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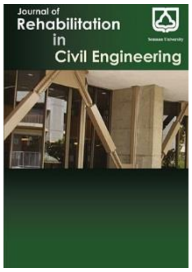

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Cross Section Effects on Convergence-Confinement Method in Multi Stage Tunnel Excavation

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ABSTRACT

Dimensionless coefficient (λ) in convergence confinement method indicates the relaxation of stress in the wall of the tunnel at different excavation movements. This factor is contemplated a constant number in previous studies and tunnel geometric characteristics (such as depth, cross-section shape, radius, soil material, etc.) are not included in its determination; however, ignoring these effects can cause significant errors in the analysis of tunnels. In this article, the effect of excavation pattern and tunnel cross section shape on stress reduction factor is investigated. For this purpose, at first, by considering the conventional cross sections of the tunnel (circular, horseshoe, and double arch), applying finite difference numerical simulation software FLAC 2D and FLAC 3D, the type of excavation (full face and multi face) was inspected in estimating the stress reduction factor by considering depth, radius, and dissimilar points around the tunnel. At last, studies were carried out between the 2D and 3D analyses and the experiments conducted at Karaj Subway to verify the results obtained from the above 2D analyses. The results of this study indicate the significant effect of radius, depth, point position around tunnel cross-section and its shape on stress reduction factor. Convergence around tunnel variation was observed about 21 percent in horseshoe tunnel. However, the maximum and minimum convergence value was in circle and double arch respectively in a constant radius and depth. The results illustrate the variety percentage error in tunnel wall about 27, 10 and 7 percent for circle, double arch and horseshoe respectively. Nonetheless, percentage error was decreased by increasing the tunnel radius. Applying variable stress reduction factor in the all-around of tunnel cross section can lead to more realistic simulations of complex behavior of tunnels during the excavation. Moreover, this method can be utilized for the analysis and design of tunnel due to its time saving nature and at the same time sufficient accuracy.

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1. Introduction

Underground structures in urban areas have been built to reduce traffic volumes. Any underground structure requires a supporting system that can resist the stresses and displacements resulting from the tunnel unloading. Determining the forces applied to the lining is vital for the analysis and design of a tunnel. However, prediction of stress distribution in soil and rock tunnels, especially those constructed in urban areas, is still the main challenge for designer engineers [1]. Tunnels in urban areas are usually constructed in shallow depth and soil ground layers; this causes anisotropic conditions of stress and deformation around the tunnel which makes it difficult to analyze. These deformations can lead to instabilities of surface or subsurface structures adjacent to the tunnel. This is because the characteristics of the ground on which the tunnel has been built can vary greatly as a result to the uncertainty of the depth of alluvium, complex ground layers, strength parameters, deformability, and presence of subsurface and surface structures or water [2]. Various parameters on the deformation and stress distribution are affected in areas where underground excavation has occurred. Many studies have been investigated the deformation occurred around the tunnel and ground surface during the tunnel construction among which those carried out by many researchers can be mentioned [3-8].

Various methods have been applied for the analysis and design of tunnels, among which experimental, analytical, and 2D and 3D numerical methods can be noted [9]. Experimental and analytical methods are only used for the isotropic and homogeneous conditions of circular tunnels [10-12]. Due to the complexities involved in tunnel excavation, anisotropy of stress, existence of layered soil and non-circular cross-sections, experimental and analytical procedures are not well able to express all aspects of tunnel behavior [13-16].Despite to that, numerical methods can model various conditions of excavation and installation of tunnel lining, as well as simulate ground-tunnel-lining interaction [17-20]. Even though 3D models are able to realistically simulate the behavior of excavated areas around the tunnel, they require more time to simulate tunnels and the model definition is hard to be done. In addition, 3D models cannot be easily applied. Thus 2D methods are can be implemented to governing the problem [3,16,21]. There are numerous methods for the two-dimensional simulation of tunneling such as the gap method [21,22], convergence-confinement method [23-28], volume loss control method [29], gradual softening method [30,31], and disk method [32].

As mentioned by Mousivand et al. (2016) the gap method cannot applied for multi stage excavation method. Volume loss control was also applicable to simulate back analysis of tunnel by an appropriate given volume loss. The gradual softening was only utilized by the reduction in elastic modulus of soil inside the tunnel. This cannot taken into account of other soil parameters in tunnel excavation [33]. The convergence-confinement method (CCM) could well gain forces applied to the lining of the tunnel. Modeling the effects of the third dimension of the tunnel can be done by considering the convergence effects of the tunnel prior to installing the lining and considering the time delay before the tunnel lining. Furthermore, CCM can properly simulate interaction between lining and ground around the tunnel [24-27]. The third dimension of the tunnel in the procedure can be simulated by the stress relaxation, λ, occurred around the tunnel during excavation. This factor depends on various parameters, including ground material, depth, shape of cross section, and excavation pattern. In previous research, this factor is contemplated as a constant value in all points around the tunnel and the effects of the mentioned variables are not included [23 and 24], However, this value has a direct effect on stresses and deformations around the tunnel. In addition, excavation type is considered full face (FF) to compute the stress reduction factor, λ; the issue in multi face (MF) tunnels may cause excessive errors.

This study aims to investigate the influencing factors on the parameter λ around the cross-section of a tunnel in soft ground applying a parametric study in order to ameliorate the accuracy of the convergence-confinement method in shallow tunnels. Radiuses of 2, 3 and 4 meters and depths of 10, 20, 30 and 40 meters were considered. For each tunnel, three conventional cross-sections in the tunneling (circular, horseshoe, and double arch tunnels) were evaluated. Finally, the 2D and 3D analysis were compared against experimental results of the Karaj Subway Tunnel Line 2.

2. Calibration of Model Parameters

2.1. Geological Properties and Excavation Method of Karaj Subway Tunnel Line 2

Karaj City which is capital of Alborz province of Iran, hosting a population about 1.97 million people is one of the country's forth metropolitan cities of Iran.

Considering the urban fabric of the city and having multiple industrial and satellite towns with about 1.6 million daily trips, the city still deals with the problem of transport which can only be solved through the use of strategies based on scientific principles and rail transportation. For this purpose, Tehran Subway was constructed and extended to Karaj and suburbs. In consonance to the latest reports, five subway lines are intended for the city of Karaj among which line 2 is currently excavated with a length of about 27 km in two phases. This line has constructed between Kamal Shahr city and Shahid Beheshti Street. The first phase of this line with the length about 14.5 km is under construction from the western part of the capital to the Karaj station. Fig. 1 shows a plan and cross-section used in Karaj Subway Tunnel Line 2 [34].

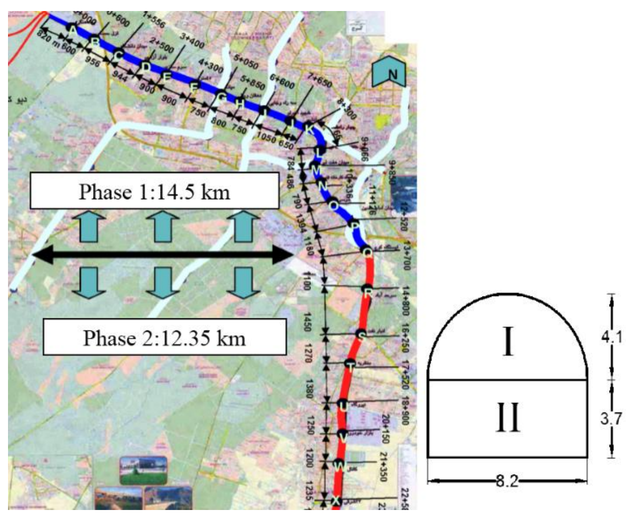

Fig. 1. The plan and cross section of Karaj Subway Line 2 [34].

According to the results of the studies and experiments accomplished on existing boreholes in the project, tunnel excavation was traditionally performed based on the NATM. The tunnel excavation method was carried out in two stages of top heading and bench. In the upper part of the tunnel excavation, pneumatic and hydraulic hammers were applied in more difficult ground conditions. Immediately after the excavation and preparation, lattice frames with metal mesh were installed. After final configuration and placement of the second layer of mesh, shotcrete spraying was achieved. In the lower part of the excavation, the excavation starts by creating a central box. After creating sufficient working space, excavation of the side part was done. Finally, lattice was installed and the operation of shotcrete was performed [34].

2.2. Initial model Parameters

In order to apply back analysis, various parameters must be considered, such as soil conditions, excavation steps, time and length (step), shotcrete thickness, and distance between the tunnel face and shotcrete and lining. To this end, the three-dimensional finite difference software FLAC 3D is applied. The burden thickness is 9-12 m in all the examined sections which is composed of only one type of soil. Reports indicated lack of water in different soil layers (to a depth of 60 meters from ground level). So, this analysis has been done in form of dry soil modeling.

As a result to the laboratory test results, constitutive model which can be applied in this section was Mohr-Coulomb available in the FLAC software. In consonance to settlements occurred around tunnel and ground surface this constitutive model can present the acceptable results. This model has an elastic-perfectly plastic material behavior. Moreover, the model requires five parameters for analysis [35]. Ranges of strength parameters of soil layering and lining materials obtained from in situ and laboratory studies are presented in Tables 1 and 2.

Table 1. Initial geotechnical properties of soil [34].

γ	C	φ	E	ν	ψ
(Kg/m^3)	(KPa)	(Deg)	(MPa)		(Deg)
18-19.75	22-33	18-27	20-50	0.3-0.4	0

Table 2. Lining mechanical properties used in the tunnel analysis [34].

Thickness	ν	Compressive strength	E
(m)		(KPa)	(MPa)
0.3	0.2	18	7.4E+03

The behavior of the tunnel lining is also considered as elastic-perfectly plastic.

In order to measure and control the movements and deformations of the ground and surface structures as a result of excavation and construction of Karaj Subway, a wide monitoring system is predicted and implemented with high precision along the tunnel and at sensitive buildings and structures located in the tunnel. The monitoring system was designed and implemented aiming to control safety and predict the possible dangers during different stages of excavation and tunnel construction operations. For this end, on average, every 40 meters of the tunnel is provided by a monitoring station where deformations resulting from excavation, including deformation of the tunnel walls (convergence), ground surface settlement, and sensitive buildings located in the path are measured and immediately processed and analyzed applying special software so if there are any unusual changes, appropriate executive measure can be taken. Instrumentations positions used around the tunnel and ground level are presented in Fig. 2. Settlement gauges are within 7.5 meters of the tunnel in the perpendicular direction.

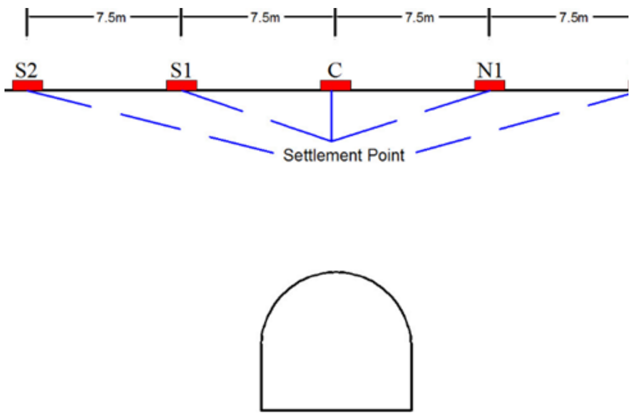

Fig. 2. Instrumentations position in ground surface [34].

An example of the ground surface instrumentation data is depicted in Fig. 3. Figures 3a and 3b are ground surface settlements after excavation of the upper and lower parts of the tunnel, respectively [34].

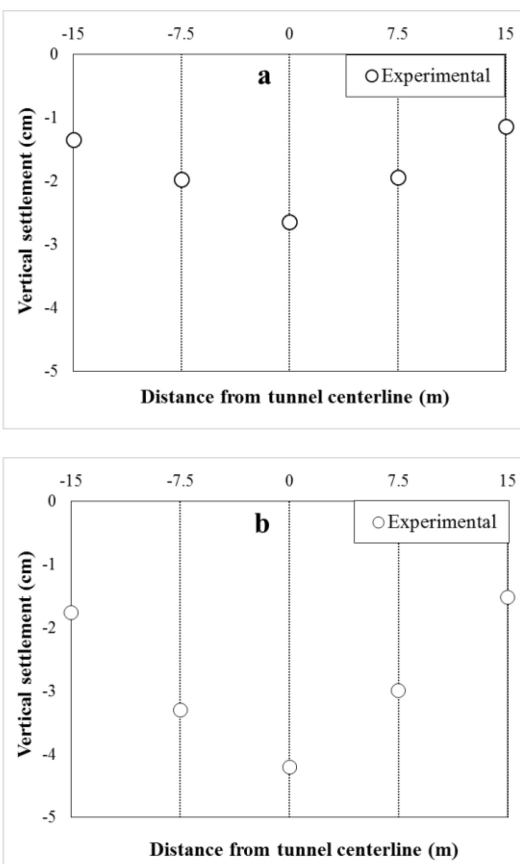

Fig. 3. Ground surface settlements curve of Karaj Subway Line 2; (a) after the excavation of the upper side, (b) after the excavation of the bottom side [34].

2.3. Boundary Conditions

In numerical analyses, the way model parameters, including location of boundary condition, type of support, and number and distribution of elements, are selected is directly affected by the accuracy of models. Basically, a grid in certain areas, such as places with stress concentration, weak areas, and target locations, must be finer than in other areas. During tunnel excavation, redistribution in stress is high, thus a finer mesh must be applied near the tunnel face to the extent possible. With increasing distance from the tunnel, it is possible to reduce the density of mesh. In this study, a grid similar to the one in Fig. 4 is used to analyze the tunnel. Model dimensions are obtained by conducting a series of experimental analyses (Fig. 4).

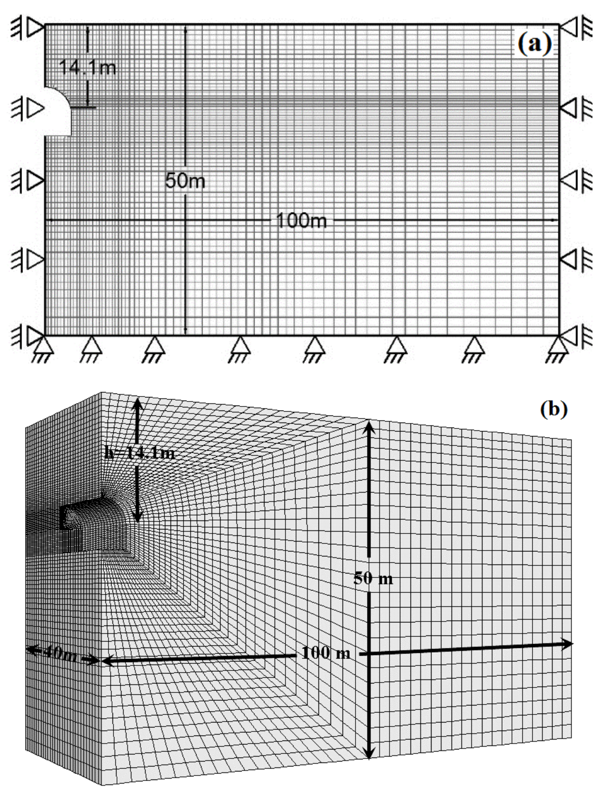

Fig. 4. Location, 2D, and 3D meshing and lateral boundaries of the Karaj subway line 2 (Measurements is in meters)

Vertical boundaries should be so far away from the center of the tunnel so that horizontal displacement of the ground under the influence of stress changes is equal to zero. Such boundaries are modeled as rollers as a result to vertical displacements. Horizontal boundaries should be considered sufficiently below the tunnel where the impact of excavation on the boundaries can be neglected. In this case, by assuming the bedrock, the amount of displacement in the horizontal boundaries can be considered as equal to zero and fixed in x and y direction.

3. Results and Discussion

3.1. Parameters Calibration by Back Analysis

For back analysis, a try and error process is applied and the sample algorithm is presented in Fig. 5. In this method, after the selection of the constitutive model, the initial model parameters are estimated. To avoid excessive repetition, the initial parameters acquired from laboratory tests have been used in the paper (Table 1). Then, utilizing numerical modeling, three-dimensional tunnel conditions are simulated.

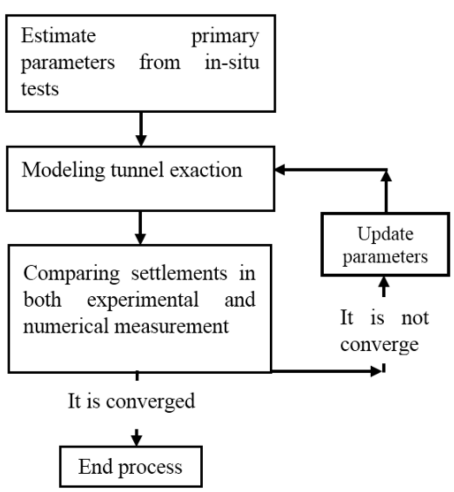

Fig. 5. Different parts of one stage in the back analysis used in this study

The acquired surface settlement by the software is compared with the instrumentations value. If the results are similar, the selected parameters are acceptable; otherwise, the cycle is repeated by changing the parameters.

The Karaj Subway back analysis was applied to the upper part of the tunnel to determine the exact soil parameters. After performing a series of numerical analyses by the finite difference software, FLAC 3D, and matching their results with the results of the instrument, the exact soil parameters were determined and the results are presented in Table 3.

Comparison of the values obtained from back analysis and the results of instrumentation is presented in Fig. 6. As can be observed , the simulated values are very close to their real values which indicate high precision of back analysis.

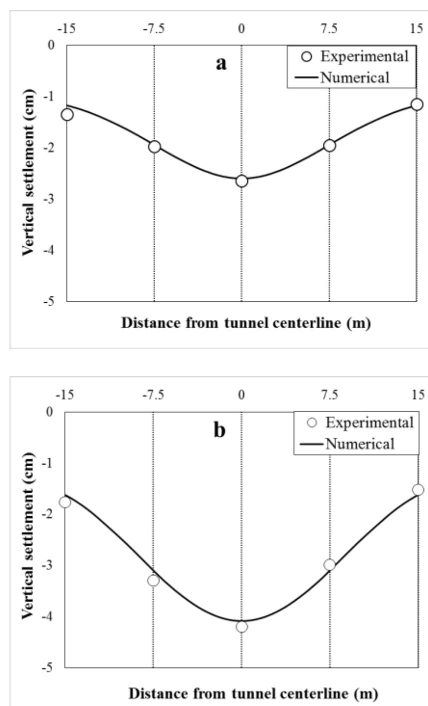

Fig. 6. Calibration parameters of MC constitutive model; (a) uper side, (b) bottom side

Table 3. The obtained soil geotechnical parameters from the back analysis

γ (kN/m^3)	C (kPa)	φ (Deg.)	E (MPa)	ν
18.6	22	20	30	0.3

3.2. Excavation Pattern Effects on the Convergence-Confinement method

In this study, three different cross sections (circular, horseshoe and double arch) were utilized to measure the effects of the excavation pattern in various tunnel cross-sections on the stress relaxation using the convergence-confinement method. The sections were selected in such a way that the upper parts of the three tunnels were similar (Fig. 7). The bottom part consisted of the circle of radius in the double arch tunnel, a rectangle with dimensions in the horseshoe tunnel, and a half circle with the radius in the circle tunnel. For this purpose, various cross sections at four different depths (10, 20, 30 and 40 meters) and with three different radii (2, 3, and 4 meters) at different points around the tunnel are studied.

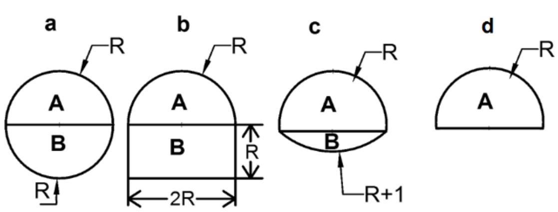

Fig. 7. Differenet tunnel cross sections used in the tunnel analysis

Two different excavation methods were contemplated in order to measure the effect of excavation pattern on the ground characteristic curve (GRC).

A. Full face excavation method: In this case, different cross sections (circular, horseshoe, and double arch) are excavated all at once.

B. Top heading and bench method: In this case, tunneling is occurred in two stages of upper and lower sections

3.2.1. Ground Reaction Curve (GRC)

Ground reaction curve presents the convergence taking place around the tunnel, in the absence of lining, at different pressures. In order to compute exact curves, modeling of the tunnel was performed using the finite difference code, FLAC. A ground characteristic curve is depicted for all the points around the tunnel with the gradual reduction of confining pressure (the resultant of shear and radial stresses) and total displacement occurred around the tunnel (the resultant of radial and tangential deformations).

A. Point position effect

In order to examine the effects of point position on the ground characteristic curve, depth, radius, and cross section type are assumed constant. Three different locations around the tunnel (crown, wall, and floor) are studied in this section. Fig. 8 presents the tunnel convergence in the horseshoe cross section with radius and depth of 4 and 20 meter, respectively. The horizontal axis of charts is the tunnel convergence and the vertical axis is the ratio of current stress (P) to in-situ confining stress (P0). Convergence taking place around the tunnel is different at three points around the tunnel. Accordingly, convergence has the lowest value in the tunnel wall and the greatest value in the tunnel floor. This demonstrates the differences in behavior of the three tunnel positions in the face of tunnel unloading which is as a results to changes in the stress relaxation at different points around the tunnel according to the current stresses and changes in the time tunneling.

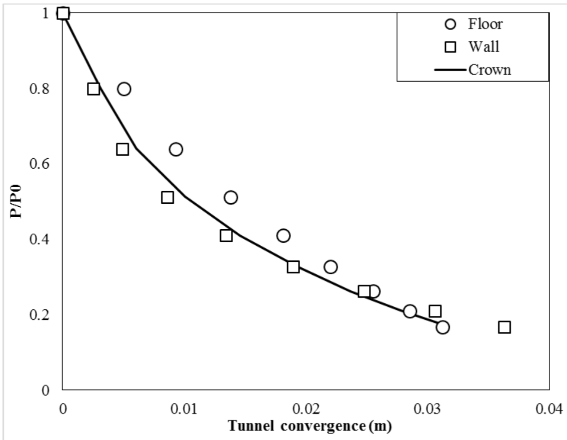

Fig. 8. Point position effect on ground reaction curve of the horseshoe tunnel (radius=4m and depth=20m)

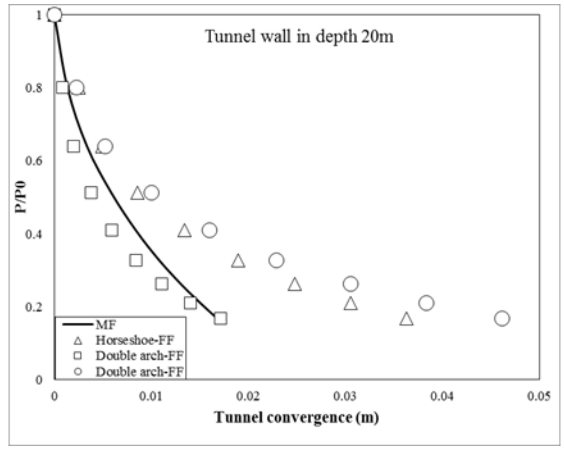

Fig. 9. Cross section effects on ground reaction curve at the tunnel wall (radius=4m and depth=20m)

B. Cross section effect

The tunnel cross section had significant effects on the ground reaction curve. Such finding was acquired by carrying out a series of analyses on three different cross sections, including circle, horseshoe, and double arch tunnel. The analysis results of the three cross sections with a radius of 4 meters and a depth of 20 meters at the tunnel wall are indicated in Fig. 9. To comparing full face and multi face effect on tunnel convergence, the convergence of upper half of tunnel was studied (MF). Contemplating the same point position around the tunnel, the convergence taking place around the tunnel is different in various cross section types. Accordingly, the convergence in the double arch tunnel is lowest and in the circular tunnel is greatest. This demonstrates the differences in behavior of the three tunnel cross sections in the face of tunnel unloading. The convergences took place in various locations around the tunnel in the full-face excavation of double arch and multiple face excavation tunnels are almost similar. This demonstrates that the excavation of the lower part of the double-arch tunnel has insignificant effects on stress release around the tunnel cross section.

3.2.2. Stress reduction factor (□)

The stress reduction factor in the convergence-confinement method as shown in Fig. 10 is obtained by the intersection of the three curves, including ground reaction curve (GRC), support characteristic curve (SCC) and longitudinal deformation profile (LDP):

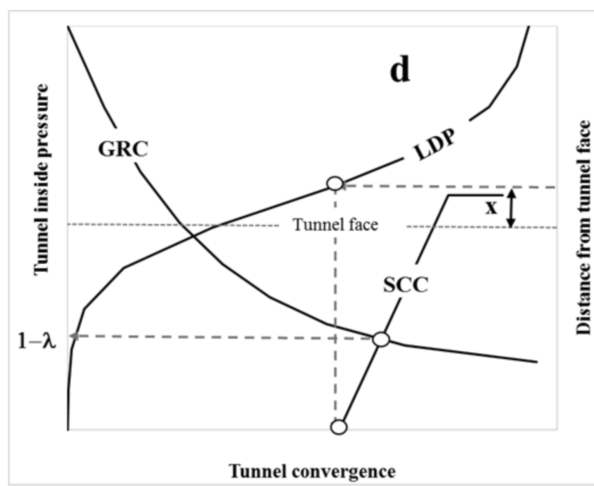

Fig. 10. The method to determine the stress reduction definition using three curves (GRC, SCC and LDP) (based on Mousivand et al., 2017)

In this study, the stress reduction factor, λ, is determined in three surrounding points of the tunnel (crown, floor, and wall) in each tunnel cross section.

A. Effect of the point position around the tunnel

Assuming both the radius and depth of the tunnel, effect of position around the tunnel cross-section was investigated for three different cross sections, the results of which are presented in Fig. 11. In this figure, the vertical axis is equal to the stress reduction percent error of the tunnel in both the full and multiple faces ($\mu = \frac{(\lambda_{FF} - \lambda_{MF})}{\lambda_{MF}} \times 100$) and the horizontal axis is equal to different points around the tunnel. Where $\lambda_{Full\,face}$ and $\lambda_{multiple\,face}$ are stress reduction factors in the case of full face and multiple face excavations, respectively. As seen in Fig. 11, μ in all the three cross-sections have different values in different parts of the tunnel. The differences between the various cross sections have little value on the tunnel floor and reach maximum in the tunnel wall. The reason for this variation is differences in the lower part of various cross sections. As can be seen in Fig. 11, a square shape (horseshoe) has relatively low effects on changes of μ; however, the semi-circular shape (the circular cross section) has maximum impact on the changes, especially in the tunnel wall.

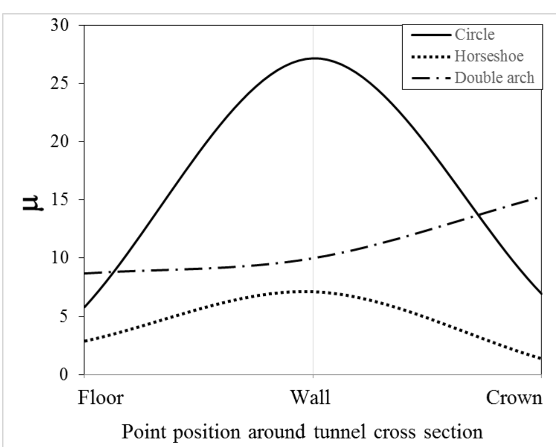

Fig. 11. Point position effects on μ (percent error of full face to multiple face stress reduction factor) (radius=4m, depth=10m)

B. Effects of tunnel radius

In order to measure the effects of the tunnel radius on the stress reduction factor in two cases, full face and multiple face, researches were done on the tunnel walls by assuming a constant depth, h=20m, the results of which are presented in Fig. 12. In this figure, horizontal axis shows tunnel radius and vertical axis indicates μ. Tunnel radius has a significant effect on μ at various cross sections; however, by increasing the radius of the tunnel, its effects on the error disappears. This means that for a tunnel with a radius greater than 3 meter, μ is independent of the cross-section of the tunnel.

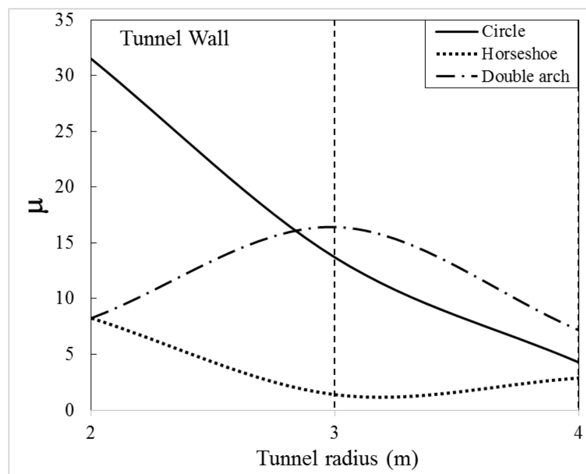

Fig. 12. Tunnel radius effects on μ (tunnel wall, depth=20m)

C. Effects of tunnel depth

To measure the effect of the tunnel depth on the stress reduction factor in various excavation patterns, full face and multiple face, studies were performed on the tunnel wall where the tunnel radius was considered constant and the results are depicted in Fig. 13. The tunnel radius and depth have significant effects on the parameter μ in various cross sections. Increasing the tunnel depth leads to different behaviors in various cross sections. In the horseshoe and circular cross sections, with increasing the depth from

10 to 25 meters, the amount of error increases; but in depths greater than 25 meters, the error rate is drastically reduced. However, the behaviors in the horseshoe cross-section are different from those in the two other cross sections.

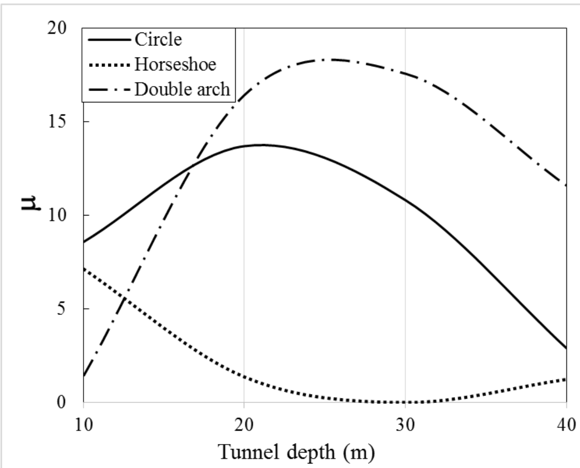

Fig. 13. Effects of tunnel depth on μ at the tunnel wall (radius =3m)

3.3. Validation of 2D Analysis Using Experimental Results

Due to the fact that the tunnel is excavated applying the multi face excavation type, stress reduction factor is required to be separately calculated at each stage. According to the performed analyses, it was observed that the multi face excavation had insignificant effects on the stress reduction factor [36]. The end of the tunnel construction is considered to validate the mentioned method.

For this purpose, the same stress reduction factor is used in each excavation step.

Two types of stress reduction factor are utilized in this paper as illustrated in Fig. 14. Where λ_{uni} means that the stress relaxation obtained from the average of stress reduction factors all around the tunnel cross section is equal at all the points around the tunnel and λ_{var} means that stress relaxation has various values at all the points around the tunnel.

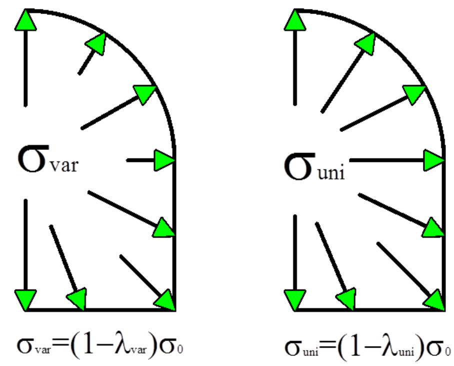

Fig. 14. Variable and uniform stress reduction factors used in validation

3.3.1. Ground surface settlement

The 2D modeling of Karaj Subway is done with unified and variable stress reduction factors. The ground surface movement for 2D, 3D and experimental results are presented in Fig. 15.

As can be seen in the Fig. 15, deformations of the 2D analysis are very similar to those of the experimental and 3D analyses.

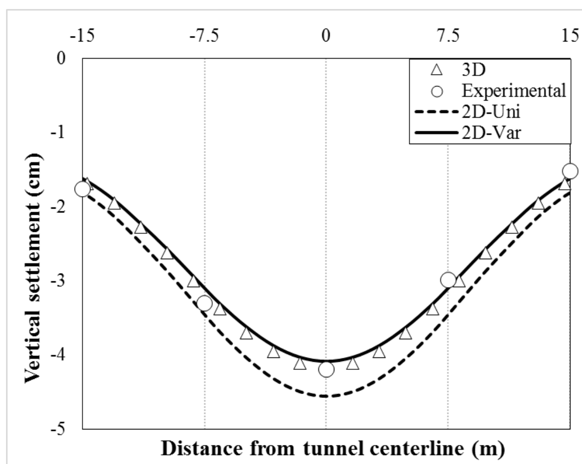

Fig. 15. Vertical movement of ground surface at the end of the tunnel excavation

The 2D analysis with the unified stress reduction factor caused greater displacement than the one occurred in reality. This may lead to overdesign of the tunnel lining.

However, applying variable and precise stress reduction factors causes more real simulation of the excavation process, and thus, more accurate result is obtained. This indicates that the use of variable stress reduction factor is essential around the tunnel.

3.3.2. Horizontal displacement

The results of horizontal displacements of the ground at a distance of 6 meters from the tunnel centerline are presented in Fig. 16.

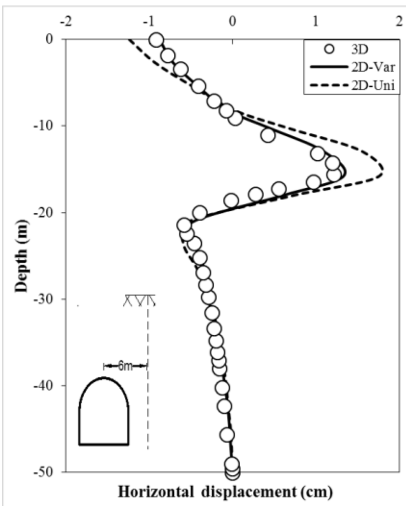

Fig. 16. Horizontal displacement ground in 6meter distance from center line

Due to the lack of experimental results of horizontal displacements, only 2D and 3D analyses are compared. Displacement in this figure is vertical cross section. The uniform stress reduction factor in the 2D analysis leads to greater displacement compared to the 3D analysis which causes large errors to occur in the analysis and design of the tunnel. However, the 2D simulation of the tunnel considering the variable stress reduction factor shows best fitting results to the 3D analysis and can be used as a good alternative to analyze the 3D tunnel.

4. Conclusions

In this paper, the effect of tunnel excavation patterns, full face and multi face, with different cross sections (circular, horseshoe, and double arch) was investigated on the stress reduction factor (the convergence-confinement method). At first, to determine the exact parameters of soil, the Karaj Subway Line 2 back analysis was used by the software FLAC 3D. The effects of depth, radius, and cross section of the tunnel on the stress reduction factor, applying the parameters obtained from the back analysis, were studied by a numerical modeling. Then the modified 2D method validation was discussed in predicting the behavior of the tunnel. The obtained results are presented as follows:

1- The parameters set, acquired by the back-analysis method in this paper, are very similar to the values obtained from the instrumentation. This reflects the precision of the method in determining soil physical properties.

2. The point position on the cross-section and its shape has diverse effects on the tunnel convergence curve.

3. The convergence took place at the points around the tunnel has dissimilar values; this issue was seen in various depths, shapes, and types of excavation.

4. The percentage error of the stress reduction factor in the excavation model, μ, differs in different tunnel cross-sections at any point of the tunnel. This issue has the lowest value at the tunnel floor, yet reaches its maximum at the tunnel wall.

5. The radius of the tunnel greatly affects μ. Moreover, most changes occur in the radius

of 2 meters. This amount decreases with increasing the radius; and the radius of 4 meters is almost ineffective on μ.

6. The radius of the tunnel has the greatest effect on the circular cross-section, but shows little impact on the two other cross sections, the horseshoe and double arch.

7. Depth as the radius has influence on μ. By increasing the depth of the tunnel from 10 to 25 m, the μ value also increased. However, with further increase in the depth from 25 to 40 m, the coefficient μ is reduced.

8. The 2D modeling of the tunnel using the uniform and/or variable stress reduction factor leads to the appropriate simulation of the third dimension of the tunnel. Yet, the values of vertical settlements and horizontal displacements took place during the excavation using the uniform stress reduction factor are much more than the real and three-dimensional values and lead to large errors in the analysis and design of the tunnel.

9. The 2D modeling, while consuming less time, can accurately model the tunnel behavior in different parts of the cross-section applying the variable stress reduction factor.

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