An equivalent beam model for the analysis of tunnel-building interaction

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1. Introduction

Underground transportation systems have been in demand in many major cities. These systems require a tunnel which is constructed in urban areas, particularly in soft ground and in shallow zones. Measurement, designing and performing of underground structure can be known as the most important civil engineer’s challenge (Bernat and Cambou, 1998; Liu et al., 2008).

Influence on adjacent buildings is of major interest for tunneling operations in urban areas, due to the high interaction between tunneling and existing structures (Pickhavar et al., 2010; Dimmock and Mair, 2000). This problem/issue was previously analyzed using a combination of in situ observations and numerical modeling. Analysis of previous case histories paved the way for the establishment of various empirical relationships between tunneling-induced ground movement and associated structure damage (Burland and Wroth, 1974; Boscardin and Cording, 1989; Burland, 1995; Mair et al., 1996). These methods are widely used in practice. In reality, a rigorous analysis of the tunneling-structure interaction problem is a hard task, due to (I) the high interaction between tunneling and adjacent structure, (II) 3D nature of this problem and (III) the non-linear geometrical behavior involved that leads to use an appreciate numerical method (Mroueh and Shahrour, 2003). Different approaches have been used to represent the building with varying level of details in the numerical methods. According to the simplified operations are executed in two consecutives.

Abstract

The aim of this work is to study the effect of structural characteristics, including stiffness, geometry and weight on tunnel–adjacent structure interaction. Ground materials, tunnel geometry and excavator device are related to a part of metro tunnel of Tehran. To describe the ground behavior due to tunneling, a 3D code with an elastoplastic soil model was used. The adjacent building was modeled in two ways: one as an equivalent beam or shell and the other as a real geometry (3D frames). The obtained results from this theoretical work indicate particularly that the stiffness of adjacent structure controls the ground movement distribution induced by tunnel excavation which in agree with other researchers. As it was predicatively, increasing in structure weight leads to create the large displacement components in the ground. The structure width plays also a significant role in displacement distribution of ground. The comparison of the obtained results using two methods of structure modeling shows a very good conformity between them.

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study of structural characteristics effects of adjacent building on ground movement induced by tunnel excavation. The adjacent building is modeled firstly as an equivalent beam that allows us easily to achieve parametric study operation. In the second part of work, the structure is considered with its real geometry. The study of interaction between tunnel and adjacent structure was done using an indirect method developed in this work. PLAXIS and SAP (powerful in structural problems analysis) codes were used with the consideration of displacement field compatibility at soil media and structure interface. Tunnel geometry and ground properties are corresponding to a part of metro tunnel of Tehran city which was constructed using a slurry shield machine with an outside diameter of 9.0 m. The obtained results by two methods structure modeling were finally compared.

2. Modeling and parameters

PLAXIS 3D code only generates the triangle mesh, but it can use the meshes in very fine size. Meshing is introduced in five modes: Very coarse, coarse, medium, fine and very fine. The important ability of code is to make finer meshing regarding a region and or surround of a line. However, the precision is increased by use of finer mesh in a region but causes time to add for run problem (PLAXIS code manual, 2005). Medium mesh mode is used in present work and in more sensitive zones, mesh dimension gets finer. Selection of this size of mesh is not worrying, because coarse meshes have been used in 3D settlement analysis by PLAXIS 3D code in some projects such as Rennsteig tunnel in Thuringia city. Also, for modeling Steinahalenfeld tunnel in Stuttgart city, very coarse mesh with hardening elastoplastic constitutive model was used that had a good agreement with real value from in situ information (Mair et al., 1996). Fig. 1 shows FE mesh and also the lines of displacements measurement.

In this study, the most suitable constitutive model presented in PLAXIS code was selected. This model is elastoplastic with the isotropic hardening mechanisms. It can be considered as development of non-associated Mohr–Coulomb model. In fact, major limitations of Mohr–Coulomb model are removed by adding a cap surface to describe plastification under isotropic stress, and an isotropic hardening mechanism to express non-linear plastic behavior before the failure. Evolution of yield surface in deviatoric mechanism is controlled via deviatoric plastic strain. Volumetric plastic strain controls the cap evolution. The plastic hardening and elastic modulus are properly considered as function of confining pressure. Basic properties of this model are:

- Hardening plastic and elastic modulus is dependent on confining stress according to the exponential rule (exponential dependence of stiffness on stress).
- Parabolic relationship between deviatoric stress and strain.
- Separation of initial loading from unloading-reloading.
- Coincidence of failure surface on Mohr–Coulomb criteria.

Nonetheless, this model is useful in monotonic loadings only and some of important soil behavior aspects, such as failure surface dependence on confining pressure and critical state concept are not taken into account.

This model has eight parameters, fortunately all of which have clearly physical meanings and are determined easily by the classical laboratory tests. Parameters of model are:

c: Soil cohesion.
φ: Maximum internal friction angle.
ψ: Dilatation angle.
\( E_{50}^{f} \): Secant modulus in standard triaxial test at the reference confining pressure \( (\sigma_{3} = \sigma_{0}^{\text{ref}}) \).
\( E_{50}^{c} \): Tangent modulus related to the consolidation test.
\( E_{50}^{u} \): Modulus related to the unloading and reloading states.
m: Controls the dependence of plastic and elastic modulus on confining stress.
\( v_{ur} \): Poisson ratio in unloading-reloading state.

In the PLAXIS code, the mobilized shear strength in interface bond is a function of shear strength of soil. This option is controlled using the parameter \( R_{\text{inter}} \) that is equal to or less than 1.0, for real soil-structure interaction the interface is weaker and more flexible than the associated soil layer, which means that the value of \( R_{\text{inter}} \) should be less than 1.0. The \( R_{\text{inter}} \) in this study is supposed to be 0.7. Because of the interface behavior before yielding is considered elastic, the gapping or overlapping (i.e. relative displacements perpendicular to the interface) could be expected to occur. On the other hand, the gap can be developed between the equivalent beam and ground surface. In the present work, the gap in certain case appeared, however, its value was very small without an effect considerable on settlement profile in ground surface.

A section of line 1 of Tehran metro near 7tir square station was modeled to achieve the aims of this study. Shield method was used for tunnel construction. The information concerning the soil properties, tunnel geometry and tunneling device were taken from Tehran urban and suburban railway organization. Concerning the geological aspects, 7tir station is located in the end part of non-homogeneous alluvial formation in Tehran north and its lithologi-
cal composition consists of sand, gravel, cobblestone and clay. Forma-
tion of this area is of a good permeability and depth of ground-
water table is 74 m. Geotechnical data of this station shows the
in situ alternative layers of GP, GW, GC, SC and SM. Values of geo-
technical parameters are obtained based on jacking and direct
shear tests (Fig. 2).

According to geotechnical information, the parameters of con-
stitutive model were estimated. The values of parameters are listed
in Table 1.

Table 2
Mechanical parameters of tunnel lining.

<table>
<thead>
<tr>
<th>$EA$ (kN/m)</th>
<th>$EI$ (kN/m)</th>
<th>Tunnel lining (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.05E6</td>
<td>8.21E4</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 3
Parameters of modeled structure.

<table>
<thead>
<tr>
<th>Equivalent structure</th>
<th>$W$ (kN/m/m)</th>
<th>$EA_{max}$ (kN/m)</th>
<th>$EI_{max}$ (kN m²/m)</th>
<th>Structure</th>
<th>Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.03E7</td>
<td>7.97E7</td>
<td>2-Storey</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1.72E7</td>
<td>3.98E8</td>
<td>4-Storey</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>3.10E7</td>
<td>2.39E9</td>
<td>8-Storey</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>5.86E7</td>
<td>1.62E10</td>
<td>16-Storey</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Poisson ratio for equivalent beam element to load modeling assume to be 0.25.

3. Equivalent beam consideration

The structure of adjacent building is considered by an equiva-
 lent elastic beam with length of $L$ and width of $B$ (Fig. 1). Bending
stiffness ($EI$) and axial stiffness ($EA$) represent the overall stiffness
of the structure. The advantages of this method are; simplicity in
considering adjacent building stiffness according to structural sys-
tem and weight of building and also, in 2D conditions, the small
amount of computational resources is required and therefore the
ability to perform extensive parametric studies can be achieved.

The second moment of area for the equivalent beam was then, cal-
culated using the parallel axes theorem (Appendix A). Considered
structures in analyses were as 2, 4, 8 and 16-storeys. Diverse
parameters of structures have been presented in Table 3.

Different steps of FE calculations performed in the first part of
this work can be concluded as:

- Analysis of ground for considering the gravity.
- Introducing the equivalent beam and ground analysis.
- Effacing the deformation field engendered by the beam.
- Performing the tunnel and capturing the deformation.

4. Discussion on equivalent beam results analysis

In this section, the results of analyses are presented. The focus is
on ground horizontal displacement and ground settlement distri-
bution. There are presented, in Figs. 3 and 4, the profiles of hori-
zontal ground movement at 6 m offset from the tunnel center
line in the cases of with and without consideration of structure
stiffness, respectively. The depth of tunnel is 17.7 m and the width
of buildings has been considered to be 100 m. Each of curves cor-
responds to one building with specific storey and stiffness. In addi-
tion, soil movement corresponding to Greenfield (GF) analysis has
been included. The maximum horizontal movement in GF condi-
tions along the vertical line is reached at $z = 18.14$ m. From there
it reduces towards the surface so that at $z = 11.50$ m horizontal dis-
placement is zero. In continuing, the movement toward ground
surface increases so that horizontal displacement of 2.5 mm occurs
at the ground surface. The presence of building causes a reduction
in horizontal movement at ground surface. For example, it changes
from 2.5 mm corresponding to GF to 0.9 mm for a 2-storeys build-
ing. Although horizontal movement is less than GF at ground sur-
face, it increases with depth and becomes larger than that obtained
for GF conditions. These two figures indicate that with the addition

![Fig. 2. Schematic cross section of geometry and material of line 1 of Teheran metro near 7tir square station.](image)
of building storey, soil movement increases. With comparison of curves in the cases of with and without consideration of stiffness, it is observed that consideration of building stiffness leads to decrease horizontal soil movement. It can be generally said that structure stiffness is a factor that resists against horizontal deformation of soil induced by tunnel excavation. The presented results in Figs. 3 and 4 indicate that the horizontal movement in the surface has the opposite direction in comparison with movement at tunnel depth. That is physically real because the region near ground surface is in contraction state due to tunnel excavation. On the other hand, the horizontal movement is toward the tunnel centerline, whereas in depth the ground movement is outward of centerline. Settlement distribution of ground surface in two cases of with and without consideration of building stiffness has been presented in Figs. 5 and 6. It is clear that settlement distribution is effectively influenced by building stiffness. In fact, building stiffness causes the uniform settlement beneath the foundation, so this uniformity is increased by increase in stiffness. One of the most important interests of equivalent beam method is that for a given adjacent building, we can attribute the stiffness to building with respect to its structural characteristics. For example, for a weighty masonry building an insignificant stiffness can be considered.
Fig. 7 shows the effect of building width on ground horizontal movement due to tunnel excavation. In this figure ground horizontal movement has been drawn versus depth for vertical line placed at 6 m from tunnel center. The building is considered to be 4-stories with 15, 30 and 60 m width. For comparative purposes, the results of green field analysis for $B = 100$ m are included. These curves indicate that horizontal movement is increased with increase in building width. The profiles of soil vertical movement in ground surface for different building widths have been presented in Fig. 8. These results indicate that for the great values of width the maximum settlement is decreased but a large domain of ground is influenced due to tunnel excavation.

Fig. 9 shows the soil horizontal movement profiles of vertical line placed in 6 m distance from tunnel axis where the eccentricity is 7.5 m.

Fig. 10. Horizontal soil movement profiles in ±6 m distance from tunnel axis where the eccentricity is 12.5 m.

Fig. 11. Vertical soil movement profiles in ground surface for 4-storey structure with different lengths of building.

Fig. 12. Structure columns plane.

Fig. 13. Process of interaction between SAP and PLAXIS.
results show that eccentricity of building influences the soil horizontal movement around tunnel. In fact, an asymmetrical geometry of structure with respect to tunnel centerline results in asymmetrical displacement field of soil. When eccentricity takes the great values, the effect of building on ground movement due to tunneling will be negligible [Fig. 10].

Possibility of accurate studies on tunnel front behavior with respect to construction methods is one of the most important
interests of 3D FE analyses. In the present work, the effect of building length on ground movement around tunnel front has been studied. To do this, a 4-storeys building with 15 m width was considered. The results of analyses for two different lengths of 10 and 50 m of building have been presented in Fig. 11. It can be seen that ground vertical movement in direction of tunnel excavation is influenced by building length. In fact, for the case of building with smaller length, the distribution of longitudinal vertical movement is sharper than the case of building with the bigger length.

5. Consideration of structure as real geometry

Consideration of structure as real geometry and stiffness in soil-structure interaction problems can give more realistic response in comparison with the equivalent beam. Although such consideration necessitates us to have the accurate information from present adjacent building. This information is related to materials, geometry and structural system that are generally difficult to obtain. The preparation of data for existing old buildings will be more

Fig. 15. Bending moment distribution in tunnel lining, (a is front section plan of structure b is middle section and c is rear section of structure).

Fig. 16. Vertical displacement in the ground surface (a is front section plan of structure b is middle section and c is rear section of structure).
difficult. Therefore, it is reasonable to use other methods to model adjacent buildings in tunneling or excavation problems. These methods must be simple and have a good agreement in comparison with the results, while the adjacent structure is modeled as its real form. In the previous sections the adjacent building was modeled as an equivalent beam that allowed us to study the effect of various building properties such as stiffness, geometry, weight, width, length and eccentricity of building with respect to tunnel axis, on the tunnel-structure interaction problem easily. The question arising is how much equivalent beam properly faces to interaction problems. To answer this question, one 10-storeys steel structure is considered as real structure, and its results are compared with the results of equivalent beam. The resistance system of structure is bending frames in two orthogonal directions, and the connection of columns to foundation is considered as pin. Footing is considered to be as mat with 20 m × 20 m × 1.2 m dimensions. The column plane of structure has been shown in Fig. 12.

The SAP code was used for the analysis of structures. The dead and live loads combination is only considered in this study.

The excavation of tunnel creates a displacement field for the ground. For shallow tunnels, the created displacement field influences the adjacent building and urban services. On the other part, the presence of adjacent building depending on geometry, weight, and its stiffness controls the ground displacement field due to tunneling. To study this important interaction between tunnel and adjacent structure, it is recommended to use a unique finite element calculation code in which the behavior of ground material and so the behavior of structure are properly described. At least, in the practical works in geotechnical engineering there is rarely existence of such general finite element code. In this paper, the interaction between tunnel and real adjacent structure is studied using an indirect method for which two finite element codes SAP (strong in structural analysis) and PLAXIS (strong in geotechnical engineering problems) have been performed alternately. To achieve this aim, it will be necessary to use an iterative process between two codes. In Fig. 13, the analysis process using two codes schematically is presented. As can be seen, the process is based on transportation of total forces \( (F_x, F_y, F_z) \) and total displacements \( (U_x, U_y, U_z) \) between two software i.e. SAP and PLAXIS 3D respectively; this process is updated in each steps. In the first stage, the structure is analyzed by SAP code and the forces of support points are saved to be sent to the PLAXIS code. Now PLAXIS code is executed and gives displacements distribution for mat foundation lied on ground surface. The displacements at the columns support points are saved and sent to SAP code. These displacements are induced to support points of structure then SAP code is executed and gives a set of new forces at the support points. The necessary condition for stopping the iteration process is to satisfy the displacement field in the interface of structure and ground. On the other hand, this defines the compatibility condition applied between

![Fig. 17. Ground horizontal movement profiles (a is front section plan of structure b is middle section and c is rear section of structure).](image-url)
structure and ground. This iterative process is continued until the differences of two sequence steps were about zero. The reactions of columns and their displacements components for the first and final step of analysis have been presented in Tables 4–7.

Fig. 14 shows the 3D FE mesh for PLAXIS code in which the positions of foundation and columns have been specified.

6. Comparison of two models

In this part of work the internal forces particularity bending moment of tunnel lining, ground surface settlement and its distribution, and also ground horizontal movement profile, obtained by two methods of building modeling are compared.

Bending moment distribution of lining versus central angle of the tunnel sections, for two methods of building modeling has been presented in Fig. 15.

The central angle is measured anticlockwise from horizontal plane. There can be seen a very good conformity between obtained results by two methods.

The ground surface settlement is an important factor that must be controlled in interaction problems. The ground surface settlement versus mesh width for two methods has been shown in Fig. 16.

It is clear that the response of equivalent beam method is very close to the obtained results from analysis with real geometry of structure. There is a small difference between two methods in location of structure foundation. This difference is due to uniform distribution of building weight in the first method in comparison with the concentrated load of columns in second method.

Ground horizontal movement profiles obtained by two methods have been presented in Fig. 17. These profiles are located at 6 m distance from centerline of tunnel. From this figure we can conclude a very good conformity between the equivalent beam and the real geometry methods.

There is a small difference (less than 0.2 mm) between the obtained results by two methods particularly in section G that is due to special manner of structure modeling.

7. Conclusion

In this paper a set of FE analyses were performed to study the effects of adjacent building characteristics on interaction between tunnel and adjacent structure. The adjacent structure was modeled by two different methods. The analysis results obtained by these methods were then compared with each other. The conclusions from this study are summarized as following:

(1) Structure stiffness plays an important role in tunnel-structure interaction problem. In fact ground movement due to tunneling is controlled by the structure stiffness, in particular, neglecting the structural stiffness yields to unrealistic ground surface settlement.

(2) Weight of structure is a very fundamental factor in ground movement caused by tunnel excavation. Ground movements are generally increased due to increase in the structure weight.

(3) The obtained results indicate that horizontal movement is increased with increase in building width and also for the great values of width the maximum settlement is decreased but a large domain of ground is influenced due to tunnel excavation.

(4) Eccentricity of building from the tunnel centerline is also an important factor. Asymmetrical deformations are the first effect of structural eccentricity.

(5) Adjacent building was modeled by two methods: equivalent beam and real geometry. The comparison of obtained analysis results indicates that the equivalent beam method for practical purposes can be used as a simple way for introducing the adjacent building characteristics in tunnel-adjacent structure interaction problems.

Appendix A. Calculations of equivalent beam characteristics

The building is modeled by an equivalent elastic beam (in 2D analyses) or shell (in 3D analyses) that lies on the ground surface. Young’s modulus $E$, second moment of area $I$, and cross section $A$ are the structural properties of equivalent beam. Each storey of building is considered as a slab, therefore, considering one slab for footing, one $m$ storey building can be modeled as $m + 1$ slabs (Fig. 18). If the vertical mean distance between slabs is $H$ and the thickness of each slab is $t_{slab}$ then, using the parallel axes theorem (Timoshenko, 1955), second moment of area of equivalent beam can be calculated. Second moment of area $I$ and the area $A$ for slab are defined as:

$$I_{slab} = \frac{t_{slab}^3 L}{12} \quad A_{slab} = t_{slab} L$$

(1)
where $L$ is out-of-plane dimension of the slab. Assuming the neutral axis to be at the mid-height of the building, the bending stiffness for the equivalent beam is then calculated as following:

$$ (E_L)_{beam} = E_c \sum_{m=1}^{m} \left( I_{slab} + A_{slab} h_m^2 \right) $$

(2)

In which $h_m$ is the vertical distance between the structure's neutral axis and the $m$th slab's neutral axis. Axial stiffness for equivalent beam is obtained by the following expression:

$$ (E_A)_{beam} = (m + 1)(E_A)_{slab} $$

(3)

Fig. 18 shows the geometry of structure with respect to tunnel position (Franzius, 2003).

References


