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Surface Settlement at Intersection of Tunnels using by 3-D Numerical Analysis: Case Study

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Abstract

Monitoring and controlling soil behavior during the excavation of new tunnel nearby the existent tunnel is so crucial in providing safety for adjacent structures. The interaction between excavating tunnel (line 2) underneath the present metro station (Line 1) in their intersection was examined in this study. To simulate the conditions of stress and displacement caused by excavating over the current station, the process of tunnel excavation is modeled by Cut & Cover method. For the station's foundation, the pile-raft system is used to reduce settlement and the effects of interaction between the station and the new tunnel. The new tunnel under the station has been surrounded by soldier beams (soldier piles) in a distance of 20 cm from the tunnel wall. In the design phase for the tunnel Line 2 which will be excavated using a TBM-EPB (Tunnel Boring Machine-Earth Pressure Balance), the control of station's safety near this line is a principle. Therefore, exploring the interaction between the excavating tunnel and the present station and also assessing the surface settlement in this area are of great importance. To investigate this mechanism, the limited three-dimensional components analysis is applied by employing Abaqus 6-10.1 software. The Mohr-Coulomb Behavioral model is used for the soil. Results show that by the usage of pile-raft system, the surface settlement resulting from the excavation of new tunnel is reduced. Also, the results demonstrate a decline in the relative difference in terms of settlement over the raft.

Keywords: metro station, tunneling by TBM-EPB, settlement, Finite element, three-dimensional modeling

1. Introduction

In large and populous cities, subway tunnels play a major role in passenger transportation. In most urban areas, inevitably, subway lines intersect with each other at some points, which these critical points can be found in a surface or different height. The excavation of a new tunnel will induce displacement in these underground structures. Numerous damages in underground structures were reported in the past decades [1] [2]. Because of preventing financial and environmental damages, this subject undoubtedly worth searching. The excavation process in soft soils depends on parameters, such as soil structure, changes in groundwater levels, geometrical parameters including the depth of tunnel excavation and the distance between the tunnel and adjacent structures, which all items may cause these shifts.
At Shariati Square area, Line 2 of Mashhad subway system (figure 1) intersects the present station of Line 1. Therefore, to anticipate surface settlements and interactions arising from excavating tunnel Line 2, the quantity of settlement and the in-stress changes in this location have been analyzed.

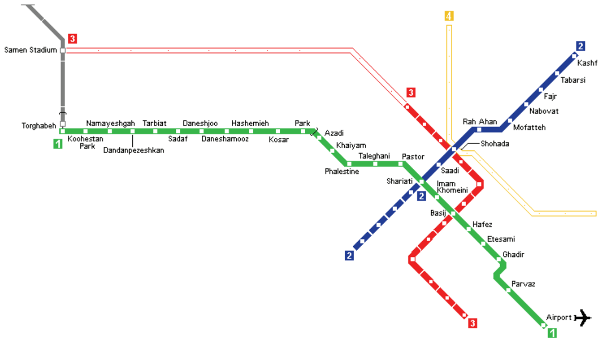

Fig. 1. The situation of Mashhad subway lines relative to each other[1] (Mashhad Urban Rail) [3]

In order to investigate the effect of new excavation over adjacent structures a case study conducted by Xiao and et al., 2018 in Shanghai showed that the cut-and-cover tunnel uplifted due to the nearby deep excavations while the shield tunnels settled [4]. Also, to control the displacement of the cut-and-cover tunnel, the cross walls should be constructed after the excavation of large pits, and

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[1] Line 1 (Green): With the length of 26 kilometers, from Shariati to Vakilabad (under construction) and its extension to Shahid Hasheminejad International Airport.
Line 2 (Blue): With the approximate length of 17.5 kilometers, from Kuhsangi to North Tabarsi
Line 3 (Red): With the approximate length of 19.5 kilometers, from Passenger terminal station to Ghassemabad.
Line 4 (Orange): With the approximate length of 15 kilometers, from Shahid Rejaei Township to Khajeh Rabi`.

dewatering in the confined aquifer also has an active effect to reduce the heave. In addition, The Large Pipe-Shed (LPS) ground stabilization was utilized to perform ground stabilization prior to the new tunnel excavation [5]. Huange and et al., 2013 developed a finite-element parametric study of tunnel behavior caused by nearby deep excavation which demonstrates the influence of the excavation on the underlying tunnel is significant in a range of ~5× excavation width measured along the tunnel axis; unloading further than 10 m away from the axis of the tunnel has little effect on the tunnel structure [6]. Chen and et al., (2015) presented Divided Alternate Excavation Method (DAEM) to control the existing tunnel deformation induced by an adjacent excavation [7]. The proposed construction method is applied in the case of tunnel excavation running metro tunnels has advantages in controlling deformation of the underlying metro tunnels.

Through a 3D modeling, Sadeghiani and Towhidi (2000) considered the surface settlement parameters such as construction sequence, the span and the not-covered, axial stiffness and the linings' bending, materials, the distance between the two tunnels, excavation method and the angle of intersection between the two tunnels [8]. They found that if for any reason the deeper tunnel was excavated first, in practice, there won't be much concern regarding excavation of the shallow tunnel in connection with the settlement. According to their conducted modeling, the excavation of the lower tunnel will cause a 150% increase in the settlement value rather than subsidence in the upper tunnel and a 6% growth in settlement relative to the settlement created in the lower tunnel.

In general, to assess the interaction of adjacent underground structures, there are four methods including; physical model experiments, field observations, experimental analysis methods, and, numerical modeling, and this article intends to study those have been conducted in this regard.

While Kim (1996) has used the physical model experiment to investigate the interaction between construction of parallel and orthogonal tunnels and recommends that in case the boundary conditions are distant by 9D from the center of the tunnel, it can be ignored the effect of boundary conditions on tunnel excavation 9D represents the tunnel' diameter) [9], Ghaboussi and colleagues (1972) recommended in case two tunnels are distant from each other by 2D (distance from a tunnel's center to the center of the other tunnel) we can disregard the effect of interaction between them [10]. Kim also states the interaction between two tunnels is highly dependent on the distance between them. Also, in addition, the construction sequence affects construction of the tunnels as if the shallow tunnel is excavated first, its interaction impact is less than when the deep tunnel would have been excavated first [8].

In the analysis of a case study in China, Peng and Yin (2009) showed building the new tunnel at the non-planar junction with the existing lines, is presently unsafe. Therefore, they suggest the support system should become more resistant, and early grouting at all junctions and speedy execution of initial lining to ensure durability of the structures are needed [11].

Liu and et al., (2009) by using limited element three-dimensional modeling and by considering elastoplastic behavior of the materials, showed that in a region such as Sydney where horizontal stresses are relatively high, excavation of a new tunnel leads to creation of tension in the existing tunnel's lining (on the side near the excavation work front) and forming pressure in the crown and floor of the tunnel. Also, additional tensile stress is produced in the rock bolts on the side close to the excavation work front; however, in sections of the shallower tunnel which is sufficiently distant from the junction, excavation of the new tunnel beneath the existing tunnel would not have much impact on forces created in the lining of the existing tunnel [12].

With the usage of ABAQUS, three-dimensional modeling and limited element at an intersection, Husseini and colleagues (2011) stated the amount of pressure around the above tunnel shows that the pressure applied on excavation of the lower tunnel does not have much impact in increasing the pressure around the upper tunnel (Based on schedule upper line would reach the junction sooner) [13].

2. Methodology

In this research, Line 2 of the Mashhad subway system was analyzed in order of anticipating surface settlements, interactions and tensile changes in the structural components at the junction area resulting from excavation of Line 2 under the Line 1 (the existing subway). To investigate this mechanism and compare the impact of each effective factors on settlement and stress parameters, the three-dimensional finite element analysis in the software Abaqus 6- 10.1 was applied. At first, a review pertaining to geological and geotechnical situation of the region was conducted and the factors such as soil's characteristics, the distance between the station and the lower tunnel, and the traffic load were examined. Then the subway line's specifications will be introduced and the research subject, research tools and model components are described completely.

The research's goal is to examine the interaction of excavating tunnel over the existing station. For the purpose of creating the initial conditions of the earth prior to the movement of TBM through the tunnel, the executing stages of the existing station were modeled in accordance with reality as much as possible. The behavioral model used for the soil in this study was Mohr-Coulomb model, and the linear elastic behavioral model was applied to the lining's elements, the model's structural components and solid elements. Under the load soil and rock behave in inelastic fashion, and this behavior can suitably be modeled using Mohr-Coulomb behavioral model. This model is non-linear, strong and simple, and can be considered for the initial estimate of the soil or rock behavior. The behavior of this elastic model acts completely plastic, and its five basic input parameters include Young (E) modulus, dilation angle, friction angle, cohesion, and Poisson's ratio.

3. Numerical and Geometrical Model

A three-dimensional view of the model illustrating the effects of tunnel excavation Line 2 over Line 1 (the existing station) is shown in Figure 2. Figure 3 also presents details of modeling for the station, the raft-pile geometrical features and the position of the lower tunnel relative to the station. The station is located at the 0.5 meters depth and the tunnel is in 13.3 meters depth. The length, width, and thickness of the raft are respectively 35.2, 23.7, and 1.6 meters.

The station was executed in Dig n Cap method, and by using cut and cover trench style under the final roof. At first soldier piles are used, then the arched beams are executed, and eventually under the roof is excavated. This station comprises three sections that are separated by expansion joints and the raft-pile system has been used in central area of the station which is a different execution method. After execution of piles up to the station's floor level, excavation is carried out up to this level, then the rafts are executed, and finally the beams and roof are performed. The length of the station is 120 meters, its width at the central area is 35.2 meters, and the station floor level is 10 meters lower than the earth surface. The horizontal angle between Line 2 and the station is 75 degrees and the vertical distance between them is 3.3 meters.

The tunnel for Line 2 will be performed by EPB machine. Excavation and installation of the tunnel's support system have been modeled stage by stage including; first, the tunnel is excavated in a gradual manner by implementing the shield conditions up to 10 meters (shield area), then by entering to the 11 meter area, the shield's shell elements are removed and shell elements of the concrete lining and contact injection grouting which is done from back of concrete lining are applied to the model, and this process continues till end of the tunnel. The shield is modeled in the form of steel columns. The excavation diameter is 9.4 meters and the lining thickness is 0.35 meter.

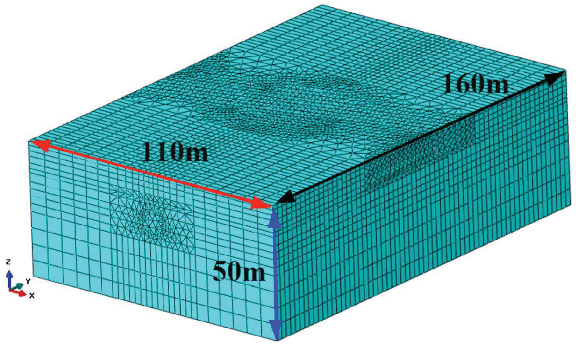


Fig. 2. Three-dimensional model

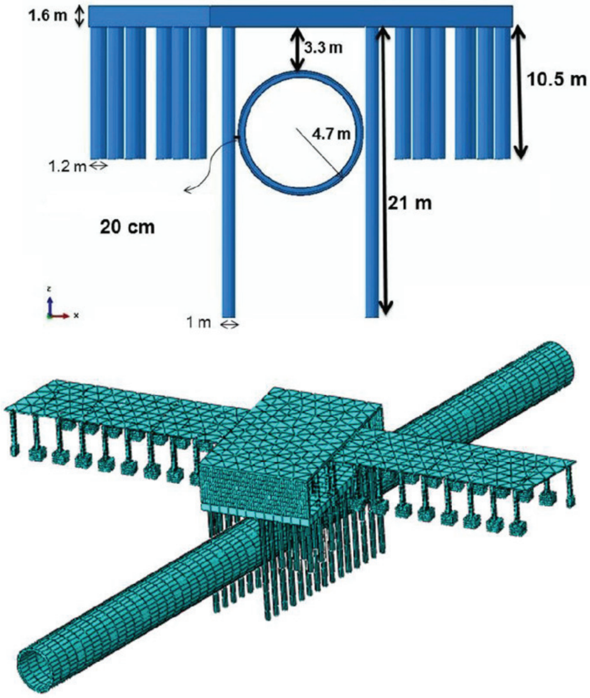


Fig. 3. Modeling the station and position of the lower tunnel relative to the station (Distance between pile and tunnel wall = 20 cm)

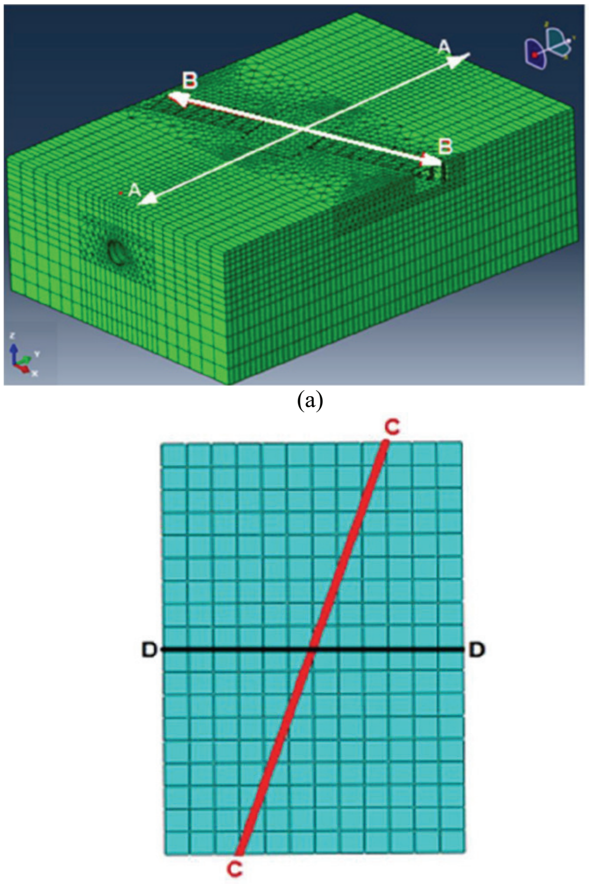
4. Geological Specifications

The soil profile located at the intersection region comprises of both coarse grained and fine grained soil. It starts with grained soil from the ground surface and continues to alternate form of coarse grained and fine-grained layers until reaching the depth of 20 meters and the further depth makes from fine grained soil. Geotechnical specifications of the soil's layers at the junction of Line 1 and 2 are according to Table 1. In the model, the ground has been modeled in the form of different layers as it is depicted in the table. It should be noted that according to the report, water level is 35 meters lower than the ground's surface and due to water level being lower than the depth where the station and lower tunnel are located, it has not been modeled.

Table 1- The geotechnical specifications used in the model

Elasticity Module E (kg/cm^2)	200	600	200	800	200	200
Lateral Coefficient Pressure (K_0)	0.56	0.45	0.56	0.45	0.61	0.61
Angle of Internal Friction Ø' (deg)	20	26	20	31	18	18
Cohesion (C)' (kg/cm2)	0.3	-	0.55	-	0.4	0.4
N_{spt}	25	30	25	35	35	50
W (%)	14	14	14	12	18	18
Soil dry unit weight (kN/m3)	16.5	16.2	16.5	16	17.5	17.5
Depth (m)	0-2	10-Feb	15-Oct	15-20	20-32	32-40
Type of soil	Over burden	SC-SM	CL-ML	SC-SM	CL-ML	CL-ML
Layer number	0	I	II	III	IV	V

In order to analysis the settlement over the existing station during the excavation of the lower tunnel and installing structural components, the monitored paths of settlement were selected according to Figure 4.



(a)

(b)

Fig. 4. Monitored paths for investigating settlement (a) on the raft, (b) on the earth's surface.

5. Research findings

In this section, the results coming from the interactive behavior between the existing subway station with the adjacent tunnel excavating new tunnel which crosses beneath the present station (with a 75-degree angle relative to the existing subway station) is stated in this section. Specifications of the basic model are according to the circumstances depicted in Table 2. Figure 5 shows the vertical shift contours after constructing the new tunnel. In order to better display the impact of interaction, the curves representing the settlement resulting from excavation of the station and the lower tunnel are separately depicted, consequently the impact of the new excavation could be better realized. In Figure 5, the curves pertaining to the ground's settlement in the A-A path and after excavation of the lower tunnel are shown. As it can be seen from the diagram, in the A-A pass the maximum surface settlement resulting from station excavation by itself is 33 millimeters. Also, maximum surface settlement due to the excavation of lower tunnel construction is equal to 39.5 millimeters which demonstrates an increase in settlement by 6.5 millimeters and it equals to 20% of settlement prior to lower tunnel excavation. The maximum settlement because of both the excavation existing station itself before the excavation of lower tunnel and considering the impact of excavating lower tunnel after its construction locates on the center of model station.

Table 2- specifications used in the model

Work front pressure	100kP
Soil Materials	according to Table 1
Traffic Load	20kPa
Lining thickness lower tunnel	0.35
Distance from the tunnel floor to its crown	0.35D
Parameters	Values

In Figure 6 the station's boundary in the A-A path is shown by a Left-Right Arrow. When the lower tunnel has not yet been excavated, while the least deformation about 4.5 millimeters occurs on the margins of the station's boundary, the most change (almost 33 millimeters) occurs in the central section of the station as a result of constructing the station. The most changes in structures occur at the middle of station, and that is the main reason why the most deflection occurs at that area.

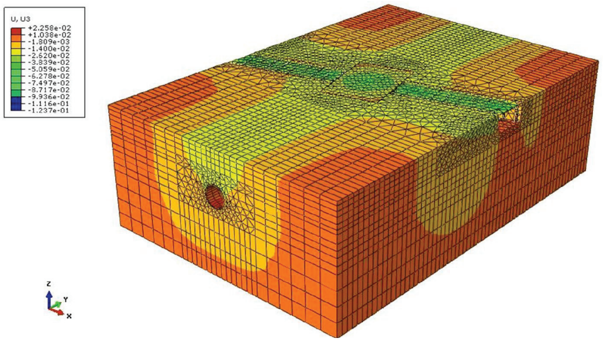


Fig. 5. Vertical shift contour after excavation of the lower tunnel

Considering Figure 6 it can be found that in the distance of 20 meters from the central axis (the severe changes in terms of the settlement level occurs) and it is due to the border area between the station and the soil. In fact, it initially was assumed that there is no traffic load but after construction of the station, this load is applied on the earth above the junction area and paths entering this area. Applying the traffic load on the area outside the station has led to 14 millimeters settlement while applying the same load on the station has caused lesser settlement and it stems from the existence of the station and the raft-pile system in this location. Also, with regard to the figure depicted above, it becomes clear that construction of the station has led to more deflection in the earth near the station.

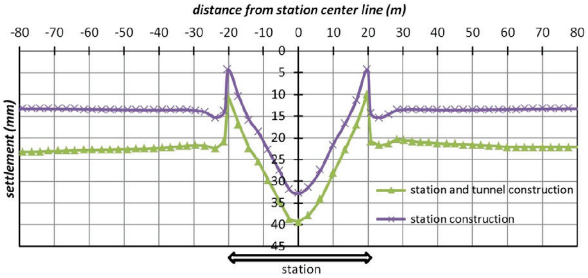


Fig. 6. Settlement of the earth's surface in the A-A path before and after excavation of the lower tunnel

Figure 6 also shows that the most impact of the excavation on the lower tunnel in the span of the station is at the central area, and by distancing from that point, changes within the station area decreases by a small amount. Also, comparing the two settlement diagrams during the construction of station before excavating the lower tunnel and after that, it is found that maximum level of ground's settlement in the area beyond the station was approximately 15 millimeters before the construction of lower tunnel while it increases to 22.7 millimeters after that.

The curve representing ground surface settlement in the B-B paths resulting from station excavation itself and excavation of the lower tunnel is displayed in figure 7. The B-B route passes over the station and across the length of the station. Station's structure is comprised of three separate parts in its lengthwise direction and these parts are separated from each other by the expansion joint. The central area of the station is a location where the pile-raft system has been implemented in its floor. This area is marked with a Two-sided Arrow. It is clear from the diagram that the maximum level of surface settlement in the B-B section resulting from excavation of the station is 41 millimeters, and it occurs on the outside of the central area and also the maximum settlement in the central area is 33 millimeters. The main cause of these settlements in the central area is the raft-pile system. According to the figure, settlements at the middle point of the central area is 13 millimeters more than ones at the internal margins. The observations show that settlement in the internal edge of the central area augments suddenly changes from 20 millimeters to 40 millimeters at external edges (it stems from presence of the expansion joint between these areas).

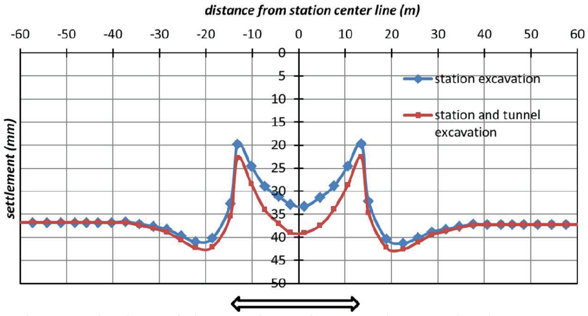


Fig. 7. Display of the earth surface settlement in the B-B path before and after excavation of the lower tunnel.

By comparing the two settlement curves before and after construction of the lower tunnel, it is found that construction of the lower tunnel had the greatest impact on settlement in the station's central area through the B-B route. The highest change at the middle point of the central area is 6.5 millimeters and the figure reduce by distancing from this point until it reaches 3 millimeters at the margins of the station's central area. The excavation of the lower tunnel has albeit affected settlements in the B-B path over 30 meters offset from the axis, while the tiny changes in settlement was recorded beyond the station's central area and its maximum was about 2 millimeters. Because the displacements on the raft is so crucial and it can affect rail equipment, vertical shifts on the raft in the C-C and D-D paths are displayed. The C-C path reflects boring tunnel by machine (TBM) which passes from beneath the station, and the D-D route belongs to the axis of existing urban train crossing in Line 1. Figure 8 shows the raft's vertical shift contour.

Figure 9 shows the vertical shift over the raft's surface in the C-C path before and after the excavation of the lower tunnel (Positive shift represents settlement). The records display that the maximum shift in the C-C reaches to 39 millimeters locating at 9 meters from the raft's central axis. The maximum differential settlement on the raft throughout the path counts 20 millimeters before the lower tunnel excavation.

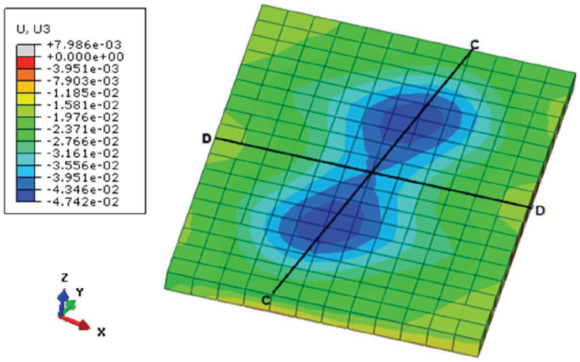


Fig. 8. To display vertical shift contour over the raft after the lower tunnel excavation

Also, in Figure 9 it is observed that maximum shift in this path after excavation of the lower tunnel is 47.5 millimeters which occurs at the distance of 9 meters from the raft's central axis in this path. This value is 8.7 millimeters more than the displacement which occurred prior to excavation of the lower tunnel and shows 22 percent increase relative to the amount of settlement before excavation of the lower tunnel. It is also observed that the raft's shift in the C-C path after excavation of the lower tunnel compared with the position before its excavation has a difference of 7 millimeters at the beginning and at the end of the path. This amount of change reaches the maximum difference of 8.7 millimeters when it nears the raft's central axis at 9 meters from the said axis and remains almost constant at the distance between the raft's middle axis and 9 meters from the central axis.

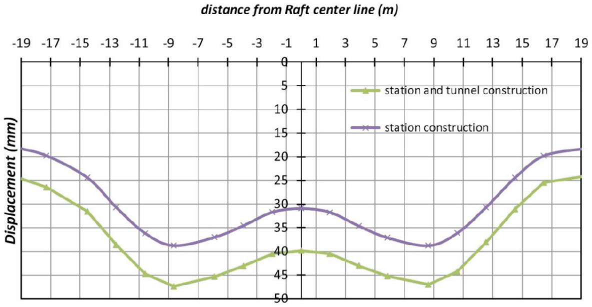


Fig. 9. Vertical shift over the raft in the C-C path before and after excavating lower tunnel

Also, in Figure 9 it is observed that maximum shift in this path after excavation of the lower tunnel is 47.5 millimeters which occurs at the distance of 9 meters from the raft's central axis in this path. This value is 8.7 millimeters more than the displacement which occurred prior to excavation of the lower tunnel and shows 22 percent increase relative to the amount of settlement before excavation of the lower tunnel. It is also observed that the raft's shift in the C-C path after excavation of the lower tunnel compared with the position before its excavation has a difference of 7 millimeters at the beginning and at the end of the path. This amount of change reaches the maximum difference of 8.7 millimeters when it nears the raft's central axis at 9 meters from the said axis and remains almost constant at the distance between the raft's middle axis and 9 meters from the central axis.

In Figure 10, the raft's surface vertical shift in the D-D path before and after excavation is displayed. It can be observed that maximum shift in this path is 31 millimeters which occurs in the raft's middle axis. Maximum amount of difference of settlement on the raft in this path is 16 millimeters. In this Figure it is observed that maximum shift in this path after excavation of the lower tunnel is 39.7 millimeters which occurs in the middle axis of the raft. The amount of increase in vertical shift is 8.7 millimeters which is equal to 28 percent of the shift prior to excavation of the lower tunnel. It is also observed that the displacement of the raft in the D-D path after excavation of the lower tunnel relative to the position before excavation differed 2.5 millimeters on the margins. This amount of change increases when it gets close to the raft's middle axis, and on the axis, it reaches the maximum difference of 8.7 millimeters.

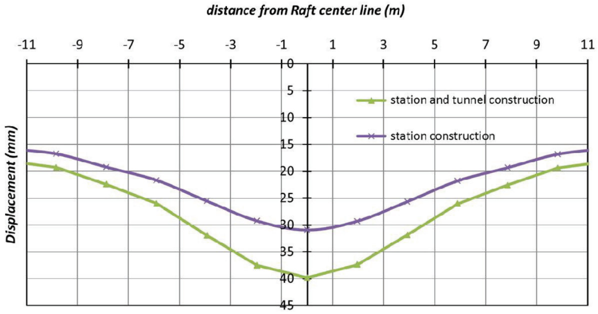


Fig. 10. Raft's vertical shift in the D-D path before and after excavation of the lower tunnel

In addition to settlements and displacements, the normal stress in the direction of Z axis on the raft, at the junction of the two C-C and D-D paths during excavation for the monitoring device is shown in Figure 11. According to this Figure, it is observed that by placing the raft and placing the load on it, the stress increases and becomes constant when it reaches 90 kilopascals (kPa). It is also observed that in stage 42 of the analysis when the excavation front reaches the raft, the stress in the raft increases. These changes in stress are increased when excavation front nears the monitoring point, and maximum change at this point is 37 kilopascals. This amount of change in the stress as compared to the situation before excavation of the lower tunnel is equal to an increase of 41 percent. When the excavation front passes beyond the monitoring point, the stresses are moderated and eventually reach a constant mode. Studies by Liu and colleagues (2009) [12], Asgarpanah (2011) [14], and Towhidi (2010) [15] confirm this trend of changes for the forces and for the lining anchors.

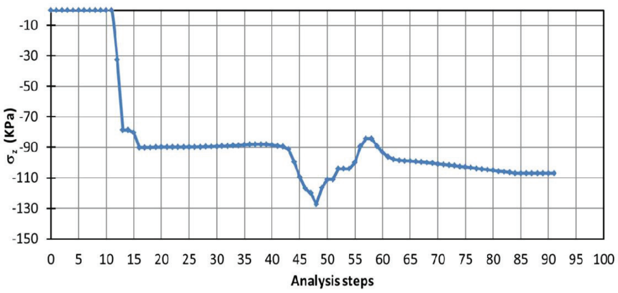


Fig. 11. Changes in stress in the raft during the stages of construction of the station and construction of the lower tunnel

6. Conclusion

In the basic model maximum surface settlement resulting from construction of the station was by itself 33 millimeters. Also, maximum surface settlement created after excavation of the lower tunnel is 39.5 millimeters (located on center line of A-A path) which has a 20 percent increase as compared with initial settlement. However, the most commutative surface settlement (43 millimeters) occurs on 20 meters from center line of B-B path. In terms of raft settlement, the most is 47.5 millimeters locating on 9 meters from centerline of C-C path and the most change in raft settlement because of lower tunnel excavation, equals 9 millimeters over C-C path from centerline to +/- 9 m identically and center line of D-D path.

Changes in the stress in direction of Z were monitored in the raft during various stages of excavation. According to the obtained results, the stress values at the monitoring points increased when the lower tunnel passes through these points, and these values when the tunnel passes from underneath the station are more than the final value after the tunnel had passed from the monitoring points. It can be observed that the most changes in the stress and curving occur during excavation of the lower tunnel. This issue demonstrates that in similar projects, special arrangements are needed when excavating intersecting tunnels.

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