The influence of buildings and ground stratification on tunnel lining loads using finite element method

L'influence des bâtiments et de la stratification du sol sur les charges de revêtement du tunnel utilisant la méthode d'éléments finis

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ABSTRACT: Urban development and increasingly growth of population have been accompanied by a considerable growth in mechanized Shield tunnelling. Commonly precast concrete segments used as tunnel lining in mechanized tunnelling and include relatively considerable part of tunnelling cost. The optimum design of lining that decreases tunnelling cost needs to accurate evaluation of loads act on lining. In this study, the effects of soil stratification, building's geometry, position and weight on lining loads were studied. A 2D finite element model was applied to simulate the conventional procedure of tunnel excavation and lining using Abaqus software (Ver 6.10). The geometry of tunnel, lining segments, injection grout and around soil properties were adapted from under construction Tabriz urban railway line 2 project. The results show that ground stratification and building properties (especially the position of buildings) have considerable effects on lining loads. From the viewpoint of structural design, the buildings effect on lining is critical when the surface buildings are unsymmetrical.

RÉSUMÉ : Le développement urbain et de plus en plus la croissance de la population s'est accompagnée d'une croissance considérable dans le domaine de Tunnelier. Communément préfabriqué segments de béton utilisés comme revêtement de tunnel en tunnel mécanisé et inclure une partie relativement importante du coût tunnel. La conception optimale du revêtement qui diminue les coûts tunnel besoins d'une évaluation précise des charges agir sur la revêtement du tunnel. Dans cette étude, les effets de la stratification du sol, la géométrie du bâtiment, la position et le poids des charges de revêtement ont été étudiés. Un modèle par éléments finis 2D a été utilisé pour simulation de la procédure classique d'excavation du tunnel et revêtement en utilisant le logiciel Abaqus (version 6.10). La géométrie du tunnel, voussoirs, coulis d'injection et autour des propriétés du sol ont été adaptées au tunnel de métro de Tabriz (line 2) qui est en cours de construction. Les résultats montrent que la stratification du sol et les propriétés de construction (en particulier la position des bâtiments) ont des effets considérables sur les charges de revêtement. Du point de vue de la conception structurelle, l'effet bâtiments sur le revêtement est essentiel lorsque les bâtiments de surface ne sont pas symétriques.

KEYWORDS: FEM, Abaqus, mechanized tunnelling, tunnel lining loads, surface buildings, stratification.

1 INTRODUCTION

Urban development and increasingly growth of population have been accompanied by a considerable growth in tunnel construction for subways, railway underpasses, and urban highways and a continuous development of tunneling technology in recent years. Besides conventional excavation methods such as the New Austrian Tunneling Method (NATM) shield tunneling is now a well established method which allows for tunnel advances in a wide range of soils and difficult conditions such as high ground water pressures, soft soils or small cover depths. It is well known that segments' production cost accounts for a large amount of the total shield tunnel construction cost and one of the effective methods to reduce this cost is to design the segments more efficiently.

In the usual design method the earth pressure acting upon the segment lining is calculated by the overburden pressure or Terzaghi's loosening earth pressure according to the stratum condition and the overburden height (Official Report of the International Tunnelling Association 2000). In this method only the weight of surface buildings are considered as a uniform surcharge pressure. Nowadays, the modern shield technology equipped with precise pressure control system at cutter face and simultaneous backfill grouting system makes it possible to build a tunnel without loosening the surrounding ground. Therefore, the actual earth pressure cannot be correctly predicted by conventional methods (Hashimoto et.al 2002).Some of the field measurement results have shown that the loads acting on the tunnel lining adopted in the design might be greater than the actual loads, particularly in case of good ground conditions (Mashimo and Ishimura 2003).

The effect of soil layering on the ground response to tunnelling has been investigated by several researchers (Grant and Taylor 2000). The focus of these studies has been on tunnelling induced settlement and stability of the ground above the excavated tunnel. In comparison with ground movements, little attention has been paid to the effects of the overlying strata on the stresses developing in the tunnel lining. Therefore, more study about evaluation of loads act on lining is required and the insights obtained from this study can contribute to an improvement of load consideration in shield lining design. The objective of this study is to investigate the influence of surface buildings and ground stratification on lining loads.

In engineering practice different methods are often used to calculate lining stresses (Nunes and Meguid 2009).In this study, a 2D finite element model is applied to simulate the conventional procedure of tunnel excavation and lining installation stages properly. The geometry of tunnel, lining segments, injection grout and surrounding soil properties were adapted from under construction Tabriz urban railway line 2 project.

2 NUMERICAL MODELLING

Tunneling is often modelled two-dimensionally although it is a three-dimensional (3D) problem since a full 3D numerical analysis often requires excessive computation resources (both storage and time). During tunnel construction, a volume of soil squeezing into the opening creates deformations around and above the tunnel, which cannot be simulated directly in 2D finite element analysis. Hence, various methods have been proposed to take account of the stress and strain changes ahead of the tunnel face when adopting 2D plane strain analyses to simulate tunnel construction (Karakus 2007).

In this study, a two-dimensional finite element multistep simulation model for shield-driven tunnel excavation is presented. The model takes into account all relevant components of the construction process as separate components in model (including: soil and ground water, tunnel lining and tail void grouting). The buildings were simulated by an elastic beam at the surface of the models. Each surface beam has an equivalent moment of inertia (I) and thickness (t) representing the associate building. The surrounding soil above the ground water level was discretized by 4-node first order fully integrated continuum elements (CPE4) and the tunnel liner and elastic beams (representing buildings) simulated as 2-node linear Timoshenko beam elements. The under groundwater soil and the grout material are modelled as saturated porous media using pore pressure elements (CPE4P). The time dependence of the grout material characteristics due to hydration is modelled in a simplified manner by employing a time-dependent Young's modulus and Poisson's ratio. The soil behavior is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr–Coulomb criterion with a non-associative flow rule.

The behavior of lining concrete is assumed to be linearly elastic with properties which are usual for C45/55 concrete (E=36000MPa, υ=0.2). For considering decrease of rigidity at segment joints, a transfer ratio of bending moment is introduced. This aspect is transferred to numerical analyses with Correction of the elastic modulus of the ring, according to modification factor $\zeta=0.3$:

$$E_c = (1-\zeta)\times E_{CLS} = (1-0.3)\times 36000 = 25200 Mpa \tag{1}$$

Where E_c is the virtual modulus of the ring and E_{cls} is the concrete modulus. During the parametric studies, the geological features were considered unchanged and similar to the Tabriz metro line2 site conditions that described later. The ground water ingress into the tunnels during construction phase is not considered in this study. The excavation and construction of the tunnel are simulated in 5 stages. In the first phase, the geostatic equilibrium achieved and in second step the building is constructed, but the corresponding deformations are not taken into account in further steps. In excavation step inside the tunnel the soil is excavated by de-activating the corresponding volume elements and allows that the tunnel border moves radialy accordance with overcutting value. In next step, the lining installed and grout elements are activated in the fluid state simultaneous with application of the injection pressure. After installing step the injection pressure removed and the mechanical characteristic of grout elements changed to hardened one. Based on similar projects, under good operative conditions, time duration of excavation step considered 5400 seconds and the time of lining ring erection considered 900s.

Boundary conditions, element types and mesh density of the numerical models were selected based on several sensitivity analyses as not to influence the results. The finite-element mesh extends to a depth of two times the tunnel diameter (*D*) below the tunnel spring line and laterally to a distance of 6*D* from the tunnel centerline. The locations of the lateral and bottom boundaries are selected so that the presence of the artificial boundaries does not significantly influence the stress-strain-pore pressure field in the domain. The modelled domain was 120 m in width and 45 m in depth, consisting approximately 10,000 nodes and 2,000 elements.

3 CHARACTERISTICS OF TABRIZ METRO LINE 2

Tabriz with 160 km^2 area and the population about 1,600,000 is one of most populated and important cities in northwestern of Iran. TURL2 about 22 km in length will connect eastern part of the city to its western part. This line comprises a single tunnel which has been constructed using one earth pressure balance EPB-TBM with a cutting-wheel diameter of 9.49 m and a shield with external diameter of 9.46 m in front of shield that induce overcut equal to 1.5 cm in each side of shield. For lining of the tunnel, 35 cm-thick precast concrete segments with a length of 150 cm are installed just behind the shield.

Geologically, in central part of the route, based on conducted studies in the corridor of TURL2, soil is mainly silt with low plasticity (ML) and silty sand (SM) and water table is about 9m deep. Geotechnical specifications used for soil layers of the models are presented in Table1. Mechanical properties of tunnel liner and tail void grout, utilized in the numerical simulations, are summarized in Table2.

Table1. Geotechnical specifications used for soil layers of the model

ID	Dry density (KN/m^3)	Wet density (KN/m^3)	Elastic modulus (kPa)	Cohesion (kPa)	Internal friction angle	Dialation angle
SM	16.25	20	40000	7	34	3
ML	16.8	20.35	25000	17	25	0

In general the grout pressure value considered 0.5 bar more than applied face support pressure. Therefore, the required face pressure for each model calculated and in accordance with calculated value, the grout pressure adopted for each model.

Table 2. Material properties used in numerical simulations

Material	Unit weight (KN/m3)	Compressive strength (MPa)	Elastic modulus (MPa)	Poisson ratio
Tunnel liner concrete	25	40	25200	0.2
Tail void grout (fluid)	18	0	5	0.47
Tail void grout (hardened)	18	3	20	0.3

4 PARAMETRIC STUDIES

The effects of building's geometry, position and weight on lining loads were studied. Four types of 3, 5, 8 and 10 story buildings above the center of the tunnel were modelled to apply the effect of surface buildings weight. For each floor, 10 kN/m2 was considered as weight load. In addition study of geometry effect on the model turned out to be possible through modelling of buildings with different width and different distance from tunnel center. The lining stresses of tunnel bored in coarse grained sand overlain by soft soil layer are compared to induced stresses in lining of tunnel in a homogeneous sandy soil. The values of above parameters have been selected based on Tabriz metro line 2 data and its urban conditions, as introduced in Table 3.

Table 3. Factors and their values used in parametric studies

Parameter	Description	Values
Z_0	Tunnel center depth	13.8m ,18.4m, and 23m (according to C/D=1, C/D=1.5 and C/D=2 respectively)
W	Building weight	30, 50, 80 and 100 (KN/m^2)
B	Buildings width	10, 15, 20, 30 and 40m
E	Distance between tunnel and building centers	0, 10, 20, 30 and 40m
L	Edge to edge distance between buildings	15 m, 20 m, 30m, 40m (corresponding to width of the streets along the route)

5 RESULTS

Utilizing about 240 two dimensional plane strain finite element models and conducting parametric studies by ABAQUS software, the effects of important parameters such as tunnels depth, building's weight, width and their locations on the surface together with soil stratification on the loads acting on the lining were evaluated. It is to be noted that in models tunnel lining divided into 24 sections and in presented graphs ɵ is angle between center of each section and tunnel crown.

5.1 Tunnel depth (Z0)

As illustrated in figure 1, the existence of the surface building leads to more forces compared to the green-field condition. However, the effect of the buildings on the lining forces will be reduced when the depth of the tunnel increases i.e. for shallow tunnels, surface buildings will have larger effects on lining forces. In Figure 2 the increase percentage of axial force due to 10 story building located above center of tunnels in various depths in respect of Green-field condition presented. The maximum axial force (induced in side walls and marked with line in figure 2) increases 70, 35 and 20 percent, respectively.

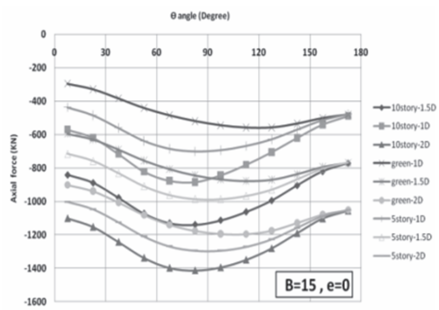

Figure 1. Axial force for various building load and tunnel depth [building 15m width above tunnel center]

The effect of tunnel depth in Green-field condition is greater compared to presence of buildings i.e. as tunnel depth increase, the axial force of lining compared to C/D=1, increases in both condition but more increase in Green-field condition could be seen. Also in Greenfield condition the most increase occurs in tunnel crown whereas the presence of building has a more effect in tunnel invert.

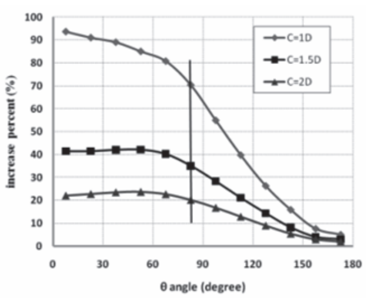

Figure 2. Increase percentage of axial force for various tunnel depth respect to green-field condition [B=15m, 10story, e=0]

Based on obtained results, with increase of tunnel cover induced bending moment in green-field condition increases. In the tunnel cover equal to 1.5 and 2 time of tunnel diameter, maximum bending moment (induced in tunnel invert) increase 20% and 37% respectively compared to 1D cover. When the building load applied on model, in proportion of building load, the maximum bending moment in comparsion with green-field, increases and occurs in tunnel crown but the increase of depth does not have considerable effects on induced maximum moment especially in high story buildings. Only negligible increase in bending moment occurs in lining shoulders as tunnel becomes depper.

5.2 Building width (B)

In figure 3, sample illustration of building width effect is shown which reveals that the increase of building width increases axial force and bending moment in tunnel lining.

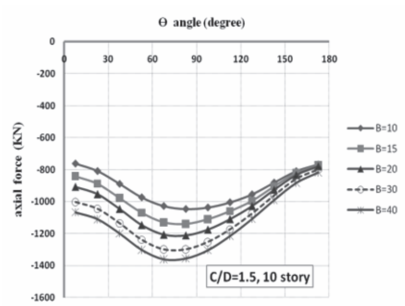

Figure 3. Induced axial force for various building widths

Figure 4, presents the increase percentage of internal forces for various building width values respect to B=10m for different loads. As shown in the figure the building width has a more effect on axial forces compared to bending moments .With increase of building width, its effect on bending moment gradually decreases. Also it could be seen that with decrease of building load the effect of building width on lining loads reduces.

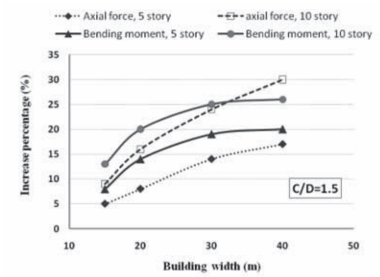

Figure 4. Increase percentage of structural forces respect to B=10m for various building loads

5.3 Location of the buildings on surface

As described in table 4, different locations of building were considered. In figure 5, a sample illustration of this parameter effect is shown for buildings with 10 m width and 10 stories on lining axial force of tunnel located at depth of 18.4 m. As shown, as a general rule with increase of building distance from tunnel centerline the effect of building on lining forces reduce. This reduction depends on building width and depth of tunnel. For shallow tunnels and building with small width the effect of building load vanishes in smaller distance .For example as shown in figure 10 in the case of C/D=1.5 and B=10m , in distance of E=30m the effect of building existence is inconsiderable and the induced axial forces graph is approximately the same as green-field condition.

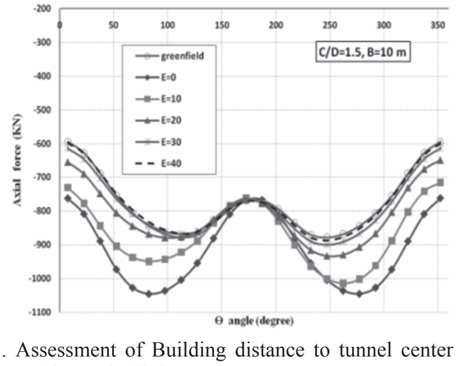

Figure 5. Assessment of Building distance to tunnel center line, 10story Building, B=10 m, Z0=18.4 m

5.4 *Edge to edge distance of building (L)*

The figure6 shows that the increase of L decreases the influence of the structure on lining loads. Also, it can be seen that with reduction of building load the influence of L on induced loads decreases. The obtained results show that in the case of building existence in both sides of tunnel, maximum bending moment occurs in lining invert. This is in converse of case that building loads apply above the tunnel center that the maximum bending moment occurs in lining crown.

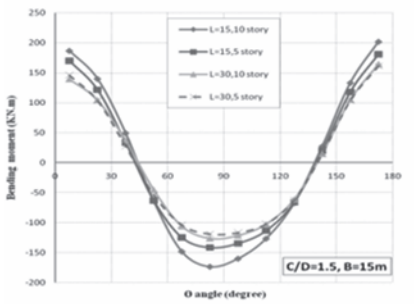

Figure 6. Assessment of edge to edge distance of buildings - Building located symmetrically on both sides, 10 and 5 stories.

5.5 *Soil stratification*

In this study the effects of soil stratification were considered in two parts. At first part based on mentioned geotechnical section of study region of Tabriz metro line 2 corridor, a two layer soil include sand overlying by silty soil (ML) modeled. The thickness of silt layer that locate above water table adopted equal to 9m. In second part a homogeneous silty soil is modeled and the effects of soil properties are studied. Figure 7 shows the effect of soil stratification and tunnel surrounding soil types on the lining loads for various tunnel depths.

In both green-field condition and building existing state, presence of silt layer increase lining loads slightly and with increase of tunnel depth the effect of silty layer reduces .A considerable growth in lining structural forces occurs when excavation of tunnel done in silty soil and for deep tunnels this effect is greater. It seems that because of approximately equal unit weight of two soil types, the greater lateral pressure coefficient (K_0) of silt layer causes more ground pressure on lining and greater structural forces induced in lining.

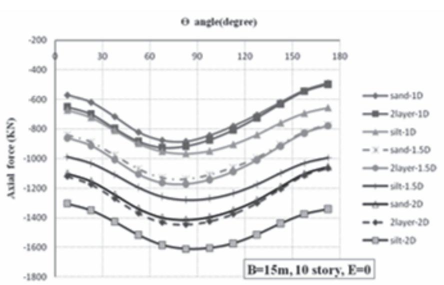

Figure 7. Assessment of soil layers types, centrally located 10 story building

In 2-layer ground the effect of silt layer is small and decrease with increase of tunnel depth .Conversely, in silty soil, growth of axial force and bending moment increases as tunnel depth increase.

5.6 *Building weight*

The effects of building weight on the lining loads for tunnel depth (Z0) of 18.4m have been illustrated in figure 8. As it is shown, increasing the building weight in numerical simulations will result in increase of lining loads in comparison with green-field; however the exact influence of building weight depends on tunnel depth, soil type and building's parameters.

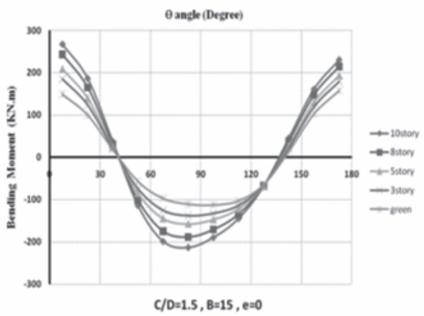

Figure 8. Assessment of building weight –Building located centrally

The increase in lining forces due to building loads disappears as Z_0 increase. For example percentage of increase in maximum axial force and bending moment due to building loads summarized in table 4 for various tunnel depth and building loads compared to green-field condition. As a general rule, building weight effect is higher for shallow tunnels whereas, the decrease of building width and increase of distance to tunnel center reduces the weight effect.

Table 4. Increase percentage of structural forces

building	C=1D		C=1.5D		C=2D	
	N(kN)	M(kN.m)	N(kN)	M(kN.m)	N(kN)	M(kN.m)
10 story	70	112	35	79	20	55
8 story	58	92	27	63	16	44
5 story	35	60	17	40	10	28
3 story	20	36	10	24	6	17

6 CONCLUSIONS

Using characteristics of the Tabriz metro line 2 and code of ABAQUS software, 240 two dimensional numerical models were analyzed and According to the results of parametric studies conducted in this research:

- As a general rule, the existence of surface buildings in 2D plane strain analysis will cause the lining loads increase compared to the green-field condition. However, the influence value depends on the combination of geometrical and mechanical parameters of the tunnels, buildings and surrounding soil.
- According to characteristics of study region of the Tabriz metro line 2 corridor, the buildings with 5 and more story has a considerable effects on lining loads. For shallow tunnels these effects is greater and with increase of tunnel depth building effects decrease.
- Based on obtained results in this study, existence of silty layer above the sandy soil has not considerable effects on lining loads, but when tunnel excavated in silty soil lining loads increase intensively compared to tunnels excavated in sand.

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