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The impact of EPB pressure on surface settlement and face displacement in intersection of triple tunnels at Mashhad metro

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Abstract. The growth of cities requires the construction of new tunnels close to the existing ones. Prediction and control of ground movement around the tunnel are important especially in urban area. The ground respond due to EPB (Earth Pressure Balance) pressure are investigated using the finite element method by ABAQUS in intersection of the triplet tunnels (Line 2, 3 and 4) of Mashhad Urban Railway in Iran. Special attention is paid to the effect of EPB pressure on the tunnel face displacement. The results of the analysis show that in EPB tunneling, surface settlement and face displacement is related to EPB pressure. Moreover, it is found that tunnel construction sequence is a great effect in face displacement value. For this study, this value in Line 4 where is excavated after line 3, is smaller than that line. In addition, the trend of the displacement curves are changed with the depth for all lines where is located in above and below, close to and above the centerline tunnel face for Line 2, 3 and 4, respectively. It is concluded that: (i) the surface settlement decreases with increasing EPB pressure on the tunnel face; (ii) at a constant EPB pressure, the tunnel face displacement values increase with depth. In addition, this is depended on the tunneling sequence; (iii) the trend of the displacement curves change with the depth.

Keywords: multiple tunnels; finite element method; surface settlement

1. Introduction

The development of the large cities requires the use the underground area for the construction of transportation infrastructures and facilities. It is highly likely that some new tunnels may need to be designed and constructed nearby existing tunnels. In which case, the Interaction effects of the tunnels in the period of planning, design and construction should be studied carefully. Compared with traditional tunnel construction, the EPB shield method has been widely used in the metro tunnel construction. In most cases, ground displacement including settlement and tunnel face displacement are controlled significant using the EPB machine in urban area. Ground movement around tunnels lead to surface settlement. The magnitude and distribution of these settlement has been studied extensively by Peck (1969), Attewell (1982), Mair (1983) and New (1991) in different methods such as empirical or semi empirical methods, by Sagaseta (1988), Veruijit (1996), Loganathan (1998), Bobet (2001), Chou (2002), Park (2005) and Dindarloo (2015) in analytical methods, by Suwansawat (2006), Melis (2002) and Mroueh (2008) in numerical methods, and by Pourtaghi (2012) and Azadi (2013) in neural network methods . However, empirical and analytical methods are restricted and cannot deal with problems involving the interaction between soil and structures and the relation between the surface movements and the heading confinement pressure. To analysis the interaction problem between a new tunnel and an existing one, numerical methods may provide a flexible to. Relationships between ground settlement and tunneling with EPB machines have been investigated in many researcher (Chiorboli (1996), Suwansawat (2006), Chakeri (2011), Ercelebi (2011), Haghi (2013), Chakeri (2014) and Fang (2014)). Several numerical analyses performed by Yamaguchi (1998) and Chen (2011) to analysis ground behavior during shield tunnel constructions, the changes of earth pressures acting on parallel shield tunnels. There are several analytical and numerical methods for analyzing tunnel face stability (Leca (1990), Anagnostou (1994), Broere (2001), Carrenza-Torres (2004), Chen (2011), Lambrughi (2012) and Shao (2014)). These analyses could be operated for 2D or 3D models as well. The analytical method is based on the Limit Equilibrium Method (LEM) and the earth pressure theory. Numerical analysis represents the more sophisticated instrument for construction’s simulation and verification of the face-stability conditions and settlement.

Mashhad, the capital of Khorasan Razavi province, is a city located in the northeast of Iran. In this paper, intersection lines 2, 3 & 4 of Mashhad Urban Railway according the truth simulated then for each ones the magnitude and orientation of face displacement and surface settlement investigated in different EPB pressures (Fig. 1).

2. Material properties

Soil texture in Mashhad is variable from sandy to clay.

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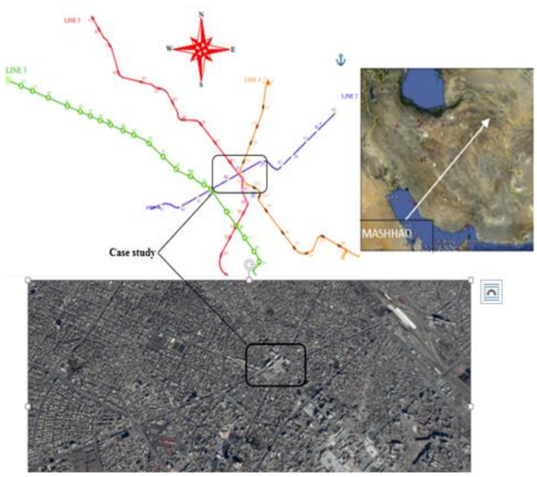


Fig. 1 Mashhad intersection location

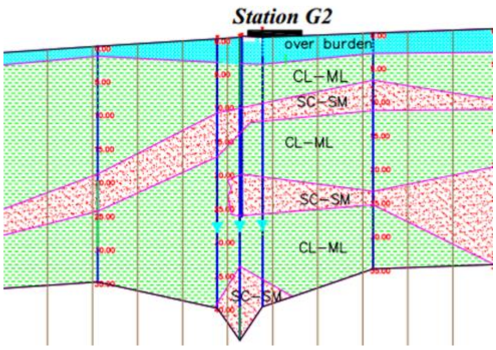


Fig. 2 Profile and geology of the region

Table 1 Physical end mechanical soil properties

Soil strata number	Type of soil	Depth (m)	Dry unit weight (KN /m^3)	Total unit weight (KN /m^3)	Elastic modulus (Kg/cm^2)	K_0 (-)	Friction angle φ(deg)	Cohesion c(Kg/cm^2)
0	Over burden	0-3	16.5	18.5	120	0.64	20	0.25
I	CL-ML	3-10	16.5	19.5	120	0.64	25	0.35
II	SC-SM	10-14.5	16.8	18.5	700	0.5	32	0
III	CL-ML	14.5-60	16.5	19.5	300	0.64	25	0.425

Table 2 Properties of the lining materials

Lining material properties	E_0(GPa)	Poisson's ratio
concrete support	25	0/3

In this region, field consist of fine and coarse grain soils. Up to depth of 20 meters, the layer is decussate fine and coars, until ground is fine for greater depths. Profile and geology of the region is shown in Fig. 2. The soil main properties in the intersection is reported in Table 1.

3. Geometrical and numerical models

In this study, numerical simulations were performed using the finite element (FE) code ABAQUS**.**

The geometry of model, which is used for FE analysis of the intersection of lines 2(part of this line in intersection is includes station), 3 & 4 tunnels, is shown in Fig. 3. The tunnels excavate by the TBM-EPB and station (which located in line 2) excavates with Rib and Pile method. Based on the fact, the crossing area are modelled in a step-by-step procedure, i.e. first excavated and then supported using the reinforced concrete lining ring where is composed of 7 segments and has a width of 1.5 m and a thickness of 0.35 m step-by-step. The shallow tunnel is at a depth of 23m and 3& 4 tunnels are parallel with the center to center distance is 3D (D=tunnel diameter) at a depth of 39 m.

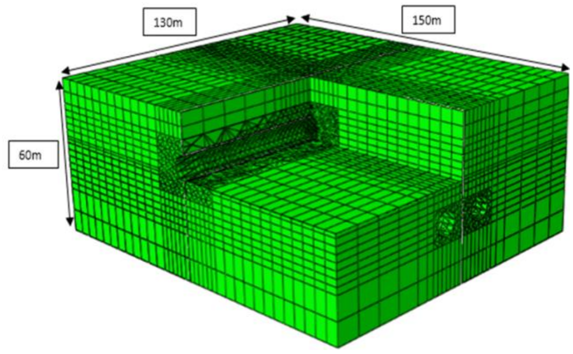


Fig. 3 3D view of model

The characteristic of parameters are as follows: the diameter of tunnels (D) is 9.4 m and face pressure by TBM-EPB is 100 KPa. The concrete lining material properties are given in Table 2.

The whole model consist of 47620 elements. Two type elements are used for rock mass modelling. A ten- node quadratic tetrahedron element (C3D10) is used to all lines & station modelling and for other nodes, an eight-node isoparametric hexahedral element with reduced integration points (C3D8R) is applied. A four-node shell element with reduced integration points (S4R) and an eight-node isoparametric hexahedral element with reduced integration points (C3D8R) are used for the structural components modelling.

In this study, the behavior of the rock mass is modelled by an elastoplastic constitutive relationship based on the Mohr-Coulomb criterion. The main physical-mechanical parameters of the rock mass are shown in Table 1. The behavior of the structural components are modelled by a linear elastic. A 2 KN/m^2 surface load is considered (traffic load, building load, etc.) Concerning the boundary conditions, the displacements are constrained in both directions at the bottom, while zero horizontal displacement is imposed at lateral boundaries.

To simulate the volume loss due to the EPB Shield tunneling, a small amount of contraction, which is expressed as a percentage of the ratio of the reduced area to the original outer tunnel cross-sectional area, is applied to the tunnel lining to simulate a reduction of the tunnel cross-sectional area. This value is 0.1%.

4. The effects of EPB pressure on the surface settlement and face deformations

In this study two analyses were carried out. The first one, model is according to actual situation in which EPB pressure is 100 KPa (named "basic model"). The other one, in which parametric analyses were conducted, the EPB

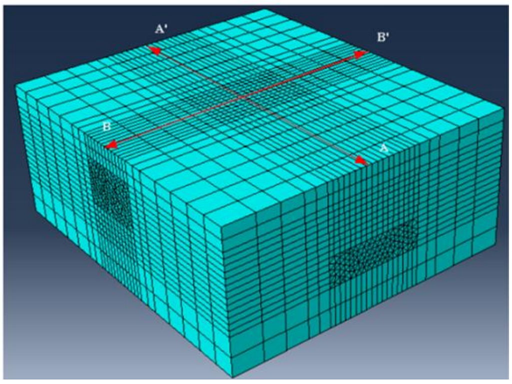
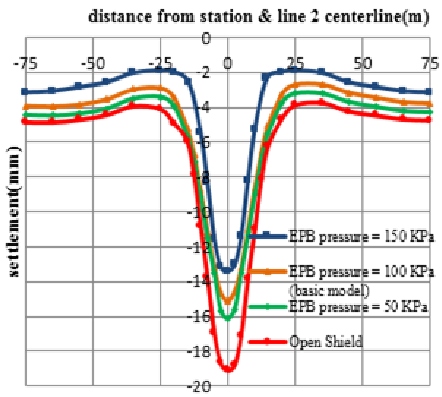
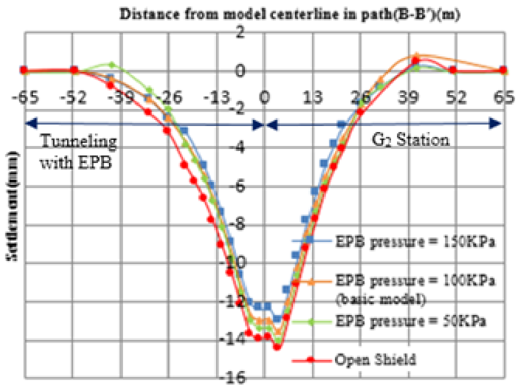


Fig. 4 View of two paths for surface settlement analysis



(a) Surface settlement along AA' path



(b) Surface settlement along BB' path

Fig. 5 Surface settlement along AA' & BB' path in different EPB pressures

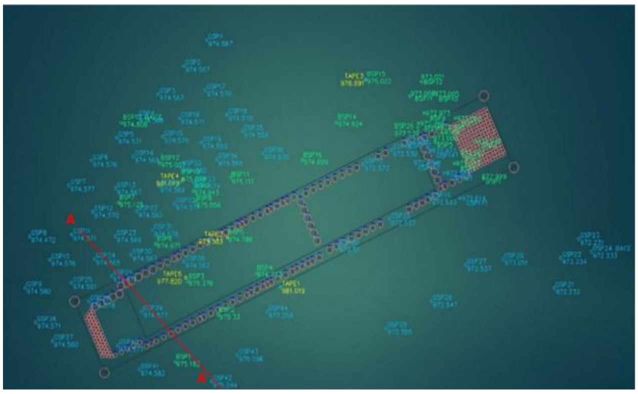


Fig. 6 Layout of surface settlement monitoring points layout of Line 2

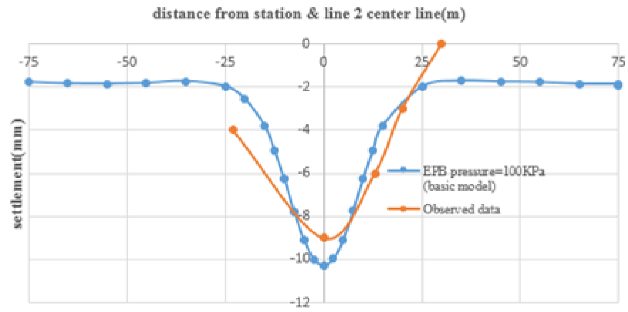


Fig. 7 Comparison of the transvese surface settlement of monitored and numerical for basic model in AA' path(EPB pressure = 100 KPa)

pressures are 0, 50 and 150 KPa.

4.1 The effects of EPB pressure on surface settlement

Surface settlement analysis was conducted in two paths which is shown in Fig. 4.

The maximum surface settlement occurs in the station & line 2 centerline and is equal 15.68 millimeters for the basic model In AA' rout. In this path surface settlement is constants in 50 meter away from centerline (Fig. 5(a)). It is well understood that the maximum surface settlement will increase while the EPB pressure has reduced. This increase for open shield (EPB pressure = 0 KPa) will be significantly greater than for the actual situation (EPB pressure =100 KPa) to 26.4% is 19.1 mm. The result of the surface settlement in BB' path is presented in Fig. 5(b).

For the basic model, the maximum surface settlement at this path is 13.57 mm, which is not exactly in center of path. In addition, the surface settlement is not constant on one side. Both of these may be due to the station existence. The difference of the dimension and stiffness of the station with mechanized part may be caused by a difference between settlement curve in BB' path and AA' path. According to Fig .5(b) the maximum surface settlement will increase while the EPB pressure has reduced.

It is clear that the effect of EPB pressure changes on surface settlement in AA' path is greater than BB', Comparing Figs. 5(a) and 5(b) indicates, because at the AA' path, line 3 and 4 are excavated by EPB while at the BB' path only half of line 2 is excavated by EPB. In addition, EPB pressure which equals 0 KPa has greater impact on the maximum surface settlement in AA' path.

4.1.1 Comparison of the surface settlement predicted by numerical method with observed data and empirical method

The results from numerical analysis of the transverse surface settlement curve during line 2 excavation was compared with observed data and empirical methods such as Peck and Loganathan-Poulos methods.

4.1.1.1 Comparison with observed data

The ground surface settlement data obtained from monitoring point in section A-A where is shown in Fig. 6 compared with numerical method (Fig. 7).

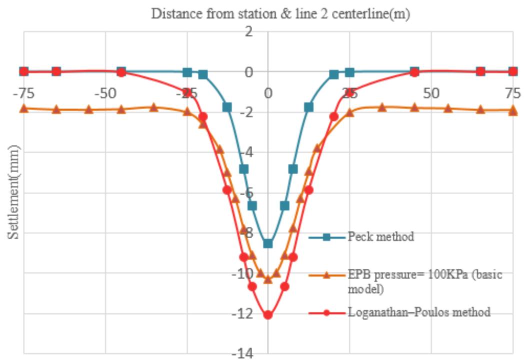


Fig. 8 Comparison of the surface settlement in AA' path obtained from empirical method and numerical for basic model (EPB pressure=100 KPa)

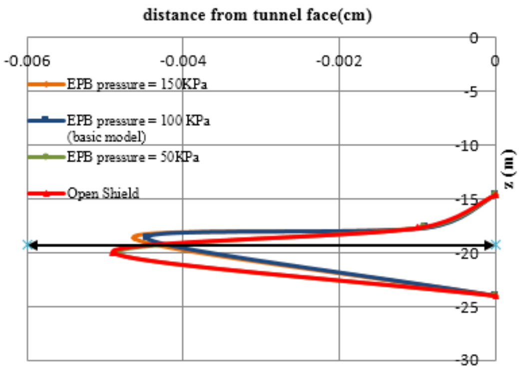


Fig. 9 Displacement in line 2 tunnel face in different EPB pressures

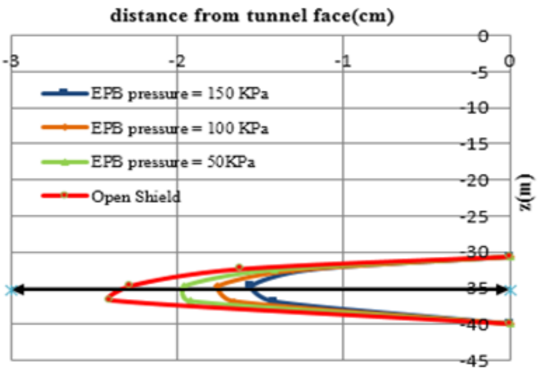


Fig. 10 Displacement in line 3 tunnel face in different EPB pressures

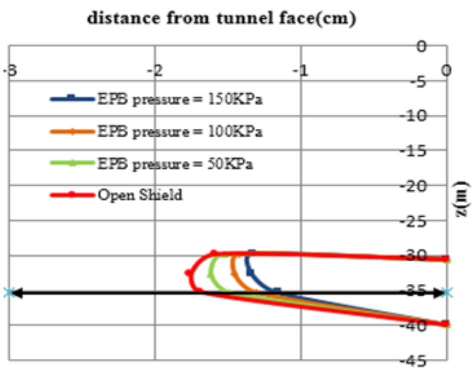


Fig. 11 Displacement in line 4 tunnel face in different EPB pressures

The observations in Fig. 7 allow us to note that numerical method can attain a good fit with the measured values in terms of maximum vertical settlement.

4.1.1.2 Comparison with empirical method

i) The Peck method

Peck and Schmidt (1969) were the first to show that the transverse settlement trough, taking place after construction of a tunnel, in many cases can be well described by the Gaussian function

$$S_v(y) = S_{v\max} \cdot e^{-\frac{y^2}{2i^2}} \tag{1}$$

where S_{vmax} is the settlement above the tunnel axis, y is the vertical distance from the tunnel axis, and i is the horizontal distance from the tunnel axis to the point of inflection of the settlement trough.

The surface settlement curve obtained from Peck method is shown in Fig. 8.

ii) The Loganathan-Poulos method

This method represents an improvement over the previous methods, which takes the ground loss into account introducing the 'gap parameter', g.

$$g = G_p + U_{3D} + \omega \tag{2}$$

where *Gp* is a physical gap representing the geometric clearance between the outer skin of the shield and the lining U_{3D} Is the equivalent three-dimensional (3D) elasto-plastic deformation at the tunnel face, and ω is a value that takes into account the workmanship.

The *g* parameter is related to the undrained ground loss, ε_0 by

$$\varepsilon_0 = \frac{4ga_0 + g^2}{4a_0^2} \times 100\% \tag{3}$$

The vertical surface displacement is expressed by

$$W(y) = 4(1-\nu)\, a_0^2 \times \frac{z_0}{z_0^2 + y^2} \times \frac{4ga_0 + g^2}{4a_0^2} \times \exp(\frac{1.38y^2}{(z_0+a_0)^2} \tag{4}$$

where a_0 is the tunnel radius, z_0 is the tunnel-axis depth, υ is the Poisson's ratio and *y* is the horizontal distance from the tunnel axis. The comparison of numerical and empirical methods in Fig. 8 Indicated that the maximum transverse surface settlement predicted based on the two methods, presented fit well.

4.2 Effects of EPB pressure on the face deformations

In shield tunneling, the deformation and displacement may occur at the tunnel face. This would be the results of insufficient face pressures applied. Therefore, it is very important to apply appropriate EPB pressure. The surface settlement in shallow tunnels or tunnel collapse may be occurred due to the large displacement in the tunnel face.

The displacement in the tunnels face in the crossing area has been indicated in different pressures of the EPB machine in Figs. 9-11.

Fig. 9 shows that the tunnel face displacement curve in line 2 is the same for 100 and 150 KPa. The maximum displacement of the tunnel face is located at 70 cm above the centerline of the tunnel face equals 0.0046 cm. This figure also shows the tunnel face displacement is the same for 0 and 50 KPa. The maximum value is located at 70 cm below the centerline of the tunnel face equals 0.0049 cm that is more than that two before cases.

Fig. 10 depicts the tunnel face displacement curves in line 3. It is understood from this figure that the curves are similar for all analyses. The maximum displacement which occurred in the center of tunnel decreases with EPB pressure increase. The curve using open shield (EPB pressure=0KPa) is different from others. In this case the maximum displacement is greater than other analyses and takes place below the centerline of the tunnel face.

Fig. 11 shows that the trend of the tunnel face displacement curves in line 4 is similar for all scenarios. It is toward the above centerline. The maximum value increases with EPB pressure decreases that is located at 2.7 m above the tunnel face center.

Several major points are understood from Figs. 9-11. The first is how the trend of the tunnel face displacement curve will be changed with the depth of the tunnel. These figures indicate that the change in the trend of the curves in line 2 that is the shallowest than the other lines because the change in the EPB pressure is significant. The maximum displacement of the tunnel face in line 2 is very small compared to the other lines. The optimum EPB pressure in line 2 face excavation is 100 KPa because for larger values the maximum displacement will not decreases. A change of EPB pressure has no influence on the face displacement curve treatment of line 3 and 4. In addition, it should be noted that the maximum displacement of the tunnel face increase with increasing depth.

This makes it clear that EPB pressure for line 2 excavation is not enough to line 3 and line 4 excavation. The comparison of the figures 9-11 shows that the tunnel face displacement value in line 3 is greater than other lines. This is because line 3 is deeper compared to line 2. The comparison of line 4, line 3 excavated sooner and the stress relaxed to the surrounding ground.

5. Conclusions

In this paper, the interactions of intersection of the 2, 3 and 4 Mashhad Urban Railway lines are investigated using a full three-dimensional (3D) finite element analysis with the code ABAQUS.

Special attention was paid to the effect of EPB pressure on the surface settlement and the tunnel face displacement.

For this particular study, the following conclusions can be drawn:

(1) The maximum surface settlement increases and decreases with EPB pressure decreasing and increasing.

(2) The change of EPB pressure has a greater effect on the surface settlement in the AA' path in comparison to the BB' path. Because both line 3 and line 4 excavated with EPB machine along the AA' path. While only a half part of the tunnel of line 2 excavated with EPB and other half excavated with Rib & Pile method along the BB' path.

(3) The ground surface settlement curve along the BB' path has a trend to move downward with start of the Station excavation. This may be due to large dimensions of the station.

(4) The ground surface settlement for basic model (EPB pressure = 100 KPa) indicated that the maximum surface settlement increases when the two new tunnels excavated at beneath the existing tunnel.

(5) The optimum EPB pressure which are applied on line 2 face is 100 KPa. Therefore, the stress and the face displacement do not reduce with increasing EPB pressure of this value. At this line, the face displacements change when the EPB pressure changes, so that the tunnel face displacement curves are toward above the tunnel face centerline for EPB pressures equal 100 and 150 KPa and are toward below the tunnel face centerline for EPB pressures equal 0 and 50 KPa.

(6) The tunnel face displacement curve is toward center of tunnel face and above the tunnel face for the different EPB pressure in line 3 and 4 respectively.

(7) The tunnel face displacement in line 3 and 4 are greater than line 2 that is due to the greater depth of this lines.

(8) In addition to the depth of tunnels, tunneling sequence is also effective in the face displacement. The tunnel face displacement values in line 4 were smaller than line 3 which can be caused by the stress relaxation of the regions around line 4 due to earlier excavation of line 3.

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