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Influences of Crushed Fault Zone in the Stability of Zaker-Sorkhedizaj tunnel, NW Iran

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Abstract: This paper presents the results of engineering geological studies of rock masses in the crushed fault zone along a road tunnel in NW Iran. The tunnel is to cross the Western Alborz Mountain Range through 530 m in length with 11.2 m span and 8 m height. Eocene tuffs and andesites crop out in whole of the tunnel route. The final segment of tunnel is composed of porphyry andesites and a strike-slip fault with reverse component has caused the crushed zone with 20-25 m extent and 20 m cover. Empirical and numerical methods were combined for safe tunnel design in the crushed rock masses. The results of the evaluations show that the crushed rock masses is completely instable in the tunnel and need to an especially support system. The performances of the proposed support systems were analyzed by means of numerical analysis. After applying the suggested support system to the crushed rock masses, tunnel deformation and the yielded elements around the tunnel decreased significantly thus it was concluded that the suggested support systems were adequate.

Key words: Crushed rock masses · Tunnel stability · Zaker-Sorkhedizaj tunnel · Empirical method · Numerical method

INTRODUCTION

Tunneling in mountainous region with active tectonic requires crossing through increasingly difficult geological conditions. Iran terrene is one of the most tectonically active regions of the world because the Arabian-Eurasian collision has been occurred. Numerous studies in the Iran have shown ongoing convergence and active tectonic in this area [1-3].

Due to ongoing movement of faults in the Iran plateau, crushed fault zones have been formed around of prominent faults. These tectonically crushed zones directly influence the safety of the working site, the choice of the tunnel support and the long term behaviour of the construction [4]. Fault rocks fall within the category of weak or soft rocks and usually cause problems such very high development of plastic zone in above part of openings and rock falls in the excavated spaces. For this reason, knowing the geomechanical characteristics of these rocks is very important in rock engineering.

A detailed geological and geotechnical study was carried out in the project area to determine the geomechanical characteristics of the rock masses. The rock mass was classified according to the RMR and Q system method. Generally, analysis of tunnel stability could be done via comparison of displacements in the crushed rock masses (resulted of numerical methods) with critical displacements obtained from the hazard warning levels [19]. Furthermore, Ground Reaction Curve (GRC) could be drown using modulus reduction method and the amount of tunnel wall deformation prior to support installation could be determined using the diagram proposed by [5].

This paper attempts to present geomechanics of the crushed rock masses in the fault zone, estimating the rock mass properties and evaluating their behaviours. Subsequently, these data would be used as input parameters for analysis the stability and design of support for the Zaker-Sorkhedizaj tunnel in northwest of Iran. This tunnel, with about 530 m in length and 11.2 m span, is to run through Qaravol Pass in Western Alborz Mountain Range in Zanjan province (Fig. 1). This project, connects route of western provinces to Gilan province in the north of Iran. Altitude of the tunnel is designed to be between 2288 to 2294 m with as much as 65m cover.

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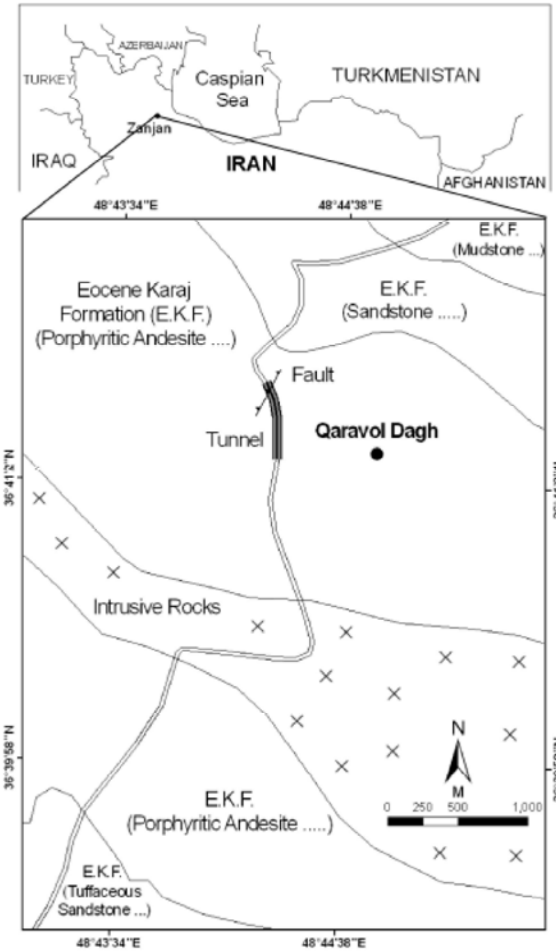

Fig. 1: Sketch maps showing the location of Zaker-Sorkhedizaj tunnel and distribution of Eocene Karaj Formation. Situation of the fault caused crushed zone relation to trend of tunnel also is shown.

Geology: The studied area is located in Western Alborz zone [6] which deforms by strain partitioning of oblique shortening onto range-parallel left-lateral strike-slip and thrust faults. The whole rocks under investigation in this study belong to the Eocene Karaj Formation. This formation is a volcano-sedimentary unit that consists of the variety of porphyroclastic rocks. In places, sub-volcanic bodies were also intruded into this formation. The Zaker-Sorkhedizaj tunnel is located in unit that composed of porphyry andesite with sandstone and green tuff at the base. Petrographical studies on the rocks in the site of project showed that main groups consist of pyroclastic rocks and lava type rocks. Therefore, based on survey of thin sections, rock units in the route of tunnel could be classified into

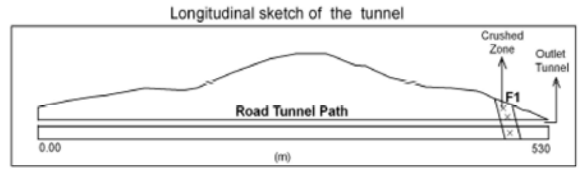

Fig. 2: Longitudinal sketch of the Zaker-Sorkhedizaj tunnel showing location of crushed fault zone in the tunnel.

crystal lithic tuff, lithic crystal tuff and porphyry andesite. The last one has constructed hilly morphology and included andesitic rocks with light green in color and porphyry texture.

In the studied area, the faults are the most basic structures that have subjected especially porphyry andesites and caused very dense fracturing in these rocks. Because of very extensive development of the fracturing in the porphyry andesites, a crushed fault zone with 20 to 25 m extent could be distinguished in the around of the most prominent fault in the site of project. This fault with trend of NE-SW is a strike-slip fault with reverse component that dips 75-85 degree to northwestward. Angel of this fault with axis of tunnel is 70 to 75 degree (Fig.1). The crushed zone of this fault in form of disruption and fragmentation of porphyry andesites can be saw in outlet of tunnel to downward of Qaravol pass. Situation of crushed fault zone was shown in the longitudinal sketch of the tunnel (Fig.2).

MATERIAL AND METHODS

The physical and mechanical characteristics of the crushed rocks were determined on obtained samples of boreholes and field tests on outcrops. The specific gravity of crushed rocks varies from 2.66 to 2.68 that showing there are no prominent variations in their densities because of the low impurity contents.

The values of minimum and maximum UCS varies from 12 to 27 MPa, respectively and the average value of 20 MPa. The low values of the UCS are mainly due to fragmentation nature of these rocks. Therefore, according to [7] the crushed rocks proved to be weak rocks. In addition, based on [8] using the UCS, very low strength were suggested for these rocks.

The average value for the rock material constant mi was determined using [9] failure criterion. The value of mi for the crushed rocks was obtained equal to 13.

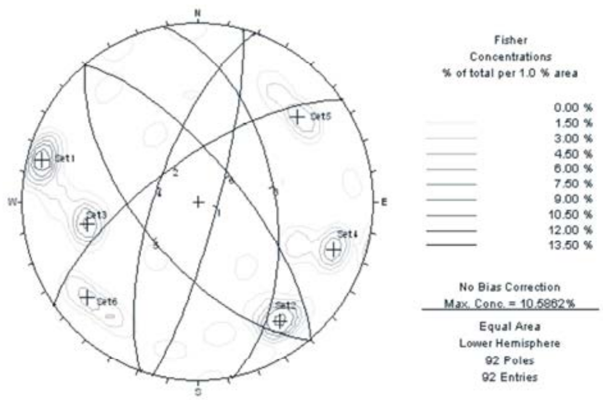

Fig. 3: Equal area stereographic projection of the fractures measured in the porphyry andesites along the tunnel route.

Rock Mass Characteristics: To acquire the crushed rock masses characteristics, site investigations were carried out on the outcrops along the tunnel route, the sidewalls and faces of galleries and the core logs of few borehole drillings. The information obtained of these investigations will be used on the rock mass classification as indices.

The most important discontinuities in the site of project are faults, joints and surface beddings. The scan-line surveys, spot measurements and field observations according to [7] were carried out on crushed rocks along the tunnel route to determine the orientations, spacing, roughness, aperture, persistence, infilling, groundwater condition, waveness and weathering states of the fractures.

The whole fracture orientations in the studied area are shown in the equal area lower hemisphere stereographic projection in Fig. 3. The points of maximum density led to identification of six main fracture sets (Dip/Dip Direction: 81/105, 70/325, 54/079, 70/289, 63/230 and 71/050) (Fig. 3). Regarding to the tunnel drives to the north-south direction (Fig. 1), it could be discuss the effects of the fracture orientations on the tunnel instabilities. According to [10] the first, third and fourth fracture sets with strike sub-parallel to the tunnel have potential of instabilities for the tunnel walls.

The spacing of fractures ranges from 200 to 600 mm (moderate spacing, [7]) and the fracture surfaces are rough and slightly undulating. The apertures of most fractures fall within very tight to open (<0.1-2.5 mm) categories [7]. They are nearly continuous with about 3-10 m in length [7] and are filled with gouges, rock fragments and clay. The andesites fracture surfaces are dominantly dry, stepped to plannar and are fresh to slightly weathered.

The Rock Quality Designation (RQD) of the crushed rock masses ranges between 17% and 27%. According to the RQD divisions proposed by [11], these rock masses set to very poor class which indicates effects of the structures on the porphyry andesites strengths.

Classification of the Crushed Rock Masses: Rock mass classification systems have been developed to create some order out of chaos in site investigation procedures [12] and to define an empirical approach to tunnel design which provide guidelines for stability performance and suggest appropriate support systems.

The RMR and Q ratings have been determined using field data and the mechanical properties of intact rock samples. The Rock Mass Rating (RMR) System [13], classifies rock masses using the following parameters: uniaxial compressive strength (UCS), Rock Quality Designation (RQD), spacing of fractures, condition of fractures, groundwater conditions and orientation of fractures. The average RMR rating for the crushed rock masses assessed to be from 16 to 22, with an average value of 19 (Table 1). This rating classifies these rocks as a very poor rock mass.

The Q rock mass classification system is also known as the NGI (Norwegian Geotechnical Institute) have been developed by Barton *et al*. (1974). It is defined in terms of RQD, the function of joint sets (Jn), discontinuity roughness (Jr), joint alteration (Ja), water pressure (Jw) and stress reduction factor (SRF). The Q values for the crushed rock masses are from 0.04 to 0.05, with an average value of 0.045 (Table 1). According to the Q classification system, these rocks can be considered as very poor rock mass.

Mechanical Properties of the Crushed Rock Masses: The rock mass properties such as the rock mass strength (σ_{cm}), the rock mass deformation modulus (Em) and the rock mass constants (mb, s and a) were calculated by the Rock-Lab program defined by [14]. This program has been developed to provide a convenient means of solving and plotting the equations presented by [14].

In Rock-Lab program, both the rock mass strength and deformation modulus were calculated using equations of [14]. In addition, the rock mass constants were estimated using equations of Geological Strength Index (GSI) [14] together with the value of the porphyry andesites material constant (mi) (value in Table 2). Mean RMR values (Table 1) have been used to estimate the GSI index for the crushed andesites (Table 2). Also, the value of disturbance factor (D) that depends on the amount of

Table 1

Rock mass classification system	RMR	Q
Rating	16-22	0.04-0.05
	19	0.045
Rock mass Quality	very poor	very poor

Table 2

GSI	mi	D	mb	s	a	σ_{cm}(MPa)	Em(MPa)	C(MPa)	φ(deg)
14	13	0.00	0.603	0.0001	0.565	1.488	563.01	0.065	42.34

disturbance in the rock mass associated with the method of excavation, was considered zero for the crushed rock masses (Table 2), it means these rocks would not be disturbed more than this during blasting.

Finally, the shear strength parameters of the rock mass (C and ö) for the crushed rock masses were obtained using the relationship between the Hoek-Brown and Mohr-Coulomb criteria [9] and are presented in Table 2.

Analysis of Tunnel Stability and Support Reqirements: One of the most important tasks in rock engineering is stability analysis and design of the support system for tunnel. The empirical and numerical methods were employed for analysis of stability and support requirements in the crushed rock masses in the Zaker-Sorkhedizaj tunnel.

Empirical Methods: The geomechanical properties of crushed rock masses together in situ stress were used for analyses of stability and support requirements in empirical methods. The ratio of rock mass strength to in situ stress could be applied for assessment of the rock mass behaviors in tunnel surroundings. The rock mass strength was calculated by the Rock-Lab program (Table 2) and the in situ stress was determined from the tunnel depth and the porphyry andesites unit weight.

Regarding to tectonic situation of area that has been located in the transpressional zone [15], the values for maximum and minimum horizontal stresses are more than the vertical stresses [16]. The equation of Sengupta in [16] could be used for these tectonic settings and overburden less than 400 m. This equation is defined as: σ_H=1.5+1.2σ_v, where: $\sigma_v=\gamma\times Z$. Considering the mean density values of 2.67 g/cm3 for the porphyry andesites and the mean values of 20 m overburdens for this section of tunnel, the vertical stress (σ_v) has been calculated as 0.53 MPa and the maximum horizontal stress (σ_H) would be 2.14 MPa.

Generally, the maximum stress concentrations, on the walls of the circular tunnel are compressive in nature and twice of in situ stress. Therefore, the tangential stress concentrations in the crushed rock masses would be equal to 4.27 MPa and the safety factor, which is the ratio of the rock mass strength to the in situ stress, was determined as 0.17. The significant low value of the safety factor for the crushed rock masses imply distinct instability of tunnel and indicate proper support requirements for a tunnel section in the crushed rock masses.

The required support system for crushed rock masses could be evaluated using the RMR [13] and the Q [17] (Table 1). According to RMR system, rock boltings (5-6 m long, 20 mm diameter and fully grouted and spacing 1-1.5 m in crown and walls with wire mesh, bolt invert), concrete shotcretings (150-200 mm in crown, 150 mm in sides and 50 mm on face) and steel sets (medium to heavy ribs spaced 0.75 m with steel lagging and forepoling if required, close invert) are recommended for the tunnel supporting in the crushed rock masses. Moreover, the Q system predict fibre reinforced shotcrete 150-250 mm with reinforced ribs of shotcrete and bolting for this section of tunnel.

Numerical Methods: Numerical analyses of tunnel deformations in the crushed rock masses were accomplished using a two-dimensional hybrid element model, called Phase2 Finite Element Program [18]. This software is used to simulate the three-dimensional excavation of a tunnel. In three dimensions, the tunnel face provides support. As the tunnel face proceeds away from the area of interest, the support decreases until the stresses can be properly simulated with a two-dimensional plane strain assumption. In this finite element simulation, based on the elasto-plastic analysis, deformations and stresses were computed. These analyses used for evaluations of the tunnel stability and design support system in the crushed rock masses. The geomechanical properties for these analyses were extracted from Table 2. The Hoek and Brown failure criterion was used to identify elements undergoing yielding and the plastic zones of the crushed rock masses in the tunnel surrounding.

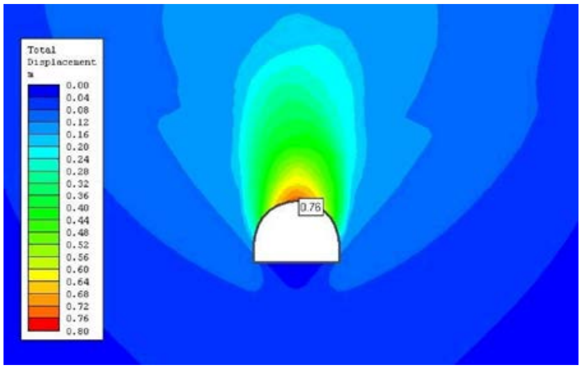

Fig. 4: The total displacement in the roof of tunnel in the crushed rock masses before support installation.

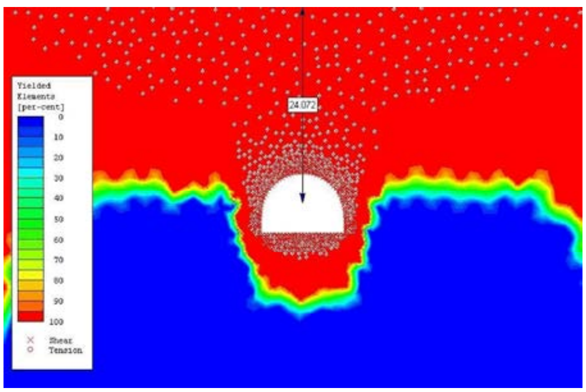

Fig. 5: Thickness of plastic zone in around of tunnel in the crushed rock masses before support installation.

To simulate the excavation of tunnel in the crushed rock masses, a finite element models was generated with horseshoe section and 11.2 m span. The outer model boundary was set at a distance of 5 times the tunnel radius and six-nodded triangular elements were used in the finite element mesh.

In the first step, the maximum tunnel wall displacement and the radius of the plastic zone, far from the tunnel face were determined. The most of displacement was taken place at the roof the tunnel. The maximum displacement for this stage was approximately 76 cm, which is the value of maximum wall displacement far from the tunnel face. The radius of the plastic zone far from the tunnel face was determined from extent failed zone represented by a number of crosses (Fig. 5) indicating elements in the finite element analysis have failed. Distribution of plastic zone in surrounding of the tunnel (Fig. 5) showed extensive developments of this zone in upper of the tunnel, so that its extent reached to surface ground. Radius of plastic zone in upper of the tunnel was approximately 24m that is very too.

In the second step, the stability of tunnel in the crushed rock masses was assessed by comparing displacements obtained from the numerical method with critical displacements resulted of the hazard warning levels. If displacements obtained from the numerical method are smaller than ones of the hazard warning levels, the stability of the tunnel will be concluded. But if these displacements become greater than ones of the hazard warning levels, then some actions must be taken to stabilize the tunnel. The hazard warning levels could be determined from critical strain (ε_c). The critical strain could successfully be used for assessing displacement measurements in tunnels, such as crown settlements and convergence. The critical strain (ε_c) is always smaller than strain at failure and calculate as follows:

$$\varepsilon_c = \frac{\sigma_c}{\mathrm{E}}$$

where σ_c is uniaxial compressive strength of rock mass (MPa) and E is Young,s modulus (MPa). The relation of critical strain, compressive strength and Young,s modulus was obtained by [19] and he presented three hazard warning levels, as follows:

Hazard warning level ²: Logε_c =-0.25 LogE-0.85
Hazard warning level Đ: Logε_c =-0.25 LogE-1.22
Hazard warning level Ø: Logε_c =-0.25 LogE-1.59

where E is Young,s modulus per *Kg/cm²*. The hazard warning levels ² and Ø indicate long time and short time stability of tunnel, respectively. The hazard warning level Đ is suggested as the base of tunnel design.

Regarding the value of Young,s modulus (E) in the crushed rock masses (Table 2), the values of critical strain for each hazard warning levels were calculated. These values are 0.029, 0.0124 and 0.0053, respectively. The values of allowable displacements on the basis of the hazard warning levels (Table 3) were determined using the values of critical strain and radius of tunnel, as follows:

$$\varepsilon_c = \frac{u_c}{a}$$

where u_c is allowable displacement on the basis of the hazard warning levels and α is radius of tunnel. By comparing displacement obtained from numerical method (76cm) with allowable displacements on the basis of the hazard warning levels (Table 3) it appears that the roof of tunnel in the crushed rock masses shows strong instability. Therefore, a heavy support system should be applied for the crushed rock masses stabilization.

Table 3

Allowable displacement on the basis of the hazard warning level I(cm)	Allowable displacement on the basis of the hazard warning level II(cm)	Allowable displacement on the basis of the hazard warning level IIIcm)
16.24	6.94	2.96

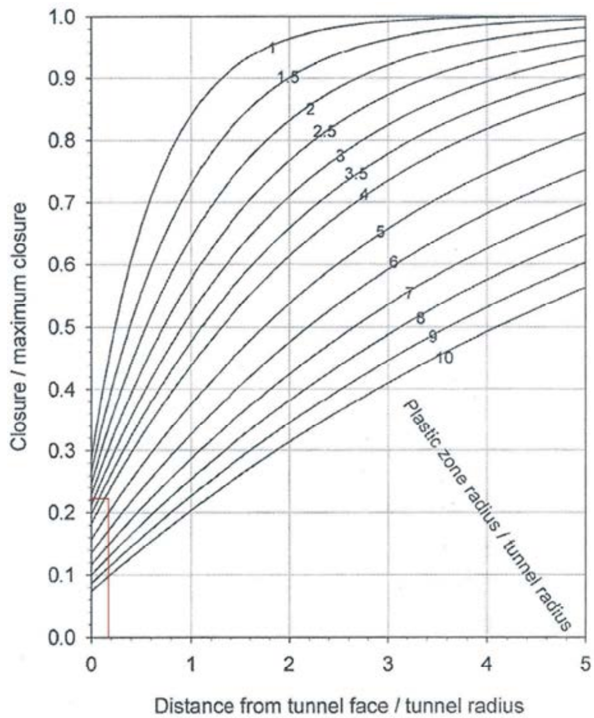

Fig. 6: The plot of Vlachopoulos and Diederichs. For the tunnel roof: Rp=24m, Rt=5.60m, X=1.00m and Umax=0.76m. The Distance from tunnel face/tunnel radius = (1/5.60) = 0.18. The Plastic zone radius/tunnel radius = (24/5.60) = 4.29. From the above plot this gives Closure/max closure approximately equal to 0.22. Thus the closure equals (0.22)×(0.76) = 0.1672m.

The third step is determination of the amount of tunnel wall deformation prior to support installation using the Vlachopoulos and Diederichs method. The plot in Fig. 6 was created using the Vlachopoulos and Diederichs equations [5]. Using this plot, the amount of closure prior to support installation could be estimated with knowing plastic zone radius (Rp), tunnel radius (Rt), displacement far from the tunnel face(Umax) and distance from tunnel face(X). Regarding Fig. 6 the Closure/max closure in the roof of the tunnel equal to 0.22 and the closure prior to support installation equals (0.22)×(0.76) m. Thus, the roof of the tunnel displace 16.72cm before the support is installed, which is greater than allowable limits (Table 3) and again the instability of the tunnel would be confirmed.

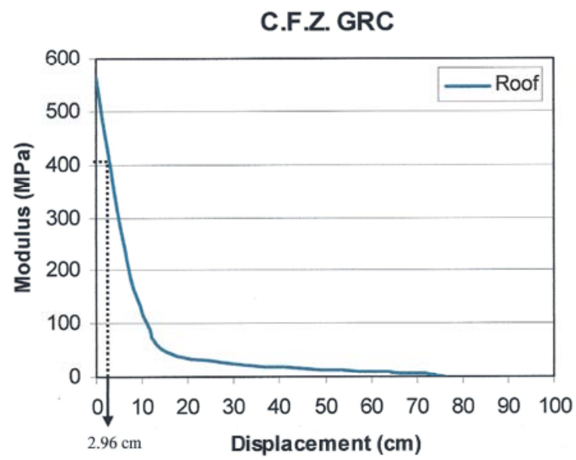

Fig. 7: The Ground Reaction Curve showing relationship between deformation modulus and displacement at the roof of the tunnel in the crushed rock masses.

The forth step is determination of the modulus that yields a critical displacement in the roof of the tunnel. A new kind of Ground Reaction Curve (GRC), which demonstrates relations between displacement and deformation modulus, was constructed using modulus reduction method for the crushed rock masses. Therefore, the GRC will be used to determine the modulus that yields the amount of tunnel wall deformation at the point of support installation. To determine this modulus, the allowable displacement on the basis of the hazard warning level Ø (as short time stability) (Table 3) was considered equal to displacement prior to support installation. Using the GRC, deformation modulus equal to this displacement (2.96 cm) were determined for the roof of the tunnel (Figs. 7). In this manner, the modulus that yields a critical displacement in the roof of the tunnel was determined as 408 MPa and considered for design of support system.

The fifth step is selection of convenient supporting system for the crushed rock masses on the basis of obtained deformation modulus (408 MPa). Initial evaluations of support system showed that minimum support such as concrete shotcretings (20 cm) with I-beam (W610×551), rock boltings (L=6 m, spacing 1 m) and steel arch of IPE20@1m is an essential support system. To reduce the amount of pressure on the applied support system in the crushed rock masses surrounding tunnels,

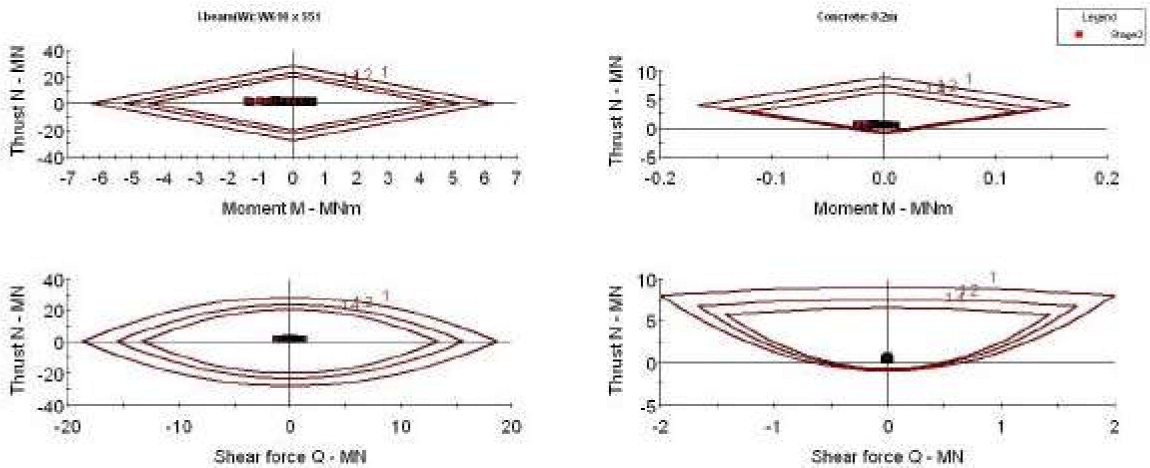

Fig. 8: Support capacity diagrams for a 20 cm shotcrete lining, reinforced with I-beam (W610×551). The dark red lines represent the capacity envelopes for three factors of safety (1, 1.2, 1.4). All the data points fall within the factor of safety =1.4 envelope, on all four plots. This means that the support system chosen has a factor of safety greater than 1.4.

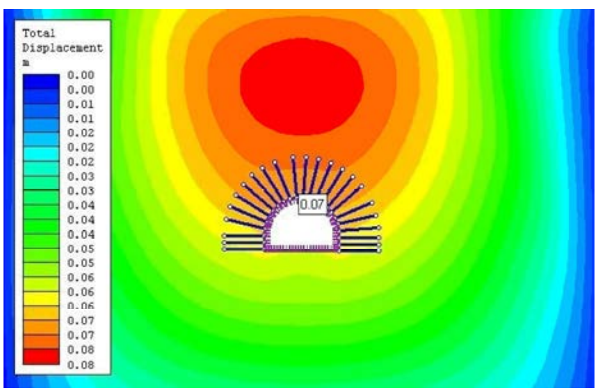

Fig. 9: The total displacement in the roof of tunnel in the crushed rock masses after support installation.

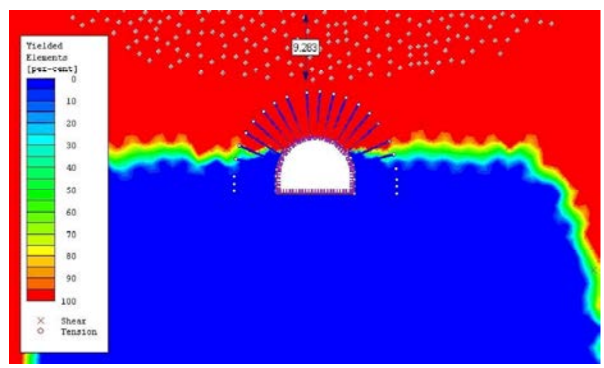

Fig. 10: The number of yielded elements and the extent of plastic zone in the crushed rock masses after support installation.

it is recommended to install support interval between allowable displacements obtained of the hazard warning levels Ð and Ø (Table 3). Determination of this displacement would be possible using instruments.

Assessment of reinforced concrete liner could be done using the factor of safety which is determined by the support capacity diagrams. For a given factor of safety, capacity envelopes are plotted in axial force versus moment space and axial force versus shear force space. If the computed liner values fall inside an envelope, they have a factor of safety greater than the envelope value. As can be seen in Fig. 8, all the computed liner values located inside the design factor of safety capacity envelope, therefore the factor of safety of the liner have been exceeded the design factor of safety.

The final step is determination of total displacement and the radius of the plastic zone since the support system was installed. After support installation, the total displacement in the crushed rock masses is nearly reduced by ten-folds with respect to the induced displacement without support as shown in Fig. 9. In addition, the number of yielded elements and the extent of plastic zone decreased (Fig.10).

CONCLUSIONS

This study provides an estimation of the crushed rock masses properties that could be used as input data for stability analysis and the design of support system for the Zaker-Sorkhedizaj tunnel. Overall, the crushed rock masses are found to be generally unsuitable for underground openings and causes instability problems for the rock surrounding tunnels. In this case, the following conclusions could be noted:

- The results obtained from the empirical and numerical methods are comparable. Both empirical and numerical solutions showed that the crushed rock masses indicate instability due to their lower strength. Numerical analysis of these rocks yielded more than 24 m plastic zones (in tunnel radius) and showed 76 cm displacement in the roof of tunnel which is very too and so fundamental support require to prevent possible failure.
- The displacement obtained from the numerical approach (76cm) is very greater than critical displacements resulted from Sakurai's hazard warning levels (2.96, 6.94 and 16.24cm) which indicating strong instability in the crushed rock masses in tunnel face.
- The closure prior to support installation in the roof of tunnel which determined from Vlachopoulos and Diederichs plot (16.72cm) is greater than allowable limits (2.96, 6.94 and 16.24cm) and instability of the tunnel would be re-confirmed.
- The Ground Reaction Curve (GRC) drew using the modulus reduction method and the modulus that yields a critical displacement in the roof of the tunnel determined (408 MPa) and considered for design of support system.
- The support system for the crushed rock masses checked by support capacity diagrams. All the data points for shotcrete lining fall within the factor of safety 1.4 envelope. Therefore the chosen liner has a factor of safety greater than 1.4.
- After support installation, the total displacement and the extent of plastic zone in the crushed rock masses is largely reduced. Nevertheless, the efficiency of the proposed support systems should be surveyed by comparing the results obtained by a combination of empirical and numerical approaches together with the measurements that will be accomplished during tunnel construction.

Recommendations: The obtained results recommend that the tunnel excavation in the crushed rock masses should be carried out on the multiple drift methods. Moreover, continuous subsurface investigations and monitoring of the tunnel periphery to control displacements are necessary for encountering to unexpected variations in rock mass conditions and behaviors.

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