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STUDY ON TUNNELING FOR UNDERGROUND METRO RAIL SYSTEM IN DHAKA CITY

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ABSTRACT

In this research, the prospect of tunneling by cut and cover and New Austrian Tunneling Method (NATM) for underground metro rail system in Dhaka city was evaluated. Both conventional analysis and 2D finite element analysis using an elasto-plastic constitutive model named as subloading t_{ij} considering plane strain drained condition were performed. A comparison was made between results obtained from conventional analysis and numerical analysis for braced cuts. The behavior of different types of soil layers are simulated. Effects of different loading conditions and presence of water table have been considered for both cut and cover and NATM excavation method. Comparing the results of different foundation types, it has been found that for shallow foundation the surface settlement at the position of the foundation is larger than that for pile foundation. From analyses, it was revealed that for greenfield like Tongi to Uttara along the MRT-4, cut and cover is more appropriate considering its simplicity in execution and NATM is preferable at flyover junction points in Cantonment and structurally obstructed places.

Keywords: Tunneling, Cut and Cover, NATM, Subloading t_{ij} Model, Mass Rapid Transit, Braced Sheet Pile.

INTRODUCTION

Traffic congestion is a major problem in Dhaka, the capital city of Bangladesh. It is the 9th largest city in the world by population which covers 360 km^2 bearing more than 15 million people. The present transportation system of the city is incapable of satisfying the demand. Construction of underground metro rail tunnel which is a new technological challenge for Bangladesh can be a good solution measure for it. As Dhaka is over-crowded with shortage of land, the system of underground metro rail tunnel utilizing the underground space for transportation not only reduces the travel time but also introduces a new mode of transport pathway.

Cut and cover excavation method and NATM have been applied in this research. Cut and cover method is a simple technology mainly suitable for shallow tunnels which generally requires a large open space having negligible structural obstacles nearby the alignment for its construction ease. Skilled professionals are less important in this technique. Whereas, NATM is a “design as you go” approach where excavation work proceeds and optimized support system or lining is provided simultaneously based on observed ground conditions by the machine itself. Mr. Rabeciwz, the principal founder of NATM, introduced this technique in 1962 [1].

A few research works have been accomplished for underground tunneling system in Dhaka city. Waheed [2] applied cut and cover excavation method along the existing rail line in Dhaka city based on the conventional method. Farazandeh [3] has proposed Mass Rapid Transit-6 (MRT-6) [4] route and applied NATM for study on tunneling system. According to the previous researches, both cut and cover method and NATM of underground tunnel construction are feasible for urban Dhaka based on the existing route conditions and structural obstacles nearby the route of interest.

Generally, a route does not enclosed by obstacles all along its way and depths of soil layers are different from one point to another point of the route. However, underground metro rail system is a subject to specific restrictions such as subsidence, crack, and environment pollution during construction. So, it is require to analyze which excavation method is effective and acceptable along the different portions of a route in Dhaka city. Moreover, Dhaka city comprises clayey soil underlying sandy soil in most of the parts. It has become a necessity to use the numerical analysis by FEM to explore the performance and applicability of cut and cover method and NATM and also to ensure optimum utilization of congested urban land area in Dhaka for underground metro rail tunneling system.

The objectives of this study are to perform the conventional and numerical analysis for the braced cut sheet pile type retaining system of tunnel considering cut and cover method, to execute numerical analysis to simulate tunneling system for NATM and finally to make a comparison among these results. Thus the stability of retaining structure and tunnel system can be investigated for the optimized selection of construction method of tunnel of underground metro rail system in Dhaka city.

METHODOLOGY OF THE ANALYSIS

A conventional analysis has been done for cut and cover excavation method using braced cut sheet pile. Two-dimensional finite element analyses have been carried out with FEMtij-2D [5]. The constitutive model used in these numerical analyses has been the subloading t_{ij} model [5]. These analyses simulate the excavation sequences of cut and cover for sheet pile with braced cut and NATM for lining structure considering typical soil condition of Dhaka city. Subloading t_{ij} model [5] has the following features [6]: (1) the model requires only a few unified material parameters; (2) the model can describe the characteristics of soils like: (a) influence of intermediate principal stress on the deformation and strength of soil; (b) influence of stress path on the direction of plastic flow is considered by splitted the plastic strain increment in to two components; (c) influence of density and/or confining pressure.

Study Area

Mass Rapid Transit-4 (MRT-4) proposed in Strategic Transport Plan, STP [4], has been considered as study route alignment for the study. MRT-4 route as shown in Fig. 1 passes from Uttara (north of Dhaka) to Sayedabad bus terminal passing Kamalapur railway station (located at south of Dhaka) via Farmgate. Major portion of the route of MRT-4 is now being used as railway of Dhaka city passing from Tongi-Uttara junction to Kamalapur railway station. Four locations (Uttara, Mohakhali, Farmgate and near Dhaka University campus area) have been selected for sub-soil analysis.

Sub-soil Properties

Comprehensive laboratory tests have been carried out for the soil samples collected along the study area. All soil analyses are combined and summarized to determine the required soil parameters to perform the FE analyses. Typical sub-soil profile along MRT-4 is shown in Fig. 2. At Uttara, it is found that the top formation of soil is clayey silt extends roughly to the depth of 16m. The subsequent layer of soil is sandy silt which goes up to the depth of 25m. Soil below up to 30m depth exhibits fine sand. At Farmgate top 6.5m is silty clay, then the subsequent layer is silty sand up to 18.5m

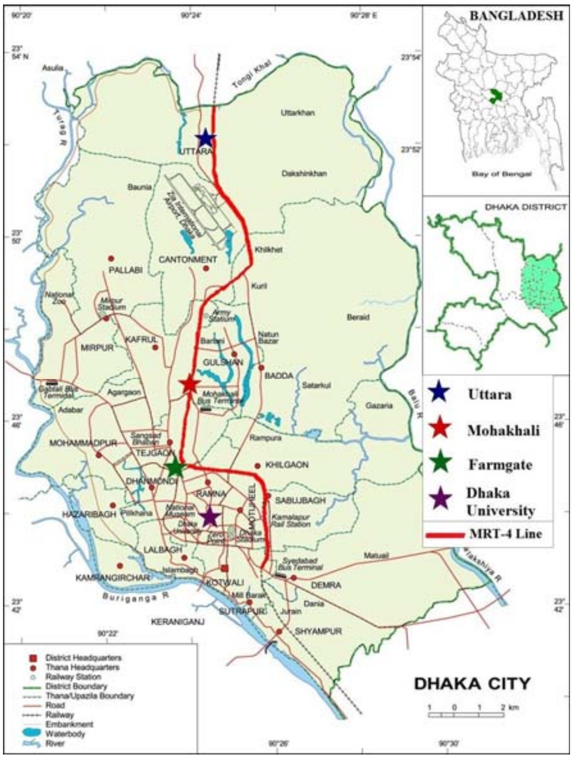


Fig. 1 Study route along MRT-4.

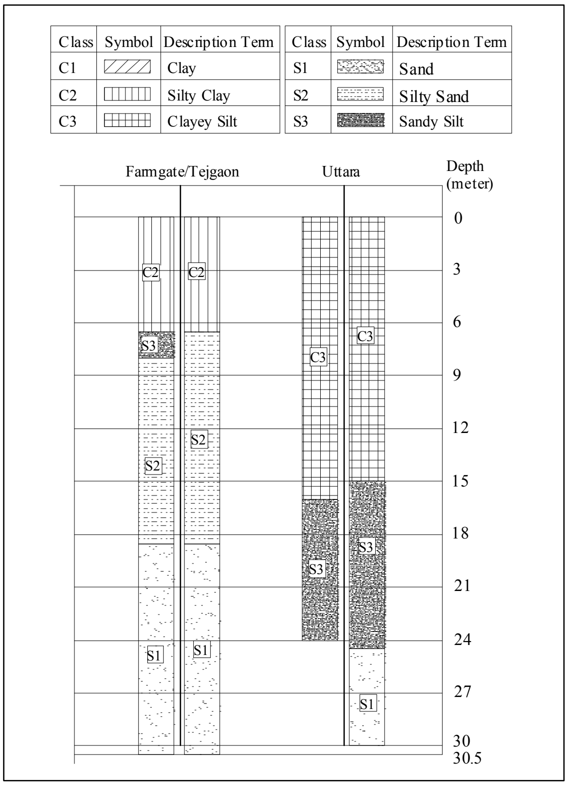


Fig. 2 Sub-soil profile along MRT-4 in Dhaka.

and it follows fine sand up to boring depth of 30.5m. The detailed sub-soil profile for the route is available in Azam [7].

Finite Element Analyses

The analyses by FEMtij-2D [5] code using Subloading t_{ij} model [5] are carried out considering plane strain drain condition. The small strain theory is used in the numerical simulation. Both the effects of structural loads (with foundation types as footing, pile) and water loads are considered in the methods of cut and cover, NATM analyses. The dimension of the model for analysis is selected in a way so that the boundary effects in the numerical model are minimum. Different types of finite element meshes under various field cases are adopted for the analyses. The sub-soil is simulated by quadrilateral elements specifying for different layers of soil. Soil and concrete are modeled as isoparametric 4-noded (quadrilateral type) element. The sheet pile (cut and cover method), lining and rock bolt (NATM) and reinforcement in pile are modeled as 2-noded beam element. The interface between soil and concrete (pile cap or footing) is simulated by 4-noded elasto plastic joint element [8] and the bracings or struts are modeled as elastic spring applying axial stiffness per unit length. The reinforced concrete pile is modeled as hybrid element [9] consisting elastic solid and beam element. Smooth boundary conditions are used. The drainage boundary conditions are adopted in assigning data in analysis only when water is present. Load from nearby building structures are considered to simulate the model. Building is existed at one side of tunnel location at a distance of 16 to 20m from tunnel centerline. The load of building is applied as pile or as footing load. The values of load as assigned in the model analysis are 638 kN and 958 kN as similar to a five and eight storied building loads, respectively.

Table 1 Model parameters of soil required for Subloading t_{ij} model

Parameter	Clay	Sand
λ	0.125~0.18	0.088
κ	0.0157~ 0.04	0.015
$R_{CS} = (\sigma_1/\sigma_3)_{CS(comp.)}$	3.6	1.64
N (e_N at p=98 kPa)	0.70~ 0.73	0.75
e_o	0.73~ 0.74	0.6
υ	0.2	0.2
β	1.5	2.0
a^{AF}	600	600

Note: λ = Compression index or slope of loading curve in e-log p' curve at the loosest state; κ = Swelling index or slope of unloading curve in e-log p' curve at the loosest state where, e is void ratio and p' is consolidation pressure; $R_{CS} = (\sigma_1/\sigma_3)_{cs(comp.)}$ = Critical state stress ratio; N or e_N = void ratio at mean principal stresses (*p*) 98kPa in the above mentioned loading curve; e_o = Initial void ratio; υ = Poisson's ratio; β = Model parameter responsible for the shape of the yield surface; a = Model parameter responsible for the influence of density and confining pressure.

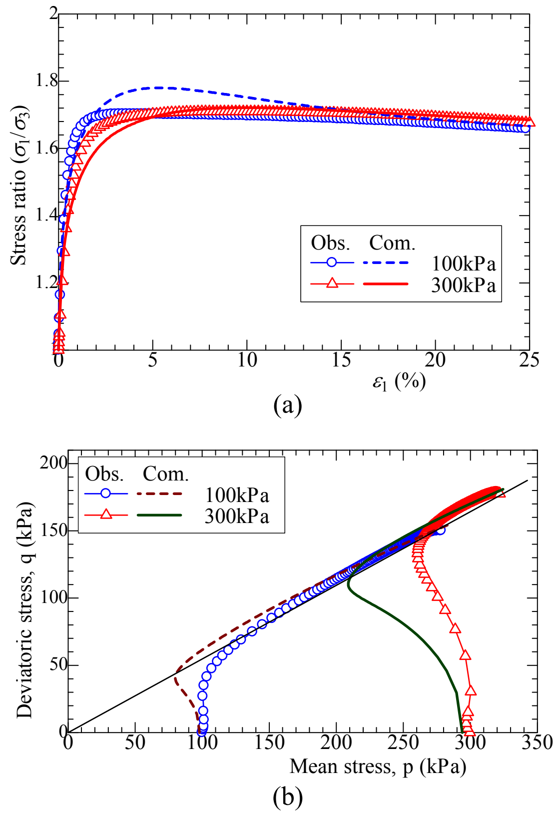


Fig. 3 Resulted simulations for model parameters of sandy soil: (a) stress ratio, σ_1/σ_3 versus vertical strain, ε_1 and (b) deviatoric stress, q versus mean stress, p.

Determination of model parameter

All the required parameters of the subloading t_{ij} model [5] defining the mechanical behavior of soil layers are summarized in Table 1. The related graphs of simulation of elasto-plastic model parameters are shown in Figs. 3(a) and 3(b). Fig. 3(b) shows the positive and negative dilatancy of sandy soil. More details about model parameter are available in Islam et al. [10]. The parameters for the sandy soil have been simulated from consolidated undrained test. However, for more accurate result consolidated drained tests need to be conducted.

Conventional Analysis for Cut and Cover

In the conventional analysis, braced cut sheet pile for cut and cover method is analyzed using the design or apparent pressure envelops theory developed by Peck [11] considering different soil profiles as presented in Fig. 4 along the proposed route (MRT-4) which is located along the existing rail line in Dhaka city (Fig. 1).

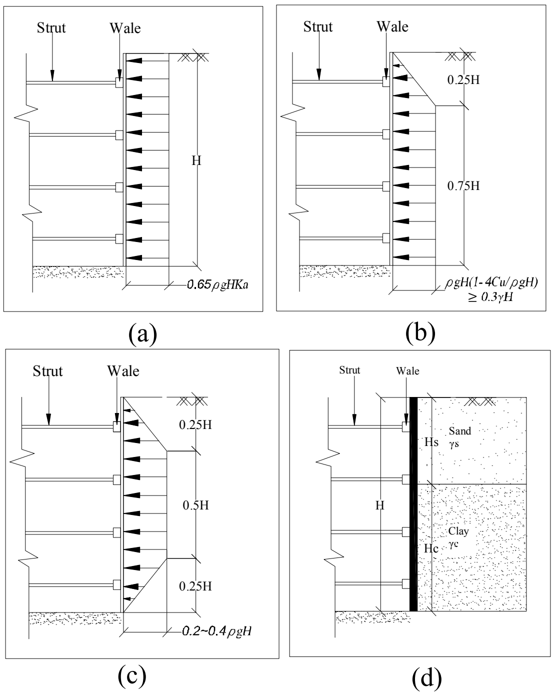


Fig. 4 Earth pressure diagram for braced cut system in (a) sandy soil, (b) soft to medium clay soil, (c) stiff clay soil and (d) layered soil: sandy soil underlying clay soil.

Numerical Analysis for Cut and Cover

Four cases have been considered where case1 represents greenfield condition and case2, case3, case4 consider the effect of building load, the effect of water and the effects of both water and building load, respectively. The analyses are executed at insertion of sheet pile wall and all bracings (wales and struts), at placement of tunnel and at backfilling. The geometry for tunnel placement for greenfield condition is shown in Fig. 5. The procedures are continued for all the four cases considering excavation depth of 12m and sheet pile depth of 18m from EGL. Case5 considers greenfield condition where depth of both excavation and sheet pile is 12m from EGL. In all cases, modeled sub-soil is 30m deep from the ground surface and 98m wide with 49m horizontally extended toward both left and right direction from the excavated centerline. The top soil is clayey soil up to 6m depth from EGL and

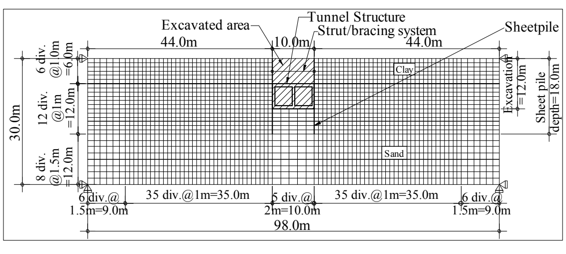


Fig. 5 Geometry for braced sheet pile.

the bottom 24m is sand. In case2, the footing is located at 16m distance from nearest excavated edge and the footing width is 4m. The building load is 638 kN which is applied at centre node of footing.

Numerical Analysis for NATM

In case1, NATM analyses are done considering greenfield condition, case2 refers building load with pile foundation and case3 refers building load with shallow foundation. The modeled subsoil is 33m deep and 93m to 100m wide. Top soil is clayey for 6m depth from EGL and rest 27m is sand. Excavated tunnel diameter is 9m and depth of crown from EGL is 11m. Building load is applied as pile in case2 (Fig. 6) where the pile depth is 15m and as footing load in case 3 where the footing width is 4m. Building load is 958 kN which is applied concentrically.

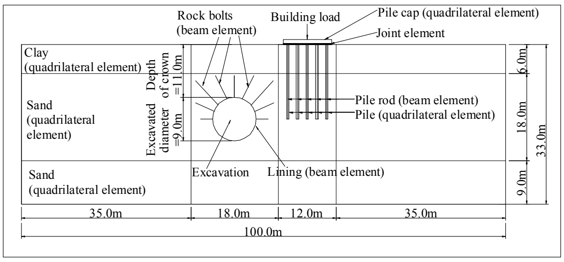


Fig. 6 Tunnel excavation geometry for NATM with pile foundation at one side of tunnel.

ANALYSES AND RESULTS

Conventional Results for Braced Sheet Pile

At a typical site (Farmgate) in Dhaka, the depth of tensile crack is found as 15.5m. So, the 1st strut is placed at the depth of 3m from the EGL and other struts are placed at 3m spacing c/c. Depth of both excavation and sheet pile are taken as 12m from EGL. The equivalent cohesion and average unit weight and apparent pressure are calculated following resulted earth pressure diagram as per

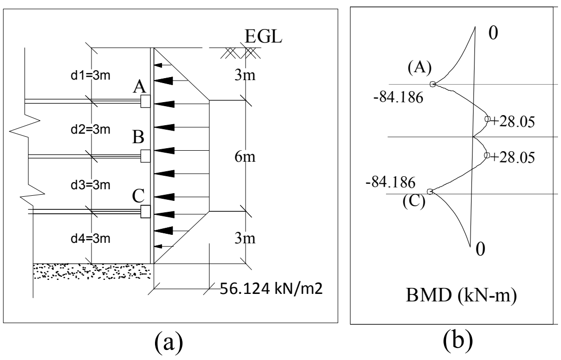


Fig. 7 (a) Earth pressure diagram and (b) bending moment diagram for braced cut sheet pile.

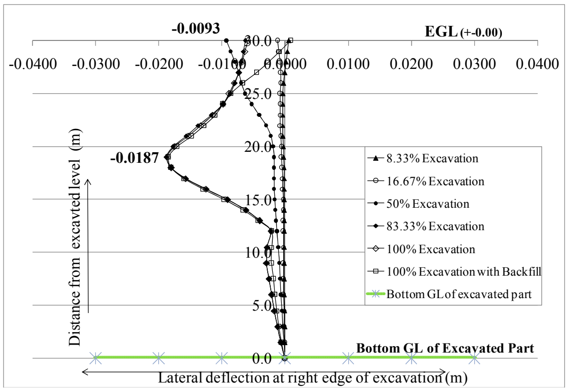
Peck [11]. The maximum lateral earth pressure is 56.124 kN/m^2 as shown in Fig. 7(a). Strut loads at level A, B and C are also determined. The bending moment diagram has been shown in Fig. 7(b). Maximum moment for sheet pile is found as 84kN-m/m of wall.

Finite Element Analysis for Cut and Cover

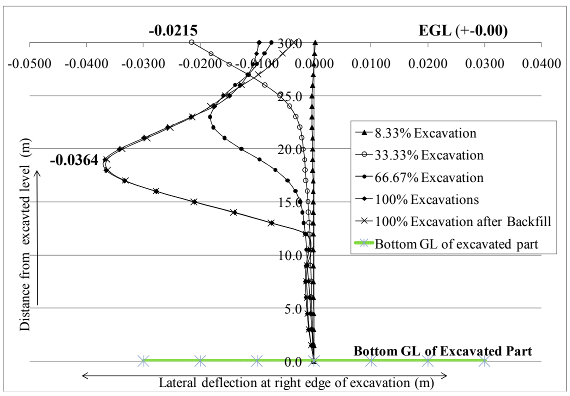
Among all five cases for cut and cover excavation method with braced cut sheet piles, the results of case1, case2 and case5 have been depicted for comparison in this paper.

The distributions of lateral displacement of sheet pile wall after backfilling are presented in Fig. 8. In all cases, pattern of displacement follows the typical deformation shape of braced cut wall. Here, the wall's upper portion is restrained from undergoing large horizontal movement. From the graphs, it is seen that the maximum horizontal displacements are 18.7mm (case1), 36.4mm (case2).

The earth pressure diagrams for braced cut sheet pile are presented in Figs. 9 and 10(a). The values of earth pressure are 138kN/m^2 (case1), 166kN/m^2 (case2). It is found that the earth pressure of conventional analysis is 56.124 kN/m^2 (Fig. 7(a))



(a)



(b)

Fig. 8 Distribution of lateral displacement for sheet pile with braced cut after backfilling - (a) case1: greenfield condition and (b) case2: shallow foundation.

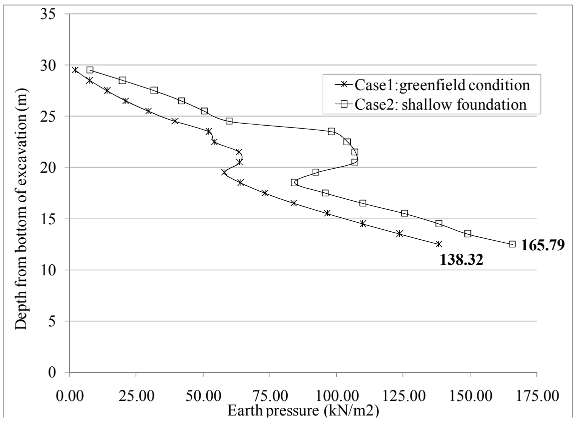
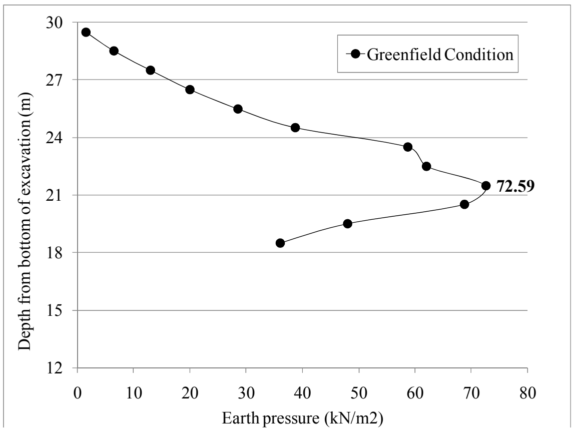
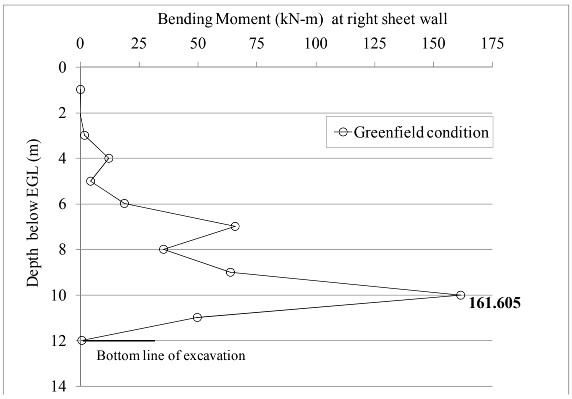


Fig. 9 Earth pressure diagram for braced sheet pile



(a)



(b)

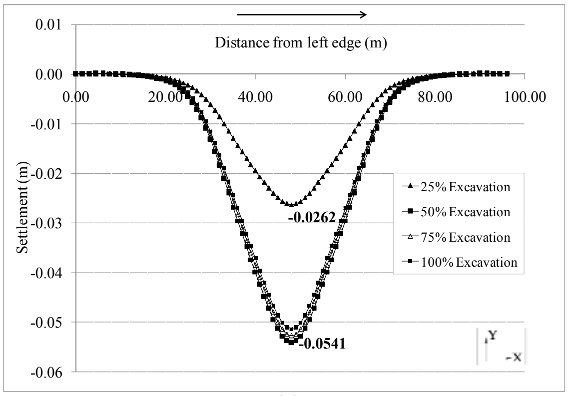
Fig. 10 (a) Earth pressure and (b) bending moment diagrams for braced cut with depth of excavation, sheet pile are 12m (case 5).

and it is 72.59 kN/m^2 (case5) in numerical result (Fig. 10(a)). The diagram pattern resembles slightly, though the conventional analysis shows a sharp edged trapezoidal shape and numerical analysis shows some sought of curvilinear shape.

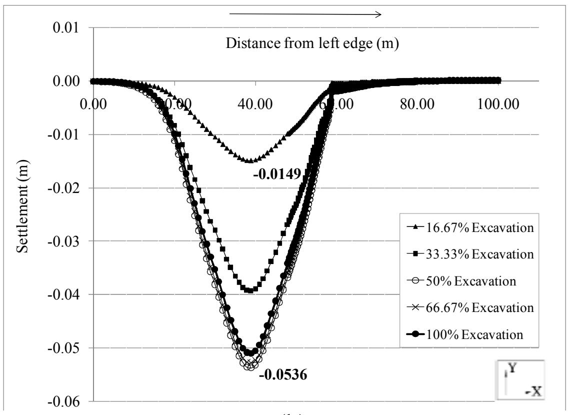
If the bending moment diagrams are analyzed by conventional analysis and numerical analysis (Figs. 7(b) and 10(b)), then it can be found that there exists a tendency of increasing the bending moment value in numerical analysis unlike the conventional analysis. In conventional analysis the moment values keep a harmonic nature while going to depth.

Finite Element Analysis for NATM

In NATM, model analyses have been executed considering greenfield condition and building loads. Case1 represents greenfield condition, case2 and case3 represent pile and shallow foundation, respectively. The building is existed at one side of tunnel at a distance of 20m from tunnel center.



(a)



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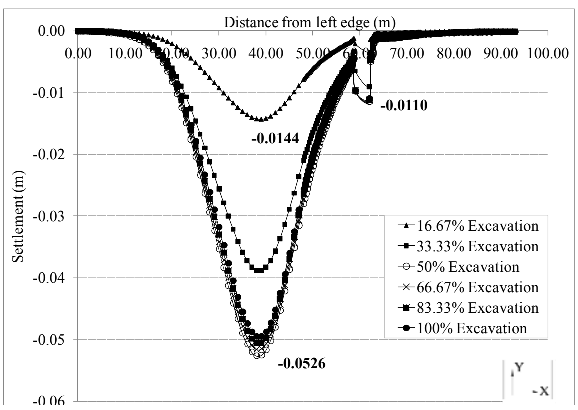


(c)

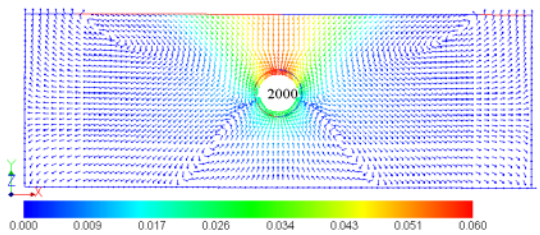
Fig. 11 Surface settlement for NATM - (a) case1: greenfield condition, (b) case2: building load as pile and (c) case3: building load as footing.

Surface settlement

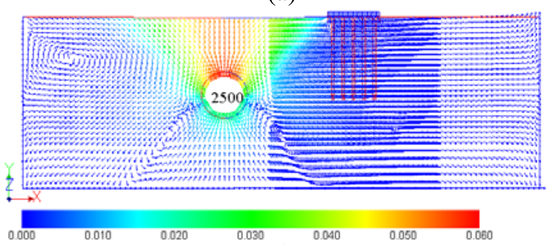
The profiles of surface settlement are depicted in Fig. 11 at different excavation stages. It is seen that the maximum settlement are 54.1mm (case1), 53.6mm (case2) and 52.6mm (case3) which are found at 50% stress relaxation of excavated elements. The widths of the affected zone along surface above the tunnel crown are around 65m (case1), 55m (case2) and 60m (case3). In case2, settlement pattern shows slight unsymmetrical because of presence of building at right side. In case3, settlement is not smooth at right side because of presence of footing as foundation of building.

Displacement vector

Displacement vector for both the x and y directions are presented here at final stages of excavation (Figs. 12(a), 12(b) and 12(c)). From this vector it can be seen that at final step (100% stress relaxation of excavated elements) the maximum resultant displacement is 60 mm (case1, case2, case3). It is visualized that the intensity of vector is highest at the crown of tunnel than the invert location of tunnel. The path of displacement vectors represents the inward stress on lining of tunnel. It is also seen in case2 that pile which transfer the



(a)



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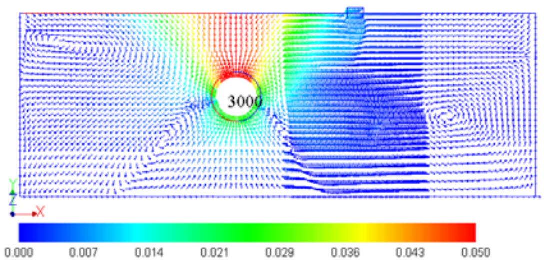


(c)

Fig. 12 Displacement vector diagrams for NATM: (a) case1: greenfield condition, (b) case2: building load as pile and (c) case3: building load as footing.

building load at deeper depth has very negligible effect on excavation of tunnel.

Earth pressure or lining pressure

The diagram of earth pressure of tunnel is presented in Figs. 13(a) and 13(b) for case2 and case3, respectively. For initial stage of excavation the diagram shows a general distribution of stress. Later with increase of stress in step by step it shows more distinct characteristics of pressure distribution especially along the rock bolt line and lining (or shotcrete). With the excavation advances beyond 25% stress relaxation of total excavated elements net active earth pressure around the tunnel reduces due to insertion of rock bolts. It reduces further when shotcrete is provided against failure by pressure at 40% stress relaxation of total excavated elements.

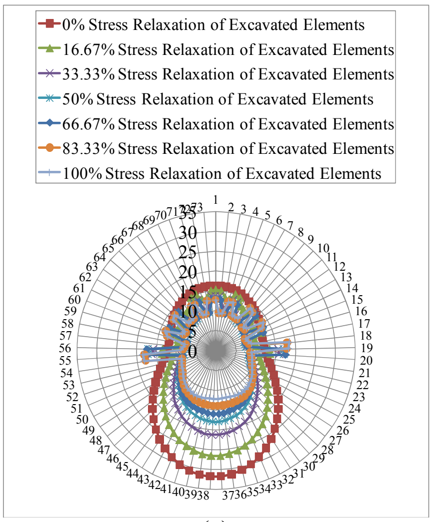
CONCLUSION

It is observed that finite element analysis using subloading t_{ij} model, the interactions of soil-structure and soil-water, the behavior of materials can be simulated as per practical situation and gives more realistic results comparing the conventional analysis which is based on many simplifications and assumptions.

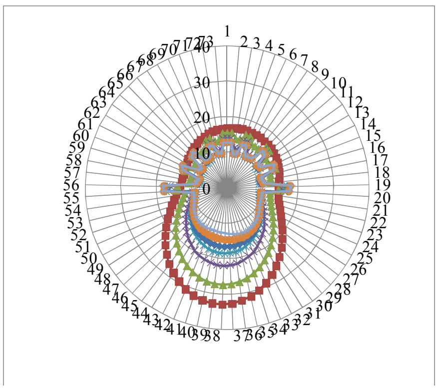
For construction of underground tunnel in cut and cover method of braced sheet pile, the lateral displacement for case2 (shallow foundation) is 36.4mm which is higher than for case1 (greenfield condition) of 18.7mm. For comparison considering case5, it is found that the earth pressures are 56.12 kN/m^2 and 72.59 kN/m^2 in conventional analysis and numerical analysis, respectively.

In NATM, considering all cases, the range of surface settlement is very small (from 52.66mm to 54.10mm). But patterns of settlement are locally affected slightly in case2 for pile foundation and mostly in case3 for shallow foundation. Shahin et al. [12] comparing the results of different foundation types has found that for shallow foundation the surface settlement at the position of the foundation is larger than that for pile foundation. In this study, same depiction has been revealed.

It is also revealed that NATM shows more stability in soil retention than cut and cover method for congested areas in Dhaka. For open spaces like Tongi to Uttara along the MRT-4, cut and cover is more appropriate considering its simplicity in execution and NATM is preferable method at flyover junction points in Cantonment and structurally obstructed places (Farmgate to Sayedabad) in geotechnical consideration. Thus an optimized underground metro tunnel system can be constructed for Dhaka city after proper prediction of ground movements and influence of tunneling with a sophisticated simulation tool.



(a)



(b)

Fig. 13 Lining stress contours for NATM (a) case2: building load as pile and (b) case3: building load as footing.

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