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3D Numerical Simulation to Consider the Effects of EPB Tunneling on the Existing Support System

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ABSTRACT: The development of transportation in the large cities needs some new tunnels to be designed and constructed nearby existing tunnels. In this study, the adverse effects of excavation a subway tunnel using an Earth Pressure Balance (EPB) shield, under a sewage tunnel have been investigated. Both the relative position of the tunnels and the excavation procedure of the new tunnel affect the ground movements and existing tunnel lining. Hence, the effects of shield operation parameters such as the face pressure, grout pressure and overcut between the shield skin and the surrounding soil are studied using a 3D finite difference numerical simulation. In accordance with the results, the largest permanent interaction effects occurred at the crown of sewage tunnel. Furthermore, excavation of subway tunnel affects the support system of existing tunnel in the longitudinal section more than cross section. In addition, the most portion of support deformation takes place when the ground moves into the overcut space. However, these adverse effects decrease significantly by increasing the face pressure, grout pressure and Bentonite injection into the steering gap between the shield skin and the surrounding soil especially when the pressure of that is more than 3 bar. Due to EPB tunnelling, the internal forces variations in the longitudinal section of sewage tunnel are more than circumferential ones.

Keywords: EPB Shield, 3D Numerical Modeling, Tunnel Interaction

INTRODUCTION

The development of transportation in large cities and the limitation of urban spaces have resulted in the need for more tunnel construction. As a result, the design of new tunnels nearby existing structures such as tunnels and their support system is inevitable. In such cases, the protection of closely-spaced existing structures as well as the new one is essential and the prediction of adverse effects of tunneling on the nearby tunnels due to ground movement and surface settlement is an important issue in the construction of new tunnel.

Tunnel deformation and surface settlements have been considered previously using a diversity of approaches including empirical, analytical and numerical methods (Addenbrooke and Potts, 2001; Migliazza et al., 2009; Chapman et al., 2004). Empirical and analytical methods are not applicable in situation which the problem involves the interaction between a tunnel and other existing structures such as a closely-spaced tunnel and its support system (Chen et al., 1999; Franzius, 2003). In addition, empirical methods can not consider different geotechnical conditions and construction techniques. So to study the interaction between an existing tunnel and a new one, numerical approaches may provide an appropriate tool.

Hage Chehade and Shahrour (2008) did a sensitivity analysis on the relative position of a twin tunnels using two dimensional numerical modeling and concluded that the lowest subsidence will be obtained when the tunnels aligned horizontally. Mroueh and Shahrour (2003) executed a 3D numerical modeling and investigated the effects of tunneling on the existing two level building. Liu et al. (2009) performed a full 3D numerical modeling coupled with elasto-plastic material model in Sydney region and investigated the effects of excavation of an adjacent tunnel on the support system of the existing tunnel; He has concluded that the excavation of a new tunnel considerably affects the existing support system and these effects significantly depend on the relative position of tunnels. Afifipour et al. (2011) analysed the effects of construction a twin tunnel under an underpass and concluded that the face pressure has more considerable effects on the underpass settlement compared to the grout pressure.

To sum up, most of research up to date has been focusing on the interaction between tunneling and other existing surface structures such as underpass and buildings. Moreover, there is little research work on the interaction between tunnel and subsurface structures. In addition, most researchers focusing on the 2D numerical modeling and in the case of 3D simulation, most research works have been done on the parallel structures such as twin tunnels and almost all of them do not consider the method of tunnel excavation and its operational parameters. So in this research, the interaction between the Tehran subway line 7 and the sewage tunnel has been investigated, and the stability of sewage tunnel have been considered. To do this, at first the tunnels geometry and ground geotechnical parameters have been studied. Then, using a full 3D numerical modeling the construction technique of the subway tunnel and its effects on the existing support system of sewage tunnel has been investigated. Finally, the appropriate EPB shield parameters which have minimum adverse effects on the sewage tunnel stability have been purposed.

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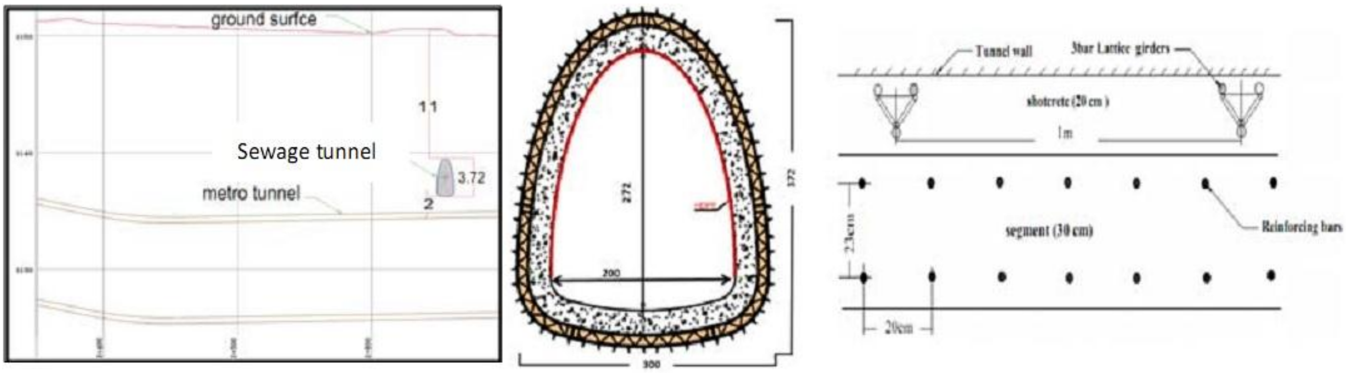
MATERIAL AND METHODS

Geometry and Geology

The Tehran subway line 7 is an East - West line and starts from the city of Amir Almomenin and terminates at the junction of Navab Highway and Gazvin Road. The tunnel length is 12 Km and will be bored using an EPB shield, with a diameter of 9.16 meters. One of the essential challenges against the construction of the subway line is crossing of this tunnel beneath the main sewage tunnel and because of the importance of sewage tunnel stability, the operational EPB parameters are investigated in this study.

The sewage tunnel has an egg section with a height of 3.7 meters, width of 3 meters and 11 meters of overburden (Figure 1a). The distance between the crown of the sewage tunnel and the bottom of subway tunnel is approximately 2 meters. The support which is installed in the sewage tunnel consist of three bar lattice girder embedded in 20 cm shotcrete and 30 cm reinforced concrete (Figure 1b) so the final width and height of sewage tunnel will be 2 and 2.7 meters respectively (Figure 1c).



a) Position of two tunnel in the cross -section c) Cross section of sewage tunnel b) section of sewage tunnel support

Figure 1. Geometry and position of sewage tunnel

According to the geological investigation and Unified Soil Classification system, there are six geological units along the subway line route, and the intersection of the subway and sewage tunnel lies in the unit 2. The geotechnical parameters of this geological unit which are calculated through in situ and laboratory tests and data processing are presented in Table 1. More than 65 percent of subway line route is below the ground water level. However, the intersection of sewage and subway tunnel is above the water level.

Table 1. Geotechnical parameters of the geological unit 2

Cohesion (kg/cm^2)		Elastic modulus (kg/cm^2)	Poisson ratio	Dry density (kg/cm^2)
C_{cu}	C'			
0.18	0.15	750	0.3	1840

Numerical producer

Because of essential consideration of complex aspects such as application of the face pressure, interaction between the shield and ground, installation of the lining rings, grouting of the annular space and simulation of the overcut, Numerical simulation of a tunnel which is excavated by an EPB shield is a hard task.

Problem layout and boundary condition

The numerical method used in this study for simulation is finite difference and the model developed for the analysis is shown in Figure 2a. The width and length of the model is 96 meters and the model height is 44.2 meters which are sufficient to minimize the boundary effects. The measurement points on the sewage tunnel which are used for succeeding result processing are shown in Figure 2b.

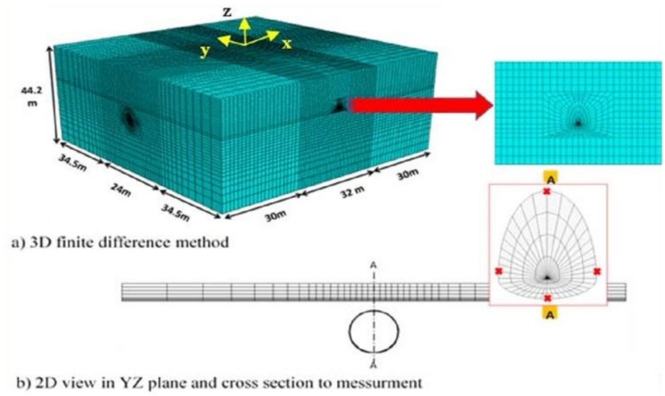


Figure 2. Finite difference model and cross section to measurement

To release the required thrust for shield movement, usually the tunnel is excavated larger than design plan which is called "overcut". Because of the shield weight the overcut around the shield is asymmetric so that the gap amount at the top portion of the shield is larger than the bottom. Most numerical analysis up to now have been done in a symmetric mode so a similar gap value is considered around the shield (Ramoni and Anagnostou, 2010). But in this study according to Loganathan et al. (1999) recommendation the ratio between the gap value at the top and bottom of the shield is considered 3:1 (top: bottom).

In this research, the traditional method of estimating ground loss is redefined based on the "gap parameter" introduced by Rowe and Kack (1983), and it is called equivalent ground loss. The support characteristics applied in the numerical simulation are presented in Table 2.

Table 2. Support characteristics for the sewage and subway tunnel

Un.St	Support type	T (cm)	E (GPa)	P.R	Unit weight (kN/m^3)	UCS (Mpa)
Sewage tunnel	Shotcrete	20	25	0.2	2300	27
	Lining	30	32	0.21	2400	37
Subway tunnel	Segment	35	35	0.2	2500	40

Un.St: Underground Structure, T: Thickness, P.R: Poisson's Ratio

The effects of tunnel boring on the existing support system

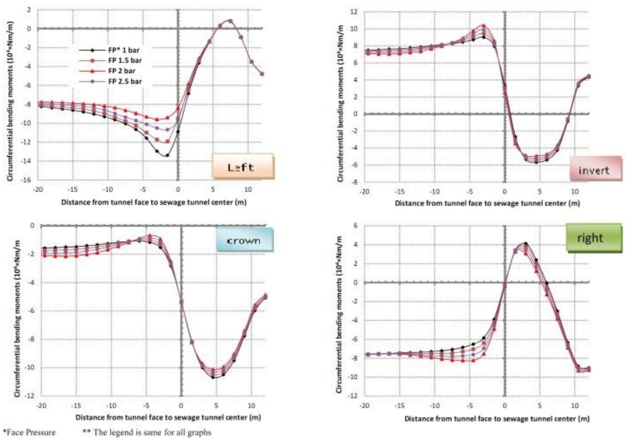
The interaction behaviour between two perpendicularly crossing tunnels have been considered when a new tunnel was driven beneath an existing shallow tunnel. If the bending moment tends to put the side of the lining facing towards the tunnel opening into tension and the side facing the rock mass into compression, it is regarded as positive, otherwise, it is negative. Positive and negative values of axial force refer to tension and compression, respectively. During numerical simulation several locations, as marked in Figure 2b, are monitored to quantify the effects of tunneling on the existing support system.

The gap between the shield skin (overcut) and the ground has significant undesirable effects on the existing lining. Therefore, it is important to prevent the ground displacement into the void space behind the shield skin. Some of new tunneling machines enable to pump the Bentonite or grout behind the shield skin and fill the overcut space. So, in the numerical simulation, two scenarios have been considered. In the first scenario, by considering the variation of pressure applied on the face, the internal support forces for the sewage tunnel have been investigated and for the second scenario, both the variation of grout pressure behind the shield skin and face pressure have been considered to evaluate lining forces. The pressure of Bentonite along the shield skin is considered constant.

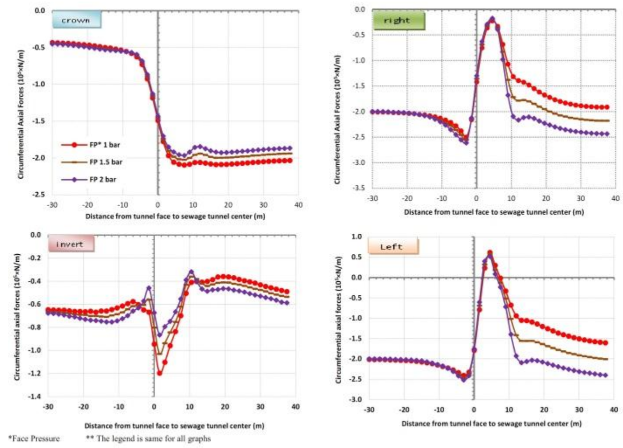
The first scenario:

The variations of circumferential bending moments monitored at the right (leading) side, crown, left (far) side, and the invert of shallow tunnel lining during the driving of subway tunnel for the first scenarios have been depicted in Graph 1. In this graph, as the face of the deep tunnel advances up to near the centre line of sewage tunnel, the negative bending moment in the existing lining gradually increases at the left side. On the other hand, the negative bending moment do not change significantly at the right side. After the subway tunnel face passes the monitoring points, the negative moments significantly decrease to their minimum and have positive values due to the overcutting execution. At the crown of the shallow tunnel, the negative moments in the lining decrease slightly in high face pressure as the face of the deep tunnel advances. After passing the centre line of the sewage tunnel, the negative moments significantly increase until around 5 m behind the tunnel face. At the invert, at first the positive moments increase slightly and then decrease more than other monitoring points while the TBM passes the centreline of sewage tunnel. The permanent change in the circumferential moment at the left side is more than other monitoring points due to new tunnel construction.

The variation of circumferential axial force has been depicted in Graph 2. The axial force at the left and right side of sewage tunnel raises slightly at first and then decreases considerably and reaches to a positive value for the right side of sewage tunnel. When the tunnel face gets distance from the centreline of sewage tunnel the axial force increases again and reaches to a stable value which is near the initial value when the face pressure is 1 and 1.5 bar for the left and right side respectively. At the crown, significant raising in the negative axial force is observed after driven the subway tunnel. At the invert there is a different pattern. As the tunnel face approaches the monitoring point, the axial force increases and after crossing the sewage tunnel it decreases and reaches to a permanent value lower than the initial value.



Graph 1. Variation of circumference bending moment at the monitoring points when the face pressure varies from 1 to 2.5 bar.

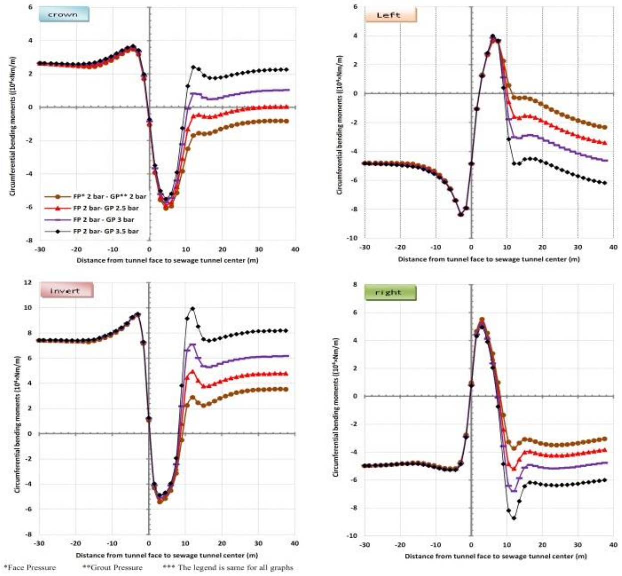


Graph 2. Variation of circumference axial force at the monitoring points when the face pressure varies from 1 to 2 bar.

The second scenario:

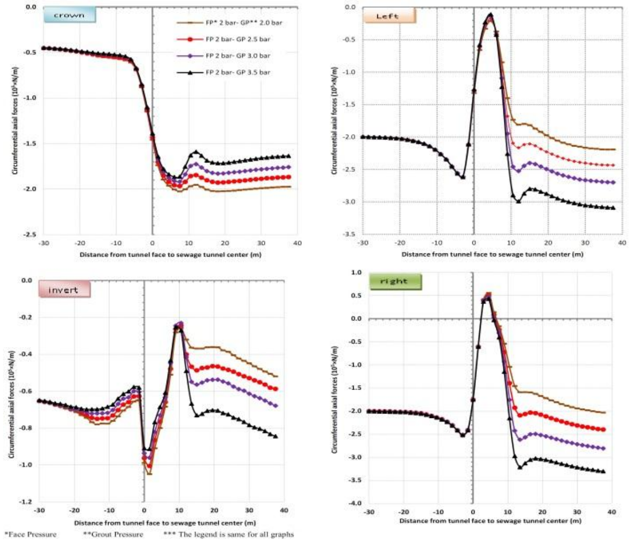
While the face pressure varies from 1 to 2.5 bar, the grouting pressure effects on the sewage tunnel lining have been considered and the results have been presented in Graph 3 when the face pressure is 2 bar. During the driving of the deep tunnel different trends are observed at the different measuring points. At the left and right side of existing tunnel lining, the moment direction changes rapidly when the tunnel face is near the sewage tunnel and after crossing the sewage tunnel the moment decreases dramatically and reach to a negative value. Furthermore, the quantity of moment reduction increases with the grout pressure increment and the difference between initial value of moment in the sewage lining and permanent value after driven the subway tunnel is minimum when the grout pressure is 3 bar. The same pattern is observed for the moment variation at the crown and invert of sewage tunnel. However, the grout pressure changes affect the invert of sewage tunnel more than crown.

In Graph 4, the variation of axial force has been presented. At left and right side of the lining, the permanent axial force increases with increasing of grout pressure and grout pressure variation affects the left side of lining more than right side. At the crown, the axial force increases up to 300 percent when the grout pressure is 2 bar and the quantity of increment decreases with increasing of grout pressure. The permanent axial force at the invert is close to the initial value when the grout pressure is around 3 bar.

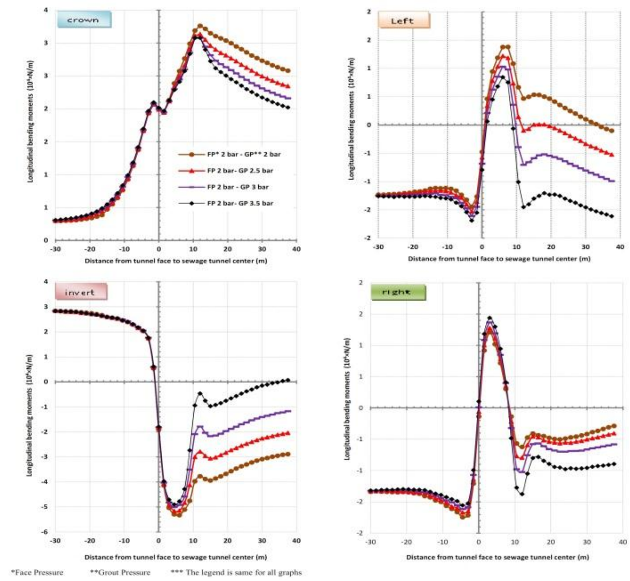


Graph 3. Variation of circumference bending moment at the monitoring points when the face pressure is 2 bar and the grout pressure varies from 2 to 3.5 bar.

The variation of longitudinal moment and axial force against distance to the sewage tunnel are presented in Graph 5 and 6 respectively. At the left and right side of sewage tunnel, at first the moment direction changes and after crossing the sewage tunnel center the moment direction return to the initial direction and the quantity of permanent moment decreases. The quantity of permanent moment at the crown increases up to 300 - 500 percent depending to the grout pressure. At the invert, the permanent moment direction changes and the quantity of moment variation increases by increasing of grout pressure. As depicted in Graph 6, at the invert, right and left side of sewage tunnel, the longitudinal axial force raises to a positive value and remain stable. However, at the invert the quantity of increment is more than other points. At the crown, the longitudinal axial force at first falls to a negative value which is means compression at the crown and after crossing the sewage tunnel centre the quantity of axial force decreases. Furthermore, the quantity of permanent negative axial force raises by decreasing of grout pressure.



Graph 4. Variation of circumference axial force at the monitoring points when the face pressure is 2 bar and the grout pressure varies from 2 to 3.5 bar.



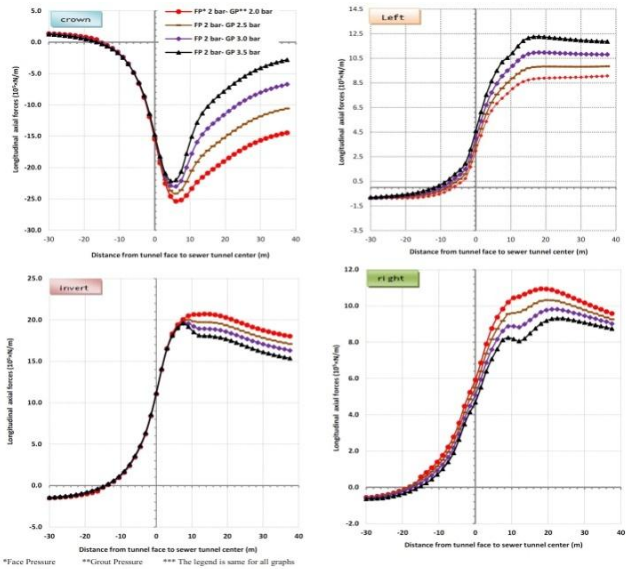
Graph 5. Variation of longitudinal bending moment at the monitoring points when the face pressure is 2 bar and the grout pressure varies from 2 to 3.5 bar.

CONCLUSION

It is generally understood that the interactions between tunnels are complex, especially for the perpendicularly crossing tunnels, which has to be investigated using 3D analysis methods. According to the 3D numerical simulation, the following conclusion can be driven.

The existing support system in the crossing area is affected first at the leading side, then at the invert, after that at the crown, and finally at the far side as the underlying tunnel face advances, however relatively far from the crossing area remains almost unchanged during new tunnelling.

The overcut has significant undesirable effects on the existing support system and cause tension or compressive state of existing support system changes during the excavation of subway tunnel.



Graph 6. Variation of longitudinal axial force at the monitoring points when the face pressure is 2 bar and the grout pressure varies from 2 to 3.5 bar.

In the first scenario, the permanent circumferential bending moments do not change significantly by variation of face pressure, but the permanent circumferential axial forces are different. The maximum variation in the permanent axial force is at the crown. The effects of face pressure on the sewage lining start from 15 meters before the sewage tunnel centreline and terminate at 15 meters after that.

In the second scenario, when the tunnel face is before the centreline of sewage tunnel, the variation of sewage lining internal forces do not change significantly by the grout pressure variation while these forces vary after the centreline of sewage tunnel. In addition, the difference between the initial values of the longitudinal internal forces and the corresponding permanent values is larger than circumferential ones.

Injection of Bentonite behind the shield skin could reduce the adverse effects on the sewage lining system especially when the grout pressure was more than 3 bar.

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