Engineering geological investigations along the Tabriz subway extension focusing on ground surface settlement, northwestern Iran

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Received: 26August Feb 2010 Revised 20 Feb 2010

Abstract

The purpose of this paper is to assess the engineering geological characteristics of soil and rock, and to predict ground surface settlement due to tunneling in main part of Tabriz subway line 2 which has a length of 12 km. The total length of the excavation line is 20 km between International fair and Kara malek. Tunnels will be excavated by employing EPB Shields 9.2 m in diameter. Geology in this section is mainly composed of sand (SM), silt (ML) and Sedimentary rocks (marl, siltstone, claystone and sandstone). Laboratory experiments and field studies were conducted for the study area. Field studies consisted of geological mapping, in situ testing, core drilling and sampling for laboratory studies. Uniaxial compressive tests, triaxial compressive strength test and deformability tests were conducted in the laboratory. For more Precise investigations, Subway path was divided into three geotechnical zones. These zones mainly consist of fine grained soils, coarse grained soils and Sedimentary rocks, respectively. Settlement predictions were performed using PLAXIS 3D Tunnel, a 3D finite element computer software. Excavation, ground support and face support steps in FEM analyses were simulated. Predictions were performed for typical geological parts in each zone, which is considered as critical in terms of ground surface settlement. Based on the results acquired from this method, ground surface settlement in some parts of Tabriz urban railway line 2 can be a problem during tunneling. Further, the ground condition improvement such as grouting and dewatering must be performed before tunneling.

KeyWords: EPB-TBM tunnelling, Tabriz subway line 2, PLAXIS 3D Tunnel, Surface settlement prediction.

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Introduction

The need to upgrade and further develop transportation infrastructure (high-speed railway, high way and urban transit lines) has led to the on-going construction of large–diameter, long tunnels under difficult conditions. Such conditions usually arise from a combination of adverse ground and groundwater regimes, very high overburden pressures or, in the case of urban tunnels, the existence of sensitive structures within the zone of influence of the tunnel. Engineering geology along the tunnel alignment plays a dominant role in many of the major decisions that must be made in planning, designing and construction of a tunnel. Thus, it is vital to conduct appropriate engineering geological investigations prior to any planning process for the construction of tunnels. Tabriz city with 160 km^2 area and the population of about 1,360,000 is one of the most crowded and important cities in northwestern Iran (Azerbaijan Province). According to the conducted traffic and transportation studies, 4 line urban railways, 48 km in length (extendable to 72 km), are considered for this city. Studies and design of Tabriz urban railway line 2 (TURL2) commenced in 2006 (TURO, 2007). TURL 2, 20 km in length will connect eastern part of the city (International Fair) to its western part (Kara malek) and will pass crowded parts of the city such as trading centers on its way (Figure 1). The total length of TURL2 will be excavated by EPB-TBM[1] and the depth of the tunnel ranges from 9 to 26 m from the ground surface.

Fig. 1. Location map of the Tabriz City and urban railway lines (No scale)

1 . Earth Pressure Balance-Tunnel Boring Machine

Geology of the site

Generally, Tabriz city has been built on the various sediments which belong to Cenozoic and Quaternary formations. The major part of Tabriz plain is composed of young and unconsolidated deposits that are mostly formed from river and refrigerated sediments with different texture and a variety in grading. Geologically, Tabriz is located in a tectonized area in northwest Iran. It is along Alp-Himalaya active belt. The Stratigraphy of Tabriz city comprises only of Cenozoic and Quaternary formations. There is no sign of Paleocene, Eocene and Oligocene sediments to indicate pre-Miocene period. This shows sedimentation has not taken place during these periods. The investigated area is totally covered with recent alluvium sediments, but the performed drillings indicate the existence of conglomerate, sandstone and marl layers under the mentioned alluvium sediments. Rock layers only extended in east part of TURL2 and in central and west part of it, are not observed in any boreholes. Stratigraphical column of the Tabriz area is shown in Figure 2 (TURO, 2007).

Engineering Geological studies

1. Field investigations

Field investigations consisted of drilling of boreholes and performing in situ tests. In preliminary geotechnical investigation, 53

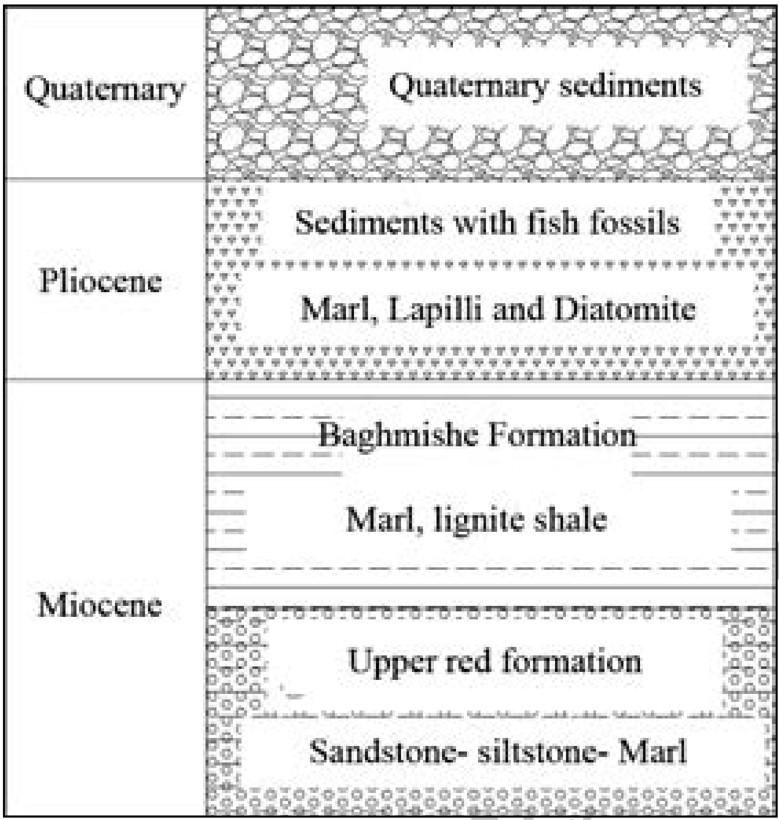


Fig.2. Stratigraphical column of Tabriz area

boreholes and 15 test pits were excavated. For detailed geotechnical investigation, 90 boreholes and 10 test pits were drilled. Based on drillings, the surface layers are alluvium and deeper layers consist of sedimentary rocks. The thickness of alluvial layers which is a combination of clay (CL), silt (ML), sand (SM) and gravel (GP), varies from 6 to 30m. It can be divided into two groups such as coarse grained and fine grained alluvium. Due to evaluating the Relative density and stiffness of soil and rock, large number of Standard

Penetration Tests (SPT) were performed in all of drilled bore holes at 1.5 m intervals. In table 1 the results of this test in some boreholes, were drilled in studied stations are shown. In classifications based on standard penetration test values (N-SPT) (Bowels, 1988), it was determined that Fine grained and coarse grained soils in Tabriz Urban Railway Line 2 are mainly very hard and dense respectively (Fig.3). Also, Geophysical investigations were carried out by measuring seismic waves (six down- hole tests) and the results showed that the shear wave velocity of soils and rocks varies from 500 to 800 m/sec, which is compatible with SPT results. During drilling of bore holes in order to determine hydraulic conductivities, field permeability tests (2 to 3 Lefranc - type tests in each bore hole) were carried out and it was determined that permeability coefficients of coarse grained soil varied from 10^{-3} to 10^{-6} cm/s and in fine grained soils it varied from 10^{-5} to 10^{-7} cm/s; when measured in rock layers, the permeability coefficients varied from 10^{-6} to 10^{-8} cm/s see (Table 2).

Table1. SPT test results conducted in three studied stations (TURO, 2007)

Station					
Khatibe Shomali		Rajaee Station		Shariatti Station	
Depth (m)	SPT Values	Depth (m)	SPT Values	Depth (m)	SPT Values
2	18	2	34	2	12
4	26	4	32	4	14
6	30	6	26	6	10
8	40	8	34	8	13
10	43	10	31	10	10
12	40	12	32	12	18
14	53	14	36	14	32
16	42	16	40	16	35
18	40	18	42	18	40

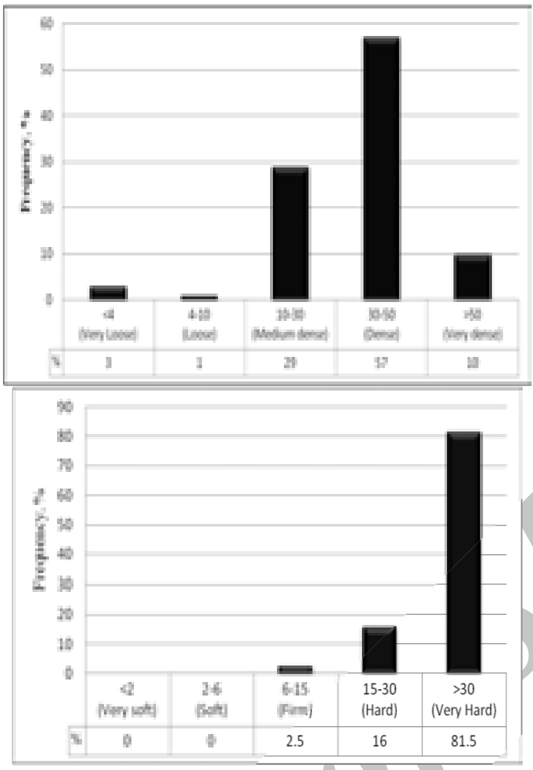


Fig.3. Histograms showing percentage distribution and classification of (a) Fine grained soils based on SPT values, (b) coarse grained soils based on SPT values (Babazadeh, 2010).

Table2. Lefranc tests results for three type of materials (TURO, 2007)

Sedimentary Rocks			Fine grained alluvium			Coarse grained alluvium		
Bore hole	Test depth (m)	K)cm/s(	Bore hole	Test depth (m)	K)cm/s(	Bore hole	Test depth (m)	K)cm/s(
BH-1	10-11	9×10^{-7}	BH-10	18-19	6.1×10^{-6}	BH-9	9-10	8.4×10^{-6}
BH-2	11-12	6.5×10^{-6}	BH-16	10-11	5.8×10^{-5}	BH-10	10-11	3.6×10^{-5}
BH-3	9-10	2.1×10^{-8}	BH-17	12-13	5.6×10^{-7}	BH-11	8-9	6.3×10^{-6}
BH-4	10-11	4.4×10^{-7}	BH-18	9-10	9.6×10^{-6}	BH-12	18-19	1.3×10^{-6}
BH-5	18-19	1.9×10^{-6}	BH-23	9-10	1.8×10^{-7}	BH-19	9-10	4.6×10^{-6}
BH-6	19-20	5.1×10^{-7}	BH-24	18-19	1.2×10^{-6}	BH-20	16-17	1.8×10^{-3}
BH-7	19-19	2.7×10^{-8}	BH-25	18-19	8.5×10^{-7}	BH-26	22-23	1.1×10^{-4}

To study the subway path accurately, it was divided into three different zones on the basis of type and engineering geological properties:

Zone 1: From beginning of path to km 3+500

This zone is located in western part of Tabriz city and drilled boreholes indicated that to the investigated depth (30 m); soils are mainly of fined grained type and according to unified classifications are ML and CL. Among these soils, there are inert beds of coarse grained soils. At this part, tunnel runs across the fine grained soils.

Zone 2: From km 3+500 to 8+00

This zone is located in central part of Tabriz city, and to the drilled depth subsurface layers are mainly composed of coarse grained soils (SM, GP). At this zone, tunnel runs across the coarse grained soils. Existence of boulders (bits of igneous and pyroclastic rocks) in this zone may cause problems during tunneling.

Zone 3: From km 8+00 to 12

In this zone located in east part of Tabriz, sedimentary rocks such as marl, clay stone, siltstone and sandstone are underlain by surface alluvium (SM, ML and CL) with thickness of 5 to 15 m. In this zone, tunnel runs across the rock layers. The cross section along TURL2 tunnels rout is presented in figure 4.

2. Physical and geomechanical characteristics of the soil and rock

In order to determine physical and Geomechanical characteristics of the main soil and rock types, laboratory tests were performed on the specimens collected from the boreholes. The dry unit weights, saturated unit weights, Specific gravities, Uniaxial compressive strengths, triaxial compressive strength, elasticity modulus, and Poisson ratios were determined on the basis of ASTM (1980) and ISRM (1981). Average values of above mentioned parameters which are necessary in numerical analysis are shown in table 3, 4 and 5 for Khatibe Shomali, Rajaee and Shariatti Station Respectively.

Table3. Average values of Geotechnical properties of soil and rock in Khatibe Shomali Station

parameters	Fine grained alluvium	Coarse grained alluvium
Bulk density)KN/m3(	18.7	19.45
Dry density)KN/m3(	16.1	16.32
Elasticity modulus)MPa(	31	23
Poisson ratio)υ(	0.36	0.32
Internal friction angle)degree(	19	34
cohesion)kPa(	36	15

Table4. Average values of Geotechnical properties of soil and rock in Rajaee Station

parameters	Fine grained alluvium	Coarse grained	Sedimentary Rocks
Bulk density)KN/m3(	18.5	19.35	20.9
Dry density)KN/m3(	16.3	16.2	17.8
Elasticity)MPa(	36	21	46
Poisson ratio)υ(	0.37	0.33	0.32
Internal)degree(	16	35	25
cohesion)kPa(	34	13	49

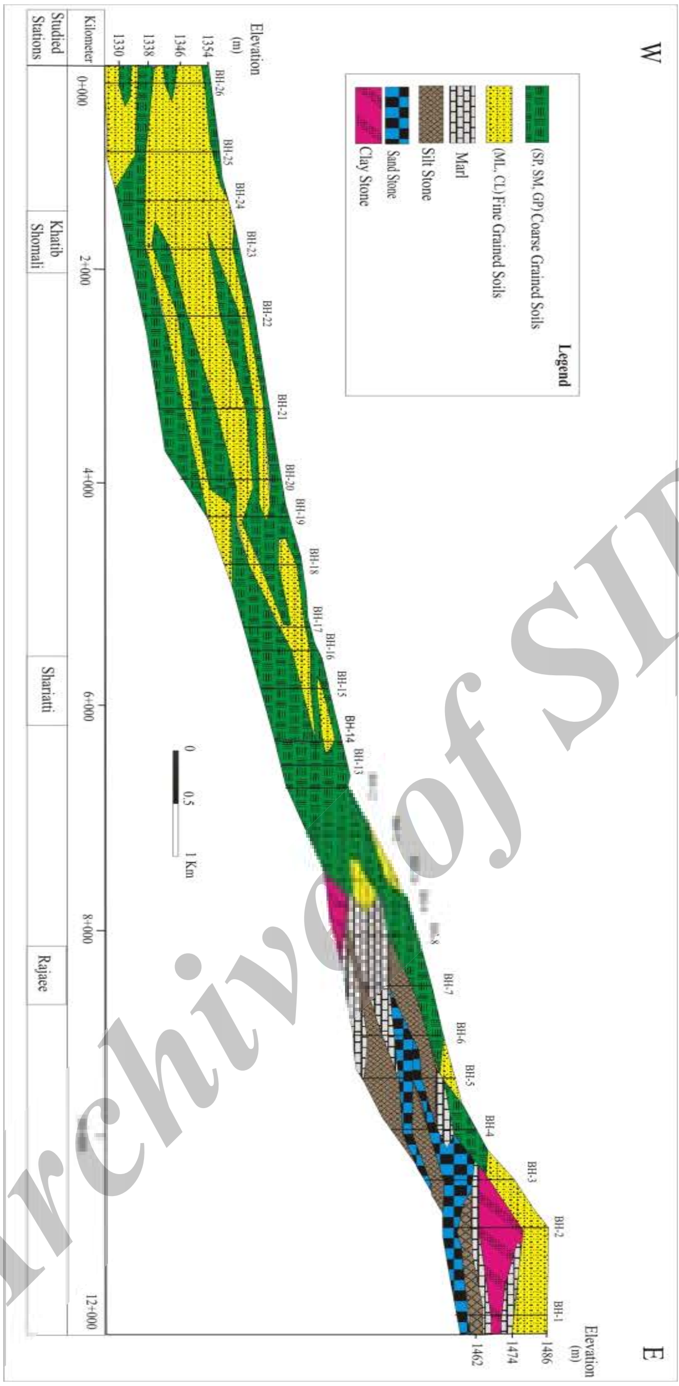


Fig4. Geological Cross Section along the tunnel rout (Babazadeh, 2010)

Table5. Average values of Geotechnical properties of soil and rock in Shariatti Station

parameters	Fine grained alluvium	Coarse grained alluvium
Bulk density)KN/m3(	18.75	19.15
Dry density)KN/m3(	16.33	16.4
Elasticity modulus)MPa(	34	24
Poisson ratio)υ(	0.32	0.35
Internal friction angle)degree(	18	34
cohesion)kPa(	38	13

In classification based on uniaxial compressive strength (ISRM, 1981), it was determined that the rock layers are extremely weak (Fig.5).

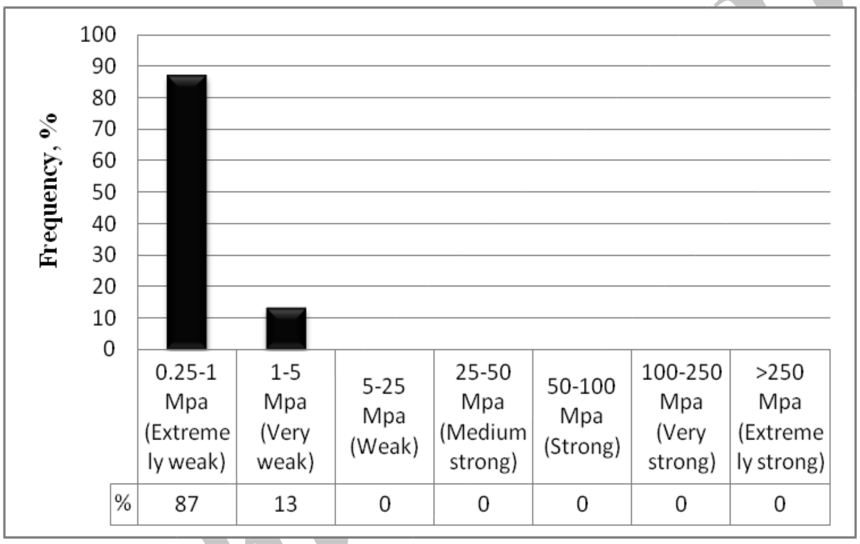


Fig.5. Histograms showing percentage distribution and classification of rock based on uniaxial compressive strength (Babazadeh, 2010)

3. Groundwater condition

Groundwater along the project alignment is concentrated within quaternary alluviums in the Tabriz plain. Alternation of low permeability rock layers (marlstones and clay stones) with high permeability rock layers (sandstones and conglomerates), caused artesian condition in some part of zone 3. These aquifers were local and had small dimensions; as the result, the above mentioned phenomenon disappeared after drilling. Piezometric measurements showed that depth to groundwater in studied areas ranges from as small as 2 m to 25 m in excess. Tunnel and station excavations in Tabriz plain alluviums will be below the water table. Though, because of low permeability of rocks and alluviums, groundwater inflows will be low. But hydrostatic and hydrodynamic pressures can cause a series of problems for tunneling.

Ground surface Settlement

The excavation of tunnels and other underground works causes a re-distribution of natural stresses and deformations in the surrounding soils and rocks. These deformations are especially important in the case of urban areas that result in ground surface settlement. The main reason for ground surface settlements is convergence of the ground into the tunnel after excavation, which changes the in situ stress state of the ground and results in stress relief. Convergence of the ground is also known as ground loss or volume loss. The volume of the settlement on the surface is usually assumed to be equal to the ground (volume) loss inside the tunnel (O'Reilly and New, 1982). Ground loss can be classified as radial loss around the tunnel periphery and axial (face) loss at the excavation face (Attewell et al., 1986; Schmidt, 1974). The ground loss is usually higher in granular soils than in cohesive soils for similar construction conditions. The width of the settlement trough on both sides of the tunnel axis is wider in the case of cohesive soils, which means lower maximum settlement for the same amount of ground loss (Ercelebi et al, 2010). To minimize damages sustained by nearby buildings, infrastructures, existing services and foundations on the ground surface, it is necessary to predict settlement due to shallow and soft ground tunneling. Methods for estimating that may be classified into three categories: empirical methods, numerical methods such as finite element, and analytical methods. In this study, the finite element methods are employed for a critical part to predict surface settlements above the tunnel in zone1 (Khatibe Shomali Station), zone 2 (Shariatti Station) and zone 3 (Rajaee Station).

Surface settlement prediction with Numerical analysis

1. Finite Element Modeling (FE)

Numerical modeling, such as finite element method is a useful tool for analysis of the stability of underground space in sequential construction and determination of the influence of effective parameters (Delezalova, 2002; Galli et al., 2004; Ercelebi et al., 2005). In last the decades, numerical simulation has increasingly become the dominant method for solving engineering problems including the stability analysis and predicting the system behavior. Tunneling analysis is a matter of 3-D cases rather than 2-D. In fact, to examine stress redistribution and ground response to tunneling ahead and behind the tunnel face, 3-D FE analysis is required to be conducted (Karakus and Fowell, 2006). In this section, using PLAXIS 3D Tunnel finite element software code, site condition is simulated and ground surface settlement is predicted. In this FE modeling, only a half part of the whole tunnel is presented by taking the homogeneity and isotropy of the soil and the symmetry of the geometry and loading conditions into account. Analyses are conducted for the following Cases:

Case 1: Shield tunneling through Fine grained alluvium (Khatibe Shomali Station)

The tunnel axis in this station is 18m below the surface and the ground water is 10 m to ground surface. The ground layer is composed of fine grained soil with thickness of 10 m, 2m coarse grained soil and 15 m fine grained soils.

Case 2: Shield tunneling through coarse grained alluvium (Shariatti Station)

The tunnel axis is 18 m below the surface and the ground water is 11 m to ground surface. The ground layer is composed of fine grained soil with thickness of 12 m which overlay coarse grained soils with more than 20 m thickness.

Case 3: Shield tunneling through Sedimentary rocks (Rajaee Station)

The tunnel axis in this station is 20 m below the surface and the ground water is 6 m to ground surface. The ground layers are composed of coarse grained soils consisting of gravel and sand with 6 m thickness which are overlaid sedimentary rocks with more than 20 m thickness.

2. Mesh Generation

A 15 node triangular element was used to generate the model mesh. The powerful 15-node element provides an accurate calculation of stresses and failure loads. The 2D Finite element models (that are the basis for generation of 3D mesh) for three shield tunneling configurations are presented in figure 6.

3. Material Model

A soil model known as the Mohr-Coulomb (MC) was used to simulate the soil behavior under excavation. This model involves five parameters, namely, Young's modulus, E, Poisson's ratio, υ, the cohesion, c, the friction angle, φ, and the dilatancy angle, ψ. In this case, dilatency angle was assumed to be zero, since it is close to zero for clay and for sands with friction angle less than 30 (Hossain & Haque, 2009). The undrained behavior of the underground and the consolidation process was neglected in these numerical computations and was assumed that drained behavior is dominant.

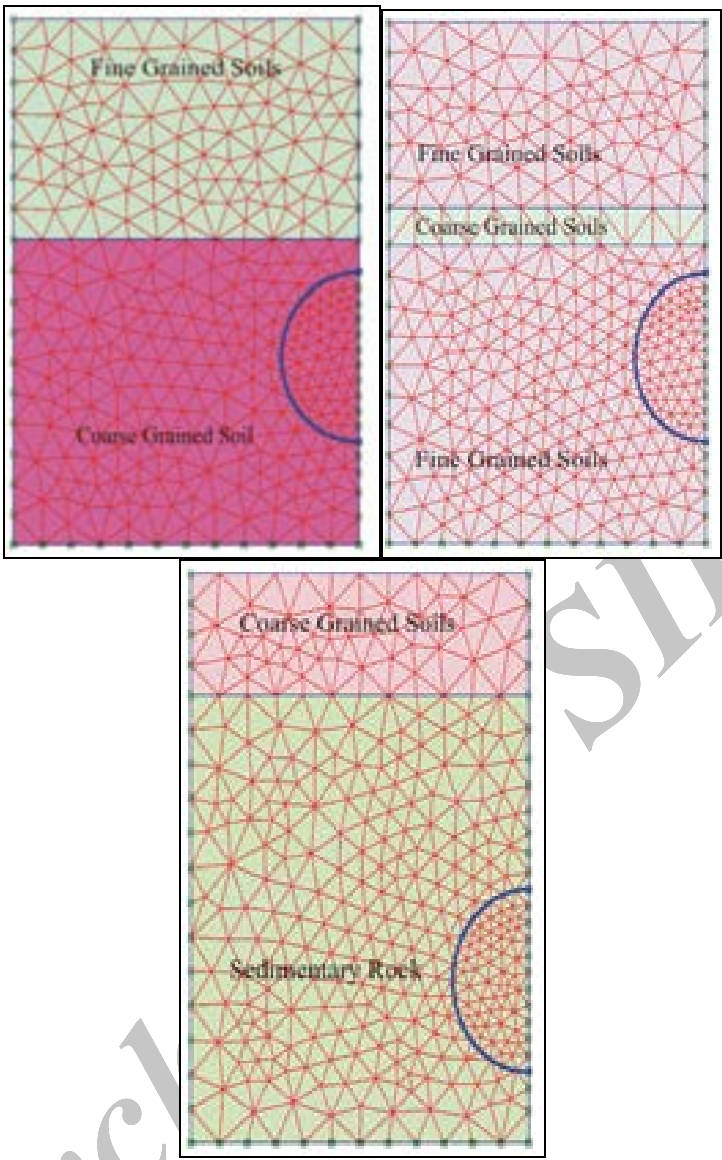


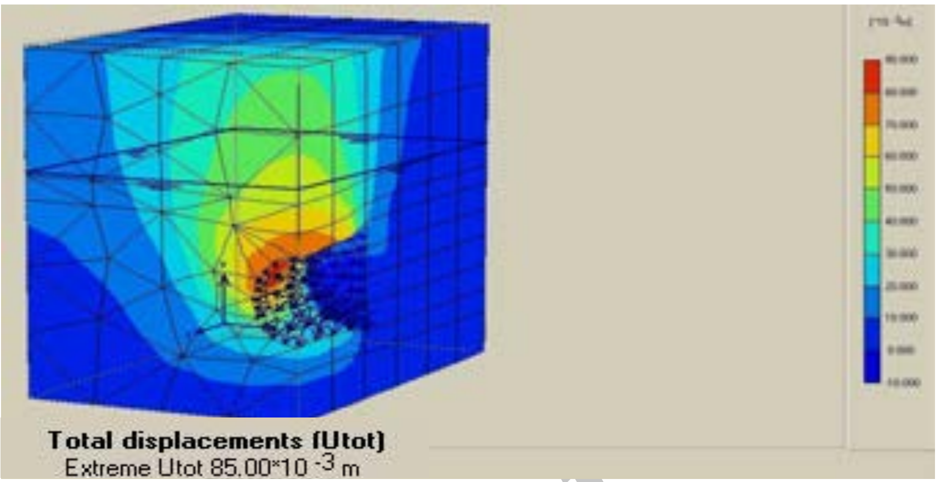
Fig.6. 2 D Finite element model of three shield tunneling configurations, (a) Rajaee Station, (b) Khatibe Shomali Station, (c) Shariatti Station

4. Material Parameters

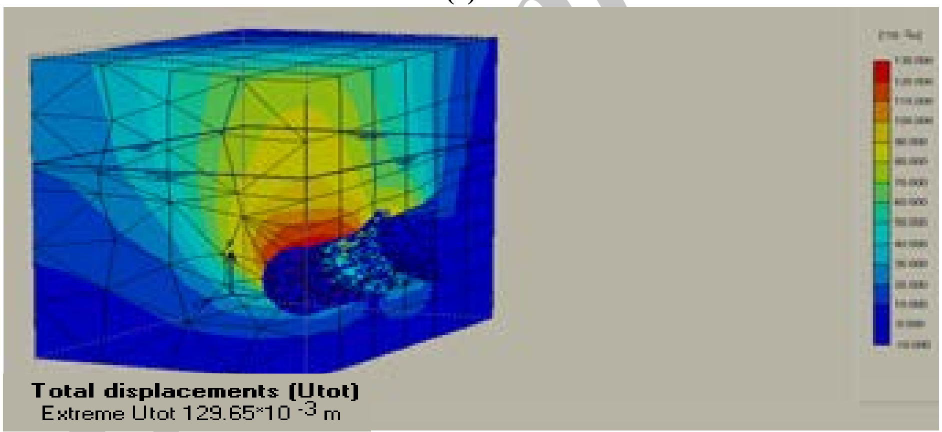
The parameters used in the FE analysis are presented in Table 1. Some of the important properties are saturated and unsaturated unit weight, and stiffness.

5. Construction sequence and calculations

For modeling EPB-TBM Tunneling, the staged construction is used. Applying staged construction, excavation of the soil and the construction of the tunnel lining is carried out in different phases. The first phase consist, of soil excavation in front of TBM and applying a support pressure of 250 kPa at the tunnel face to prevent failure. In the first phase, TBM is modeled as shell elements. Construction of tunnel lining by means of prefabricated concrete ring segments, which are bolted together within the tunnel boring machine, is the second phase of excavation. During the erection of the lining, TBM remains stationary. Once a lining ring has been bolted, excavation is resumed until sufficient soil excavation is carried out for the next lining. The tunnel lining is modeled using volume elements. In the second phase, the lining is activated and TBM shell elements are deactivated. In shield tunneling that may be composed of several steps, these phases (excavation and lining) are repeated over and over again until construction finishes. In this study, Construction stages were modeled with steps of 10 m length. For three configurations, Maximum horizontal (U_{xx}), vertical (U_{yy}), total displacements (U_t) and ground surface settlement, have been computed. In the current study, it can be seen that for all three analyzed cases, by advancing TBM through soil and increasing in excavation step numbers the amount of displacements increased (Figure 7). This may be the result of the disturbances caused by the surrounding soil and rocks.



(a)



(b)

Fig.7. total displacements during tunneling in khatibe shomali station, a) first stage b) Second stage

When applying finite element models, volume loss values are usually assumed prior to excavation. In this study, the FE model is run with the assumption of 0.25, 0.5, 0.75, 1 and 1.5% volume loss caused by the convergence of the ground into the tunnel after excavation. Ground surface settlement prediction is carried out by taking different volume loss into account for the three mentioned configurations. As can be seen from figure 8, by increasing in volume loss, the amount of ground surface settlement is increased in all stations.

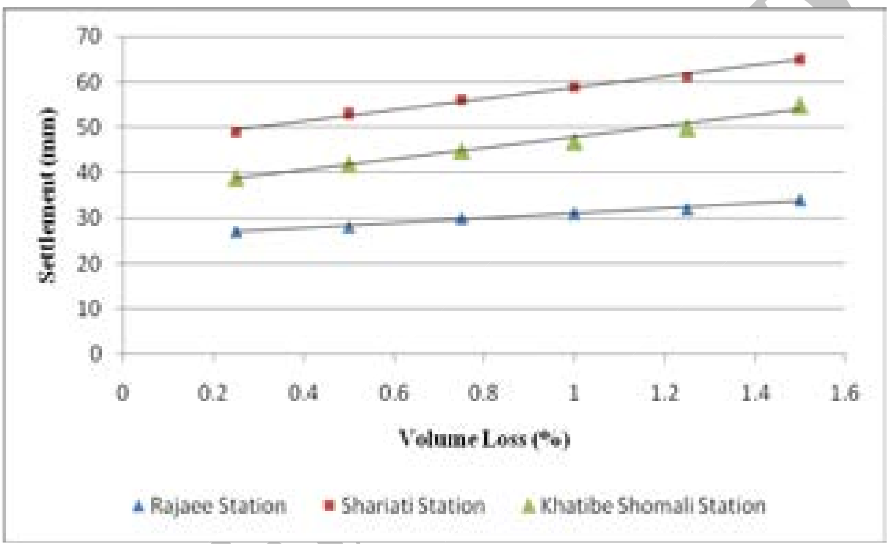


Fig.8. Variation of ground surface settlement versus volume loss in step 4

Surface settlement is also shown for some construction stages in cross section in Figure 9 to Figure11 in three Stations. As can be seen in these figures, ground surface settlement increases as the excavation continues. But the rate of increment in the starting position is reduced as the excavation stages proceeds further.

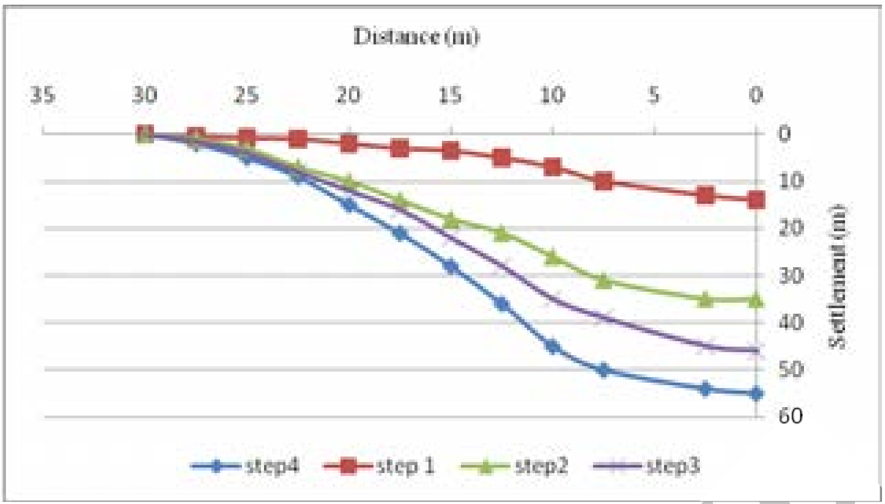


Fig.9. Ground settlement over the crown in cross section at different construction stages for volume loss of 1.5% in khatibe Shomali Station

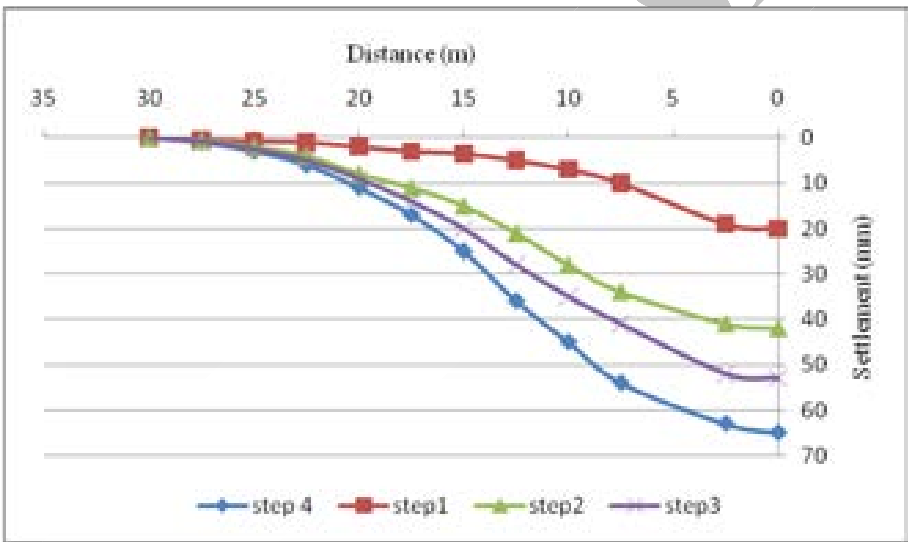


Fig.10. Ground settlement over the crown in cross section at different construction stages for volume loss of 1.5% in Shariatti Station

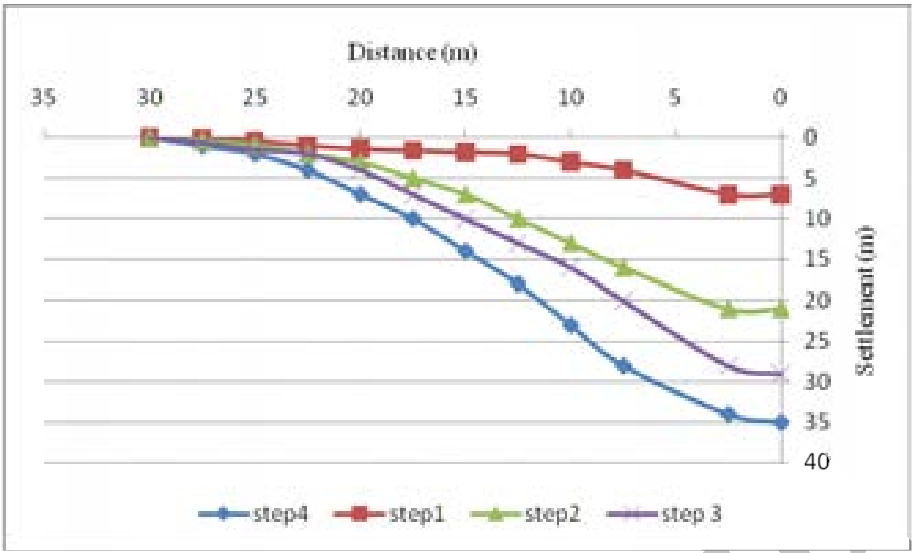


Fig.11. Ground settlement over the crown in cross section at different construction stages for volume loss of 1.5% in Rajaee Station

Summary and Conclusions

In this study, engineering geological studies were carried out along Tabriz urban railway line 2 tunnel in the northwest of Iran. Based on laboratory and in situ tests, the geotechnical properties of materials were assessed, and in order to study the subway path accurately it was divided into three different zones. Drilling of bore holes and doing sieve tests, shows that zone 3 is mainly composed of sedimentary rocks such as marl, siltstone and sandstone that are underlain by SM and ML. Also, in zones 1 and 2, alluviums are mainly classified as ML and SM respectively. According to the standard penetration test results, Fine grained and coarse grained soils in studied path are mainly very hard and dense, respectively, and laboratory tests shows that sedimentary rocks are mainly extremely weak. It was determined that the hydraulic conductivity has maximum amount of 10^{-3} cm/s and minimum amount of 10^{-8} cm/s in coarse grained soils and sedimentary rocks, respectively. However, in some parts of metro path because of high compaction and fine content, coarse grained soils showed a lower amount of permeability coefficient. The finite element software package PLAXIS 3D was used to determine the induced stresses and deformations developed around the tunnels in three stations of Tabriz urban railway Line 2, and, finally, ground surface settlement above tunnel in each station was predicted. The results of numerical modeling showed that:

1. Settlement of ground surface is relatively low in Rajaee station with 35 mm while the amount of ground surface settlement occurred in shariatti and khatibe shomali stations are 55 mm and 65 mm, respectively.
2. Calculations for different amount of volume loss showed that, by increasing of volume loss the amount of ground surface settlement increaseds. Also, displacements and settlements increase as the excavation continues, but in the last steps its rate is reduced.
3. Although finite element methods such as PLAXIS 3D, FLAC and… can predict and simulate the behavior of tunnels with high accuracy, these methods must be confirmed by field measuring

and the acquired results must be applied in practice by experienced engineers.

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