structures adjacentes. La présente étude se concentre sur un visage fermé- tunnel sous pression concept où toutes les composantes d'un processus de fractionnement mécanisés comme application de faire face à la pression, couple tête de coupe, la queue, la pression du coulis à poids de la remorque et le bouclier- frottement sur le sol, dépose, dépose du bouclier, du revêtement et de durcissement de coulis sont numériquement modélisés, pour un tunnel peu profond de 8,0 m de diamètre. L'encapsulation est réalisée en argile raide à une profondeur de 19,0 m de la surface du sol. La réponse au sol en termes de déformation et de pression des pores est surveillée à des emplacements critiques pour chaque excavation. Comme l'effet tunnel avançait, l'évolution de ces paramètres pourraient être très bien établi dans l'analyse numérique.

KEYWORDS: TBM, Mechanized Tunneling, Ground Deformation, Pore Pressure, Finite Element, ABAQUS.

1 INTRODUCTION AND BACKGROUND

Numerous field monitoring studies have reported ground movements induced by Tunnel Boring Machines (TBMs) driven in soft grounds. Finno and Clough 1985 stated that the ground response around the Earth Pressure Balance (EPB) shields is both three dimensional and time dependent. Xu et al. 2003 identified during an EPB tunneling both stress disturbance caused by the change in the effective stress and strain disturbance caused by the soil movement. According to Ocak 2009 the damages caused to the environment with an EPB excavation in the soft and shallow grounds of Istanbul drastically increased the project cost and project schedule. The recent field studies (Chen et al. 2011, Standing and Selemetas 2013 and Chen et al. 2014) pointed out the influence of various TBM excavation parameters like face pressure, grout pressure and machine thrust in altering the shape of the typical displacement profiles developed for the conventional open- face tunneling approach.

Apart from the greenfield ground movement observations, Dimmock and Mair 2008, Sirivachiraporn and Phienwej 2012 and Comodromos et al. 2014 investigated in the field, the response of buildings to the adjacent underground tunneling. Lee et al. 1994, Loganathan and Poulos 1998 and Liu et al. 2014 studied the response of piles in the vicinity of underground tunneling. Failure of the underground pipelines and deformation in the existing tunnel lining as a result of the proximity tunneling effects has also been reported in Yun et al. 2014, Fang et al. 2015 and Hou et al. 2015.

These studies urge the need for an in-depth research on the mechanism behind the ground movements induced by the shield tunneling techniques in order to predict variations in the in-situ ground condition, avoid disturbance to the nearby structure, optimize the tunneling process and adopt measures like compensation grouting to control the suspected ground movements. Mair et al. 1993, Addenbrooke and Potts 2001, Ng. and Lee 2005 and Pinto and Whittle 2014 are some of the prominent researches that emphasized more on the effects of conventional open- face tunneling concept. Kasper and Meschke 2004, Lambrughi et al. 2012, Comodromos et al. 2014 and Zheng et al. 2015, are a few studies dealing with the most widely adopted closed- face tunneling concept. However, attempts to investigate TBM- ground interaction focusing the influence of all the relevant components of a mechanized shield tunneling process are far fewer.

The present study attempts to numerically investigate the variations in the ground condition during a mechanized shield tunneling process. All the relevant TBM variables and phases during mechanized tunneling, namely, application of face pressure, cutter head torque, tail grout pressure, back- up trailer weight and shield- skin friction, soil removal, shield removal, lining installation and grout hardening were taken into account during every excavation stage. Appropriate interactions between different components like ground, TBM shield, lining and grout were also considered. The deformation and pore pressure response is monitored along the ground surface and around the tunnel for each excavation stage of 1.5 m.

2 NUMERICAL MODELLING

Numerical modelling was carried out using the general pur pose finite element suite, ABAQUS. A full three- dimensio nal model with circular twin-tunnels embedded in clay was developed with 8.16 m tunnel diameter, 16.0 m centre- to centre distance and 18.9 m embedment depth. Standing an d Selemetas (2013) is the reference for the details on site condition and tunneling operation. Figure 1 shows the twin - tunnel cross- section and site stratigraphy.

Length of the computaional domain is H + 12 D along the X- axis (across the direction of tunnelling), H+ 15 D along the Y- axis (along the direction of tunnelling) and H + 6 D along the Z- axis, where, H is the height of the overburden with respect to the tunnel- axis and D is the tunnel diameter.

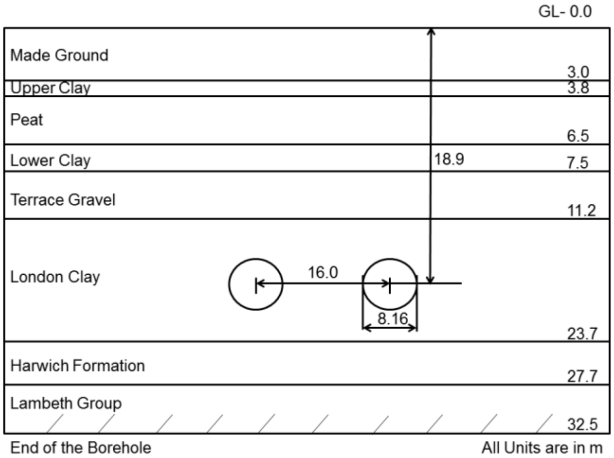

Figure 1. Site stratigraphy and tunnel alignment.

2 .1 *Three dimensional finite element mesh*

Figure 2 shows the three dimensional finite element mesh for the underground tunnels excavated using mechanized shield method.

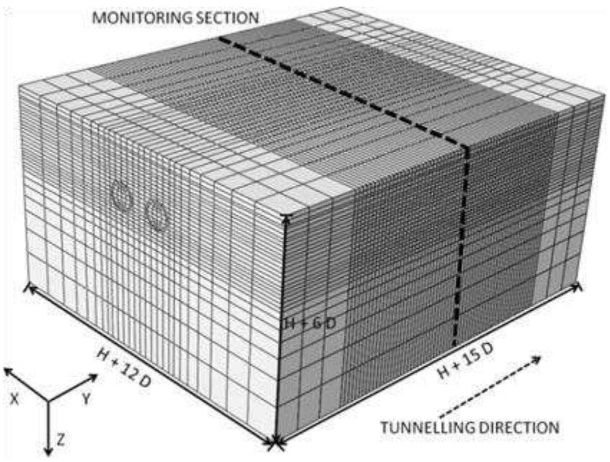

Figure 2. The three dimensional finite element mesh for the underground tunnels excavated using mechanized shield.

Meshing is done for the heterogeneous soil section with eight distinct soil layers, TBM shield, lining and grout sections. Soil and grout sections were discretized using C3D8RP (Eight- noded linear brick element with trilinear displacement, pore pressure and reduced integration scheme), whereas, TBM shield and tunnel lining were discretized using S4R (four- noded conventional stress/ displacement shell element with reduced integration scheme).

Translations in directions perpendicular to the YZ- plane and XZ- plane were constrained. Bottom boundary of the soil domain was fixed. Rotational degrees of freedom were locked for the TBM shield and lining.

2 .2 *Materials and constitutive relationships*

Soil parameters adopted in this study are shown in Table 1. Ground water table is at the ground level. TBM shield, grout and tunnel lining material parameters are presented in Table 2.

Table 1. Soil Parameters

Material	**Depth** (m)	**γ** (kN/m^3)	**E_u** (MPa)	**ν**	**e_0**	**c_u** (kPa)
Made Ground	0- 3.0	18	3	0.49	1.08	20
Upper Clay	3.0- 3.8	15	0.9	0.49	8.1	20
Peat	3.8- 6.5	15	0.45	0.49	9	20
Lower Clay	6.5- 7.5	15	0.9	0.49	1.62	20
Terrace Gravel	7.5- 11.2	20	24	0.2	0.79	(φ= 39^0)
London Clay	11.2- 23.7	19	54	0.49	0.68	60 + 3z*
Harwich Formation	23.7- 27.7	20	60	0.49	0.68	97.5 + 3z*
Lambeth Group	27.7- 32.5	21	70	0.49	0.68	109.5 + 3z*

*z = depth below top of London Clay

Table 2. TBM Shield, Grout and Tunnel Lining Material Parameters

Material	**Outer Diameter** (m)	**Thickness** (m)	**γ** (kN/m^3)	**E** (GPa)	**ν**
Shield	8.12	0.1	80	1500	0.1
Grout	8.12	0.155	20	0.5	0.4
Lining	7.81	0.35	25	26.3	0.2

Clay deposits and Terrace gravels are modeled using Drucker Prager constitutive relation with and without a cap, respectively. Shield, lining and grout behave as elastic materials and hence simple linear elastic relation is used with an assumption that less than 5 % elastic strains are developed in the material.

2 .3 *Contacts and loads*

Surface to surface contact with master- slave concept was used to define the different interactions between soil- TBM shield, soil- grout and grout- lining where the master surface is considered to be rigid compared to the slave surface. Contact behaviour was defined in tangential and normal directions with penalty friction contact formulation and hard contact with Lagrange formulation, respectively. Tie constraints were used to connect the individual segments of shield, lining and grout.

Loads applied to the soil during the mechanised tunnelling procedure are summarised in Table 3.

Table 3. Loads considered in the Mechanised Tunnelling Simulation Procedure

Load type	**Magnitude***	**Region of application**
Cutter- head torque	1.12 MN m	Excavation face at every 1.5 m interval
Face pressure	2.0 bar	Excavation face at every 1.5 m interval
Traction from shield- skin	5.54 MN	Excavated soil surface in contact with shield
Tail grout pressure	1.6 bar	Excavated soil surface after removal of shield
Back- up trailer weight	4 MN	Invert of the Lining

*Magnitudes are taken from Standing and Selemetas (2013)

Before the application of these loads, the in- situ stress conditions were established. A coupled pore fluid diffusion and stress analysis (ABAQUS 2012) was implemented. Accordingly, an effective stress principle is used to describe the behavior of the porous medium. The finite element mesh is attached to the solid phase and fluid flow is allowed through this mesh.

3 RESULTS AND DISCUSSION

Ground response discussed in this section include displacement and pore pressure variation at selected locations, monitored for each excavation stage of 1.5 m during the excavation of the left-tunnel. Results from the finite element study are compared with the field monitoring data reported in Standing and Selemetas (2013). All the relevant TBM variables and phases during mechanised tunnelling process are considered for plotting the ground responses and are numbered from 1 to 8 (1- application of cutter head torque, 2- face pressure, 3- shield- skin friction, 4- shield removal and application of tail grout pressure, 5-withdrawal of tail grout pressure followed by lining installation, 6- back- up trailer weight, 7- grout hardening and 8- soil removal). A separate analysis is carried out in the conventional open- face method where the influence of the different TBM variables is ignored; soil- shield removal and grout- lining installation alone are taken into account. Monitoring section lies in the middle of the computational domain along the direction of tunnelling. The co- ordinates (x, y, z) = (0, 0, 0) corresponds to the location on the ground surface above the centre- line of the left- tunnel lying in the monitoring section.

Figure 3 shows the vertical displacement profile on the ground surface along the monitoring section against the distance of the TBM face from the monitoring section as the tunnel advances. Both the field data and FE study shows an initial heave (< 1 mm) as the TBM approaches the monitoring section with the distance of face at about y= -20.0 m. This is followed by a progressive settlement of about 3 mm in both the field and numerical study.

Figure 4 shows the changes in pore water pressure plotted against the distance from TBM face near the tunnel crown. It is understood that results from the FE study at phase number 5 which corresponds to the withdrawal of tail grout pressure and installation of the tunnel lining closely follows the field results. Excess pore water pressures around 100 kPa was observed in both the field as well as the FE study as the TBM face approaches the monitoring section which can be attributed to the settlement of soil above the tunnel during the TBM shield withdrawal, trailed by the lining installation and grouting. As the tunnel advanced beyond the monitoring section, pore pressure reduced progressively which can be attributed to the stress release above the tunnel- crown due to the grout hardening and transfer of overburden to the lining segments.

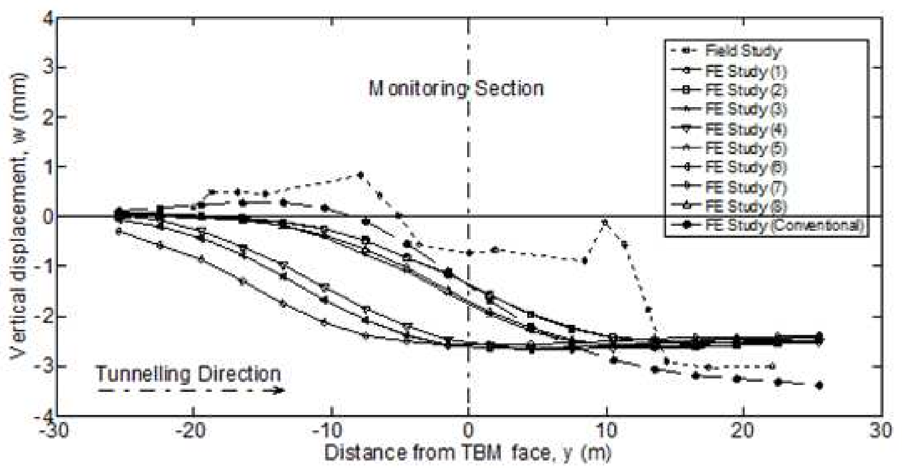

Figure 3.Vertical displacement on the ground surface at x=0.0 m in the monitoring section, as the TBM advances

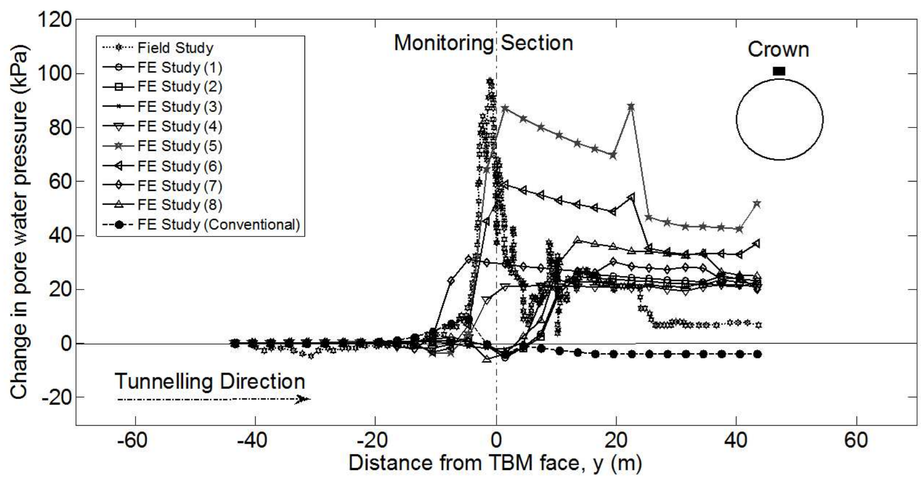

Figure 4. Changes in pore water pressure plotted against the distance from TBM face near the tunnel crown

3 CONCLUSION

Ground response in terms of deformation and pore pressure at critical locations were investigated using the three- dimensional finite element model simulating the mechanized shield tunneling process. All the relevant TBM operational parameters were appropriately considered. Even though the numerical model for conventional method with the open- face tunneling concept could satisfactorily demonstrate the probable ground deformation, it failed to record the pore pressure fluctuations around the tunnel. Whereas, the results from the numerical study involving the closed- face tunneling concept incorporating all the pertinent mechanized tunneling features, closely followed the field recorded data including the pore pressure variation. It is to be noted that information on near field pore pressure variations are significant as they can affect the adjacent structure integrity. Hence, this study highlights the necessity of properly accounting for all the important TBM variables and tunneling phases in order to clearly establish the ground responses during a mechanized tunneling process.

REFERENCES

Addenbrooke T. I. and Potts D. M. 2001. Twin tunnel interaction: Surface and subsurface effects. *The International Journal of Geomechanics* 1(2), 249- 271.

Chen R.P. et al. 2011. Ground movement induced by parallel EPB tunnels in silty soils. *Tunnelling and Underground Space Technology* 26(1), 163–171.

Chen J.-F., Kang C.-Y. and Shi Z.-M. 2014. Displacement monitoring of parallel closely spaced highway shield tunnels in marine clay. *Marine Georesources and Geotechnology* 33(1), 45–50.

Comodromos E.M., Papadopoulou M.C. and Konstantinidis G.K. 2014. Numerical assessment of subsidence and adjacent building movements induced by TBM-EPB tunneling. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* 140(11), 4014061-1–12.

Dimmock P.S. and Mair R.J. 2008. Effect of building stiffness on tunnelling-induced ground movement. *Tunnelling and Underground Space Technology* 23(4), 438–450.

Fang Q. et al. 2015. Effects of twin tunnels construction beneath existing shield-driven twin tunnels. *Tunnelling and Underground Space Technology* 45, 128–137.

Finno R.J. and Clough G.W.1985. Evaluation of soil response to EPB shield tunneling. *Journal of Geotechnical Engineering (ASCE)*111(2), 155–173.

Hou Y. et al. 2015. Excavation failure due to pipeline damage during shallow tunnelling in soft ground. *Tunnelling and Underground Space Technology* 46, 76–84.

Kasper T. and Meschke G. 2004. A 3D finite element simulation model for TBM tunnelling in soft ground. *International Journal for Numerical and Analytical Methods in Geomechanics* 28, 1441- 1460.

Lambrughi A., Rodriguez L. M. and Castellanza R. 2012. Development and validation of a 3D numerical model for TBM– EPB mechanised excavations, *Computers and Geotechnics* 40,97- 113.

Lee R.G.,Turner A.J. and Whitworth L.J. 1994. Deformations caused by tunneling beneath a piled structure. *In: Proceedings of 13th ICSMFE*, New Delhi, India, 873–878.

Liu C., Zhang Z. and Regueiro R.A. 2014. Pile and pile group response to tunnelling using a large diameter slurry shield – Case study in Shanghai. *Computers and Geotechnics* 59, 21–43.

Loganathan N. and Poulos H.G. 1998. Analytical prediction for tunneling- induced ground movements in clays. *Journal of Geotechnical and Geoenvironmental Engineering* 124(9), 846–856.

Mair R.J. Taylor R.N. and Bracegirdle A.1993. Subsurface settlement profiles above tunnels in clays. *Geotechnique* 43(2), 315–320.

Ng C. W. W. and Lee G. 2005. Three-dimensional ground settlements and stress- transfer mechanisms due to open-face tunnelling. *Canadian Geotechnical Journal* 42, 1015- 1029.

Ocak I. 2009. Environmental effects of tunnel excavation in soft and shallow ground with EPBM: the case of Istanbul. *Environmental Earth Sciences* 59(2), 347–352.

Pinto F. and Whittle A.J. 2014. Ground movements due to shallow tunnels in soft ground. I: Analytical solutions. *Journal of Geotechnical and Geoenvironmental Engineering (ASCE)* 140 (4), 4013040-1–17.

Sirivachiraporn A. and Phienwej N. 2012. Ground movements in EPB Shield tunneling of Bangkok subway project and impacts on adjacent buildings. *Tunnelling and Underground Space Technology* 30, 10–24.

Standing J. R. and Selemetas D. 2013. Greenfield ground response to EPBM tunnelling in London clay. *Geotechnique* 63(12), 989- 1007.

Xu Q. et al. 2011. Laboratory model tests and field investigations of EPB shield machine tunnelling in soft ground in Shanghai. *Tunnelling and Underground Space Technology* 26(1), 1–14.

Yun H.-B. et al. 2014. Monitoring for close proximity tunneling effects on an existing tunnel using principal component analysis technique with limited sensor data. *Tunnelling and Underground Space Technology* 43, 398–412.

Zheng G. Lu P. and Diao Y. 2015. Advance speed- based parametric study of greenfield deformation induced by EPBM tunnelling in soft ground. *Computers and Geotechnics* 65, 220- 232.