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Predicting three-dimensional displacement around the tunnel and its impact on the value of Q-system

Mohammad Hajiazizi [a,*], Mina Hashemi [b]

[a] *Department of Civil Engineering, Razi University, Taq-e Bostan, Kermanshah, Iran*
[b] *Department of Civil Engineering, M.Sc Student, Razi University, Taq-e Bostan, Kermanshah, Iran*

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ABSTRACT

An underground space stability depends on its surrounding stress and strain states. Creating underground tunnels causes significant changes in rock mass stresses. Therefore, to achieve the necessary stability, stresses and deformations around the tunnel must be evaluated carefully. Usually, stress-strain behavior analysis is conducted in two-dimensional (2D) mode. This paper proposed a new attempt to figure out the relationship between 2D and 3D deformation around an underground tunnel. So it consists of a comparison between 2D and 3D deformation modes. Afterwards, its impact on the value of Q-system in seismic mode was studied. 2D analyses are usually conservative. Therefore, the proposed relationship between 2D and 3D mode will reduce costs and economize support materials. The results of different analyses in intact and sparsely jointed rock masses show that the displacement around tunnel is greater in 2D analysis compared to 3D analysis. However, in the heavily jointed rock masses, the displacement around tunnel in 2D analysis is lower than that of 3D analysis. As 3D analysis are closer to reality, results of equations proposed in this paper could be used to calculate 3D displacement. Different analyses were carried out in 2D and 3D states for intact or sparsely jointed rock masses. A new equation proposed to show the relationship between 2D (U_{2D}) and 3D (U_{3D}) displacement according to conclusions. Local measurements (3D) and the results of 2D analysis of heavily jointed rock masses were compared. Then, the relationship between 2D and 3D displacements in heavily jointed rock masses was proposed. The results of this research have been applied on tunnel of Gavoshan Dam in West of Iran. There is good concordance between equations proposed in this paper and 3D analysis.

Keywords : *3D displacement; Q-Value; 2D displacement; heavily jointed rock mass.*

1. Introduction

Nowadays, creating underground spaces in industrial and developing countries is increasing [1]. For decades, tunnel stability has been analyzed using 2D and 3D modes. In some cases, two-dimensional assumption is enough to investigate the stress-strain state around the tunnel. However, in many cases, geometric complexities cannot be modeled by 2D analysis, hence, 3D analysis is necessary. Investigating stress distribution and the displacement around the tunnel in 3D mode provides valuable information on tunnel stability to designers. Due to lack of access to analytical solutions for complex 3D problems, various 2D numerical analyses have been investigated [2].

Using 2D analysis of finite element, Pariseau and Sorensen [3] proposed a method similar to 3D method. Their results suggest that 3D analysis is more efficient than 2D and can reduce designing costs. Dhawan et al. [4] examined 2D and 3D elastic behavior of a hydroelectric tunnel. ÜÇER [5] compared the results of 2D and 3D analysis for jointed rock masses. Ahmadi et al. [6] examined 2D and 3D analysis on a tunnel in heterogeneous rock masses.

In fact, the behavior of stresses and displacements around a tunnel is three-dimensional. Therefore, it is better to use 3D methods in order to analyze the behavior of a tunnel. The main parts necessary to be noticed on 3D analysis of a tunnel include the entrance of the tunnel, the tunnel intersections, and advancing face of the tunnel. Due to limitations in analytical methods in complex geometry and boundary conditions, 3D numerical methods and local measurements can be a good and appropriate solution for stress-strain behavior analysis [2].

In this paper, as a new attempt, the relationship between 2D and 3D displacement revealed and also the relationship between 2D analysis and Q-value presented. Therefore, 3D displacement and its impact on Q-value can be obtained by understanding 2D analysis results. Therefore, 3D displacement and thus the seismic Q-value needed for support design of tunnel can be obtained using 2D analysis and determining its maximum displacement value. The Q-system originally was developed for classification of rock masses and ground as a helpful tool for evaluating the need of support in tunnels and rock caverns [7].

2. Elastic displacement

Elastic displacement in plane strain mode can be obtained based on Brady and Brown [8] equation:

$$u_r = \frac{-P_V R^2(1+\vartheta)}{2Er}\left\{(1+K)-(1-K)\left[4(1-\vartheta)-\frac{R^2}{r^2}\right]cos2\theta\right\} \tag{1}$$

where u_r is the radial displacement, ϑ is Poisson's ratio, E is elastic modulus, P_v is vertical stress, k is the ratio of horizontal in situ stress to the vertical component, r and Θ are the polar coordinates, and R is the radius of the tunnel.

For a circular tunnel in elastic and homogeneous environment, Unlu and Gercek [2] proposed the following equation for displacements calculation around tunnel using FLAC 3D software:

$$\frac{u_r}{u_{r\infty}} = (0.22\vartheta+0.19)+(-0.22\vartheta+0.81)\left\{1-\left[\frac{0.39\vartheta+0.65}{0.39\vartheta+0.65+\frac{x}{R}}\right]^2\right\} \tag{2}$$

Where x is the distance to the opening face, u_r is the radial displacement, and $u_{r\infty}$ is the radial displacement obtained from plain-strain based analysis and

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[*] Corresponding author. Tel/Fax.: +98-21-88008838, +98-21-82084567, +98-912-5032335. *E-mail address:* mhazizi@razi.ac.ir.

$$u_{r\infty} = \frac{P_0 R(1+\vartheta)}{E} \tag{3}$$

Where P_0 is the initial stress.

3. Modeling and numerical analysis

3.1. Intact and sparsely jointed rock masses

Modeling is conducted in accordance with the following steps:

I. Geometrical sizes of model were considered 5 times greater than radius of each side of the tunnel. Geometrical sizes of model for studied model were selected 44×44m.

II. Behavioral model for homogeneous rock masses is linear elastic while it is Mohr-Coulomb for weak and heterogeneous rock masses. Mohr-Coulomb model is an elastic perfect-plastic behavioral model that its yield level is constant in the main stresses, and does not affect by strain [9].

III. Remained gravity stresses are applied on model. In addition, vertical boundaries are fixed in the horizontal direction and bottom boundary of model is fixed in two horizontal and vertical directions.

IV. In 2D analysis, element is eight-node while it is plane strain mode, and it is cubic in the 3D analysis.

V. Analyzes were conducted for a wide range of elastic modulus, Poisson's ratio, radius changes, changes in overheads, and changes of stress ratio in a elastic behavior model.

3.1.3. Investigating the effect of elastic modulus

In 2D and 3D mode, by increasing the modulus of elasticity, displacement around the tunnel reduces. In these analysis, 11 different values were used as elasticity modulus (Fig. 1).

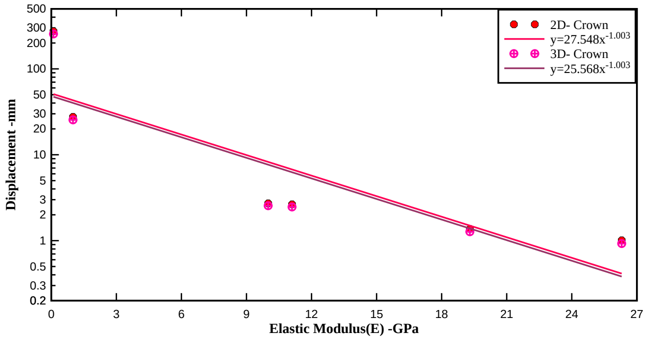

Fig. 1. Variation of the displacement with elastic modulus in 2D and 3D modes.

According to Fig. 1 in both 2D and 3D modes displacement decreases by increasing in elastic modulus value, while the resistance of the rock mass increases by increasing the elasticity modulus value. Although the obtained graph is almost identical in both 2D and 3D modes, 2D displacement sharply reduces according to equation provided for each, because in 3D mode, unexcavated parts of tunnel face undertake some part of deformations.

By concluding the above cases, Fig. 2 can be proposed for relationship between 2D and 3D displacements. As shown in Fig. 2, the displacement around the tunnel in 2D mode is higher than that of 3D mode.

3.1.4. Investigating the effect of Poisson's ratio

As Poisson's ratio increases, displacements in 2D and 3D modes increase around the tunnel. Nine different values of Poisson's ratio (0.2, 0.22, 0.25, 0.27, 0.3, 0.33, 0.37, 0.4, and 0.44) were applied to the proposed model (Fig. 3).

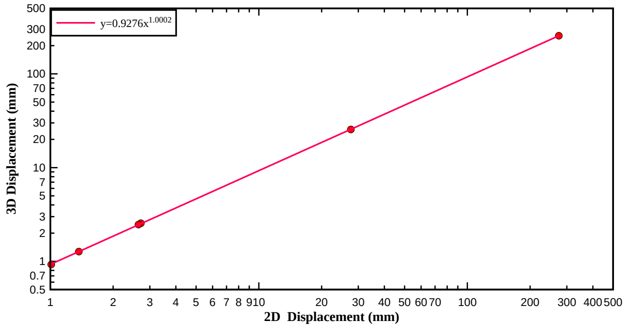

Fig. 2. The relationship between the 2D and 3D displacements for different modulus of elasticity.

As shown in Fig. 3, as Poisson's ratio increases, displacements in 2D and 3D modes increase, as well. However, the rate of displacement in 3D mode is lower than which in 2D mode due to impact of unexcavated part on the third dimension. By increasing the distance from the tunnel face the influence of Poisson's ratio changes on plane strain decreases. 2D displacement is higher than that of 3D displacement in intact and sparsely jointed rock masses as shown in Fig. 4.

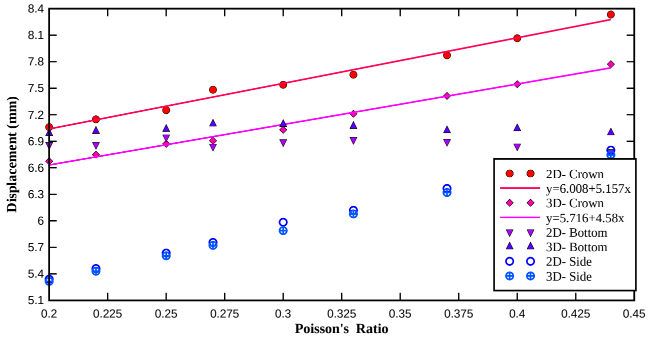

Fig. 3. Variation of the displacement with Poisson's ratio in 2D and 3D modes.

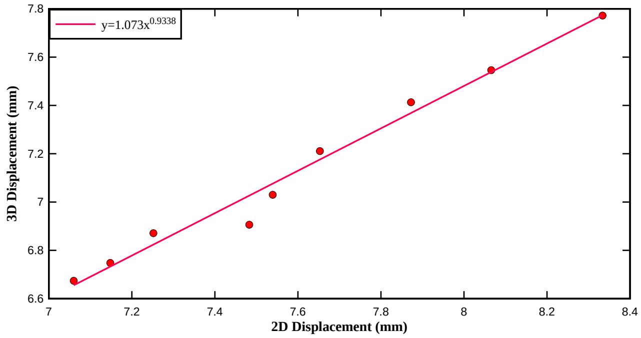

Fig. 4. The relationship between the 2D and 3D displacements due to different Poisson's ratio values.

3.1.5. Investigating the effect of stress ratio (K)

As K increases, displacement of tunnel crown declines. However, this decline occurs steeper in 3D compared to 2D mode (Fig. 5). Displacement increase in tunnel sides by increase in K. These fluctuations happen because in tunnel crown and its sides, horizontal and vertical stresses are dominant respectively.

In the equation proposed by Unlu and Gercek [2], the applied stress was hydrostatic; but in this study the ratio of stresses has been considered for lower and higher values, in addition to value 1. Additionally, the required analyses were conducted for various K ratios and elastic modulus values. K changes in 2D and 3D analysis are summarized in Fig. 6. As shown, 2D mode displacement value is higher than 3D.

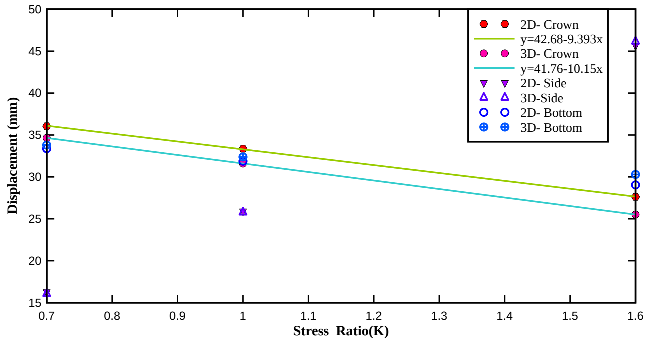

Fig. 5. Variation of the displacement with stress ratio in 2D and 3D modes.

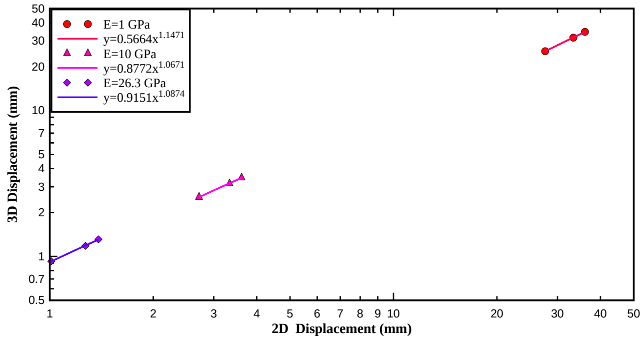

Fig. 6. Relationship between 2D and 3D displacements due to changes in stress ratio.

3.1.6. Investigating the effect of overhead depth

Fig. 7 shows the displacement changes around the tunnel in 2D and 3D modes caused by changes in overhead height. 2D displacement is higher than 3D as is obvious in Fig. 7.

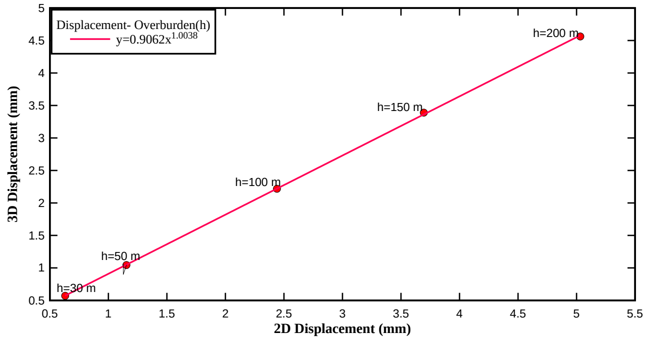

Fig. 7. Displacement changes in 2D and 3D in various overburden.

3.1.7. Investigating the effect of tunnel diameter

To investigate the effect of tunnel diameter on displacement occurred around the tunnel, six different radii (1, 2, 3, 4, 5 and 6 m) were considered. The relationship between displacement and circular tunnel radius changes in both 2D and 3D modes is shown in Fig. 8.

As tunnel diameter increases, 2D and 3D deformations increase, as well (Fig. 8). Displacement changes around the tunnel in 2D and 3D mode for different diameters of circular tunnel is shown in Fig. 9. Displacement in 2D mode is higher than that of 3D mode, as shown in Fig. 9.

3.1.8. Summary of analysis conducted for intact and/or sparsely jointed rock masses

Summary of all analytical results explained in previous sections is shown in Fig. 10. U_2DU_3D According to conclusions Eq. 4 could be used to calculate the relationship between 2D (U_2D) and 3D (U_3D) displacement for intact and/or sparsely jointed rock masses.

U_3D=0.92U_2D^1.0008 (4)

Since in 3D analysis a part of applied stresses is tolerated by third dimension and the tunnel face, 3D displacement in intact and/or sparsely jointed rock masses is lower than 2D displacement, as it is obvious in Eq. 4.

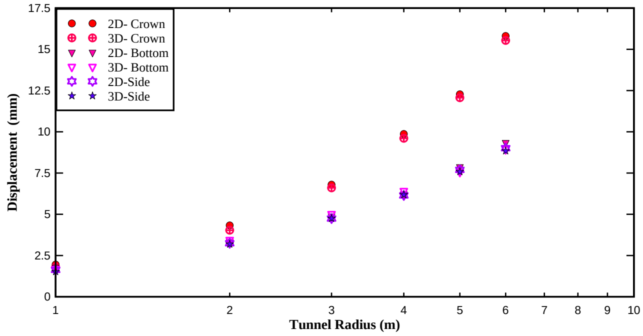

Fig. 8. Effect of changing the radius of tunnel on displacement of around of tunnel in 2D and 3D modes.

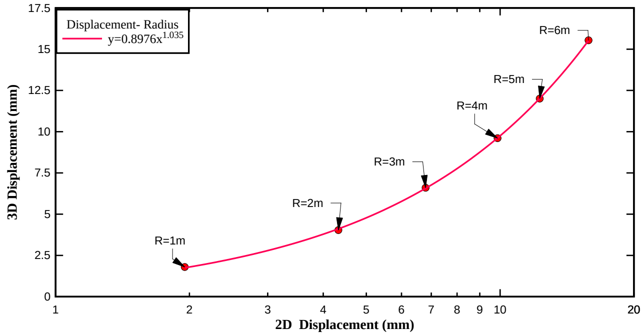

Fig. 9. The relationship between 2D and 3D displacements at different radii.

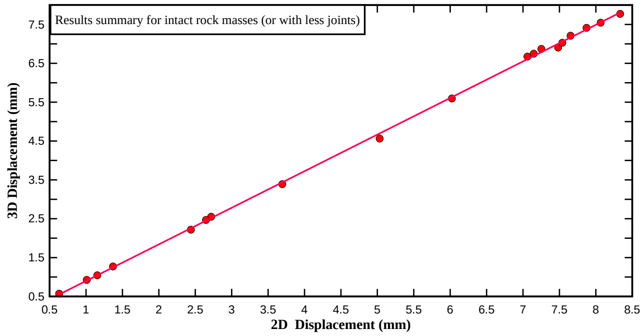

Fig. 10. Collection displacement variations in 2D and 3D around of the tunnel.

3.2. Displacement analysis in heavily jointed rock masses

The rocks are generally discontinuous, heterogeneous and non-isotropic. Hence, they show non-linear behavior. In this study discontinuous environment mechanics theory was used to analyze heavily jointed rock masses behavior. However, due to structural weaknesses and joints different mechanical properties, disconnected environments analysis methods are not carried out accurately and completely. Assuming that heavily jointed rock masses show similar behavior as continuous environments, continuous environments theory is used to analyze their behavior [10]. Discontinuities and joints have major impact on design and construction of large underground spaces.

Dhawan et al. [4] studied several underground spaces in jointed rock masses. Local measured data (extracted from Dhawan et al. [4] and ÜÇER [5]) and also the results of Dehghani [11] study have been used in this paper.

Local measurements data (3D) and the results of 2D analysis are drawn for heavily jointed rock masses in Fig. 11. The relationship between 2D and 3D displacements in heavily jointed rock masses can be proposed as follows:

$$U_{3D} = 2.5U_{2D}^{0.8} \tag{5}$$

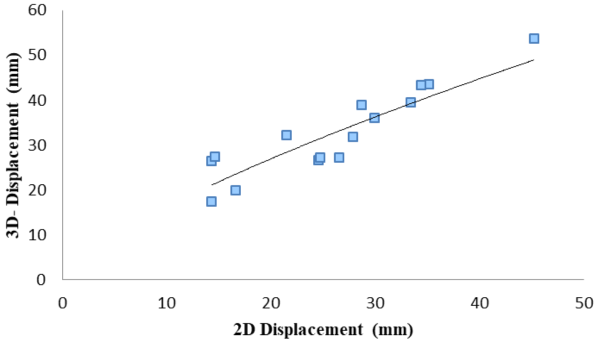

Fig. 11. The relationship between 2D and 3D modeling using in-situ measurements and numerical models.

Eq. 5 indicates that 3D displacement in heavily jointed rock masses is higher than 2D displacement in such rock masses. This happens when the third dimension joints increase the displacement in 3D analyses while they do not have similar impact on 2D.

Bray [12] demonstrated that if a rock mass contains ten or more sets of discontinuities (joints), then it could behave as a homogeneous and isotropic rock mass by only 5% error, due to assumed homogeneity and isotropic condition. Also, if a rock mass is massive and contains slight discontinuities, it can ideally behave as a homogeneous medium.

4. The Impact of 2D and 3D analysis on tunnel support system designing

In order to use the advantages of both experimental and numerical modeling, Basarir et al. [12] proposed a combination of RMR system, 3D numerical modeling and multiple linear regression analyses. Using multiple regression analysis to obtain normalized radial displacement, they provided following three-parameter (a, b, c) equation to calculate the displacement.

$$\frac{U_r}{R} = aRMR^b\left(\frac{x}{D}\right)^c \tag{6}$$

The a, b and c coefficients of Eq. 6 are given by Table proposed by Basarir et al. [13] for 100, 200, 300 and 400 m depths. $\left(\frac{U_r}{R}\right)$ is the normalized radial displacement. $\left(\frac{x}{D}\right)$ is the normalized distance to the face that x is the distance from face and D is the tunnel diameter. By combining the suggested equation in this study (Eq. 5) and Eq. 6, Eq. 7 is obtained.

$$RMR = \left(\frac{2.5U_{r2D}^{0.8}}{a.R.\left(\frac{x}{D}\right)^c}\right)^{\frac{1}{b}} \tag{7}$$

In Eq. 7, RMR value can be obtained for heavily jointed rock masses if 2D displacement is given. Barton [14] proposed Eq. 8 for the relationship between Q-value and RMR as follows:

$$\mathrm{RMR} = 15\lg\mathrm{Q} + 50 \tag{8}$$

By substituting Eq. 7 in 8, the Q-value is obtained based on 2D displacement:

$$\mathrm{Q} = 10^{\left\{\left[\left[\frac{2.5\mathrm{U}_{\mathrm{r2D}}^{0.8}}{\mathrm{a.R.(x/D)^c}}\right]^{\frac{1}{\mathrm{b}}}-50\right]/15\right\}} \tag{9}$$

Hajiazizi and Khatami [1] proposed following equation to determine the Q_{seismic}-value:

$$Q_{(seismic)} \cong 0.6D^{-0.3}Q_{(static)} \tag{10}$$

By substituting Eq. 9 in the Eq. 10, Q_{seismic}-value can be obtained based on 2D displacement as follows:

$$Q_{(seismic)} \cong 0.6D^{-0.3}10^{\left\{\left[\left[\frac{2.5U_{r2D}^{0.8}}{a.R.(x/D)^c}\right]^{\frac{1}{b}}-50\right]/15\right\}} \tag{11}$$

Therefore, Q_{seismic}-value can be obtained based on 2D displacement from Eq. 11.

5. A case study: Gavoshan Dam Tunnel

To validate the conducted study and proposed equations, the Gavoshan Dam tunnel was examined. The Gavoshan Dam in West of Iran was constructed with a capacity of 550,000,000 m3. It has a water transmission tunnel and hydroelectric power of 11 MW. The radius of tunnel is 3m. Other characteristics of the tunnel are shown in Table 1 [15]. Water level in the tunnel is below the tunnel floor level. Vertical stresses which is caused by weight of overburden have been calculated and a value of 1.6 was obtained for stress ratio in this area.

Table 1. The rock mass properties used in the present study.

E(MPa)	υ	G(MPa)	K(MPa)	C(MPa)	Φ(degree)
4609	0.3	1772.7	384.08	0.717	33.5

Using finite difference and finite element methods in 2D mode, the values of displacement in three positions of crown, floor and sides were calculated (Table 2). Using proposed equation in this study (Eq. 5), the displacement value is calculated in 3D mode. For example, in the tunnel sides, calculation is as following:

$$U_{3D} = 2.5U_{2D}^{0.8} = 2.5 \times (20.317)^{0.8} = 27.81mm$$

In addition, the bottom and crown of the tunnel displacements were obtained 26.82mm and 29.16mm respectively.

Table 2. Displacements for three position around tunnel.

	2D Modeling			3D Modeling		
Analysis	Bottom	Side	Crown	Bottom	Side	Crown
FEM (mm)	21.35	22.88	23.769	19.19	21.73	23.27
FDM (mm)	19.414	20.317	21.455	18.23	20.87	23.5

The tunnel has also been analyzed in 3D mode that is shown in Fig. 15. The results of 3D numerical analysis are shown in Table 3. Table 3 shows that there is little difference between results of this study and 3D finite element analysis, therefore the results of proposed equation in this paper gives higher displacement. Therefore, the displacement value obtained by the proposed equation for heavily jointed rock masses can be trusted. In other words, results of 3D analysis could be obtained using equation proposed in this paper without conducting 3D analysis. Values represented in Table 3 are higher than authorized values defined by Sakurai [16].

Table 3. The results of the displacement in numerical analysis and the results of this research around the tunnel.

Location of index point	3D-FEM (mm)	Eq. 5(this study) (mm)	% Error
Bottom	22.87	26.82	17.3
Side	26.65	27.81	3.9
Crown	27.12	29.05	7.1

The relation of Q-system and 3D displacement can be formulated as:

$$Q_{(seismic)} \cong 0.6D^{-0.3}10^{\left\{\left[\left[\frac{U_{3D}}{a.R.(x/D)^c}\right]^{\frac{1}{b}}-50\right]/15\right\}} \tag{12}$$

Therefore, support is essential for the tunnel. Designing the tunnel support is carried out according to Q-system. For this purpose, seismic Q-value is obtained from the using proposed equation (Eq. 11). Q-value in static mode is obtained 0.5 while it is 0.175 in seismic mode. Therefore, designing the tunnel support is conducted regarding to the value of Q = 0.175.

Table 4. Comparison of Q-value in 2D and 3D analysis.

Analysis	Q-2D Model	Q-3D Model
Static	0.5	0.015
Seismic	0.175	0.005

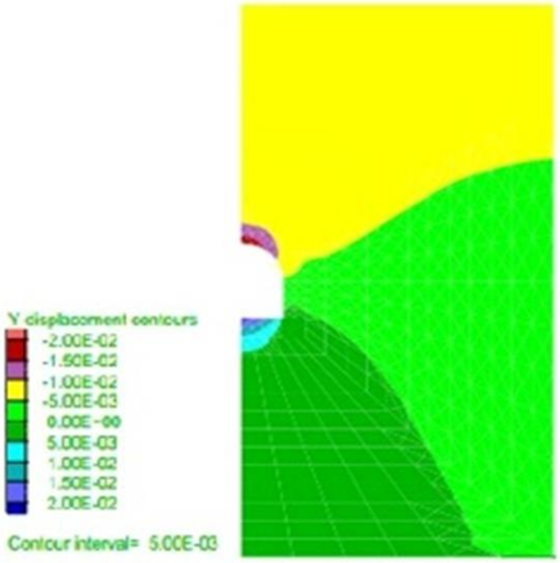

Fig. 12. Vertical displacements in 2D mode for elasto-plastic analysis.

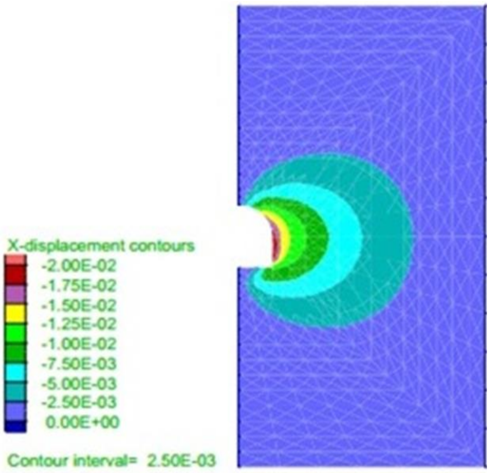

Fig. 13. Horizontal displacements in 2D mode for elasto-plastic analysis.

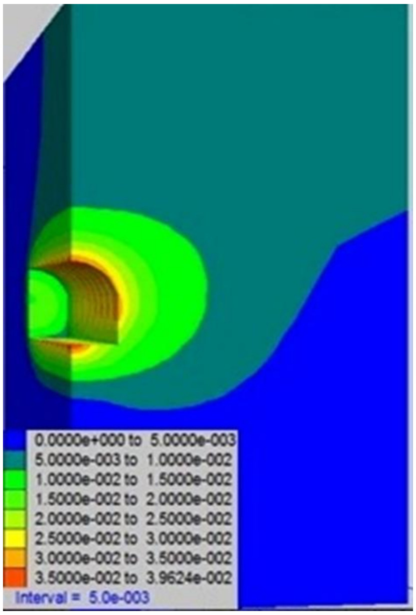

Fig. 14. Vertical displacements in 3D mode for elasto-plastic analysis.

6. Conclusion

Creating underground tunnels usually leads to abrupt changes in stress-strain behavior in jointed rock masses. Most of stress-strain behavior analysis have been conducted in 2D mode, while the actual behavior of rocks is 3D. In this paper, a new equation was proposed to calculate the 3D displacement based on 2D displacement. Then, by combining the proposed equations, Q-value was calculated in order to design the tunnel support. In other words, Q-value can be obtained through 2D analysis of jointed rock masses. For example, if the displacement of tunnel is 21.35 mm in 2D analysis, the Q-value in the seismic mode can be obtained 0.175 without further analysis. Comparing 2D and 3D analysis shows that in intact and/or sparsely jointed rock masses 2D displacement is higher than 3D. This is due to the fact that in intact and/or sparsely jointed rock masses resistance of third dimension of rock is an important factor in reducing the displacement around the tunnel. However, in the heavily jointed rock masses, the third dimension of rock is a negative factor in reducing the displacement around the tunnel compared to 2D mode. While the base of many of studies is 2D mode, using 3D mode leads to actual and reliable results. Results of the proposed equation can be used to calculate the 3D displacement and Q-value.

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