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A NUMERICAL APPROACH TO SIMULATE STRESSES AROUND TUNNELS IN SWELLING ROCKS

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ABSTRACT

The stresses generated from rock expansion in a confined underground environment will exert additional loads to the existing support system resulting in severe damage during tunnel construction. In this study numerical investigations were carried out for Zagros tunnel in Iran, where swelling has been reported to be an inherent formation property. The presence of expandable clay was investigated using X-ray diffraction mineralogical analyses. The swelling volume strain was used to estimate the amount of stress increased due to swelling. The stress path method is used to obtain the location of swelling stresses. The stress relief zone (SRZ) was considered as the criterion to define the area around the tunnel where swelling stresses exist. In doing so, in the areas where the first stress invariant after excavation becomes lesser than its corresponding value before excavation, the swelling pressure can be built up. Then tunnel stability was investigated by numerical simulations using FLAC2D. The swelling stresses calculated from the free swelling test were applied to those elements around the tunnel within the stress relief zone. A comparison between the results of numerical investigations with field observation indicates that the proposed approach is successful in simulating swelling stress in swelling rocks.

Key words: Swelling rocks, stress path, numerical modelling, FLAC, Zagros tunnel.

1. INTRODUCTION

The swelling rocks are regarded as a major threat to the stability of underground and surface infrastructures (Ewy 2014; Butscher *et al.* 2018). It has the potential to cause severe damage to underground structures and nearby buildings, and produce additional financial costs during excavation and construction (Schwingenschloegl and Lehmann 2009; Butscher *et al.* 2017; Ghorbani *et al.* 2020).

In tunnel engineering, as a particular case, swelling can produce many damaging effects such as heave of the tunnel floor, destruction and deformation of the primary and permanent support system (*i.e.,* concrete lining), and uplift of the entire structure (Butscher *et al.* 2011; Tang and Tang 2012; Galera *et al.* 2014; Butscher *et al.* 2018). The importance of swelling and its damaging effects on engineering structures and nearby buildings (*i.e.,* private properties) are repeatedly reported in the literature (Alonso *et al.* 2013; Alonso and Ramon 2013; Grimm *et al.* 2014), and it is likely to obtain more attraction in the near future (Butscher *et al.* 2018).

Simulating the effect of swelling pressure on stability analyses, however, had always been a challenging task. Swelling can take place in soils and rocks where clay minerals, anhydrite or pyrite/marcasite are present. The time-dependent volume expansion of a rock mass can be due to change in stress condition, moisture content increase, or a combination of both (Galera *et al.* 2014). The expansion of filling materials inside the discontinuities opening can also increase the potential of swelling in a rock mass (Pellet *et al.* 2013).

On the other hand, tensile cracks may develop within the rock mass due to stress relaxation: the flow can pass through this flow path similarly leads to a volume increase of swelling formations. Swelling occurs due to mechanical or physicochemical mechanisms. However, the latter mechanism is more significant in underground excavations stability (Chai *et al.* 2014). When the tunnel is excavated a stress relief zone (SRZ) is developed at some distance from the tunnel face. The swelling effect is related to the extent of this zone (Aristorenas 1992; Steiner 1992; Barla 1999; Yin *et al.* 2017). However, how the volumetric strain is estimated, to which extend around the tunnel face the corresponding swelling stresses should be applied, and how these stresses are transferred to the support system are the issues to be addressed. The strains released due to rock volume increase may apply additional loads to the support systems, and this may cause time-dependent failure of the support lining if the rock load exceeds the ultimate strength of the support system.

The existing methods for design of tunnels in swelling formations include experimental, empirical and analytical approaches (Barla 1999). Some index tests have been proposed by ISRM (1983) to determine the swelling potential of rocks in the lab with the major ones being maximum axial swelling stress, axial and radial swelling strains, and swelling stress as a function of axial swelling strain (Madsen 1999). The empirical design approach is generally used in the initial stage of the project when limited geological information is available (Taheri and Tani 2010). It is important to note that empirical models give an estimation of radial stresses applied to the support system, which are independent of

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the rock properties and tunnel dimensions. In most analytical models the interaction between rock mass and support system is based on the mechanics of continuum media. Swelling law, rheological and mechanistic models are three major analytical solutions available (Barla 1999).

Several mechanical models are proposed for such studies (Carter and Booker 1982; Aristorenas 1992; Noorany *et al.* 1999). To avoid inaccurate prediction of swelling behaviour, the stress effect should not be omitted from constitutive relationships. Hawlader *et al.* (2003) developed a time-dependent constitutive model for predicting the swelling response of shaly rock. Their laboratory investigations showed that the swelling of rocks is highly influenced by the applied stress. Recently Parsapour and Fahimifar (2016) developed a semi-analytical solution for the assessment of time-dependent swelling behaviour of rocks around circular tunnels by considering three-dimensional stress effects. However, when dealing with issues such as anisotropy of the rock and complex geological conditions as well as stress effect, only numerical simulation can be used to assess the swelling potential of rock.

As tunnel excavation progresses, the stress level around the tunnel changes continuously and at a certain distance from the tunnel face the state of stresses become a plane strain. The change in the state of stress within the rock mass can be studied using the stress path concept introduced by (Lambe and Marr 1979). This is the representation of locations around the tunnel in a 2D space along which the state of stresses inside a body changes. Tang and Tang (2012) conducted a numerical approach to simulate the swelling potential of a tunnel under wet condition. They proposed a humidity diffusion-based numerical model for simulating the floor heave processes of swelling grounds exposed to high humidity. They found that the stress disturbance caused by moisture leads to a different degree of rock damage and consequently enhances humidity diffusion. Aksoy *et al.* (2012) used numerical modelling method to simulate the performance of the support system in swelling and squeezing rocks. In their research, they presented in-situ measurements and time-dependent numerical analysis of non-deformable support system and employed a modified Cam-Clay constitutive model (Soft-Soil Creep Model) for modelling high deformable rocks. Recently, Butscher *et al.* (2017) conducted a numerical approach to assess the swelling potential of clay-sulfate rocks. Their numerical simulation allowed understanding how the water flow can influence the swelling problem. However, the stress effect as a boundary condition was neglected in their simulations.

At a microscopic scale, the total rock volume increase is due to the alteration of its molecular structure, and this is a function of applied confining stress as well as water inflow (Wong and Wang 1997). Through numerical analysis of stresses around the tunnels, several researchers (Barla 1999; Butscher *et al.* 2011) found that, considering elastic models for a stress ratio of $K = 1.0$ (*i.e.,* zero stress anisotropy), no stress releif zone (SRZ) has been developed around the tunnel and similarly no swelling was reported. It, perhaps, confirms that the physicochemical swelling is related to the stress path around the tunnel. Therefore, the first stress invariant ($I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$) is used in this research as a criterion to identify whether stress relief has been taken place. In doing so, SRZ is also considered to happen in those areas where I_1^I after excavation is reduced. It should be noted that this approach was neglected in the previous numerical approach conducted by Aksoy *et al.* (2012), Tang and Tang (2012), and Butscher *et al.* (2017).

Numerical analysis of Zagros tunnel, in western Iran, excavated in the swelling ground was undertaken using FLAC code. Two significant questions should be answered in the design of tunnels in the swelling ground: (1) how much swelling stress would be and (2) at which locations around the tunnels these pressures apply.

2. PROJECT DESCRIPTION AND GEOLOGICAL SETTINGS

The Zagros Tunnel project is one of the longest tunnels in the world located in Iran. It is approximately 46 km long and has a diameter of 6.73 m. The tunnel is excavated by a double-shield TBM using concrete segmental lining. To protect the segments against stress concentration due to rock loosening, pea gravel and then cement grout is used as a filling material to fill in the gap between segments and rock mass.

The tunnel alignment is within the Zagros mountain range at an average depth of 400 m. The study area is the first 10 km of the tunnel, where the ground condition is highly complex and consisted of different folded sedimentary rock formations. In this area, the tunnel is driven in a variety of geological formations, including Pabdeh (PE_{Pd}), Gurpi (K_{Gu}) and Ilam (Ki).

The oldest geologic unit along the tunnel alignment is brownish-grey limestone of Ilam formation. Gurpi formation consists of a combination of limy shale and argillaceous limestone. The youngest unit is Pabdeh Formation, which consists of a combination of dark grey limy shale and greenish grey argillaceous limestone. Overall, the tunnel mainly passes through four discernible lithotypes including shale, limestone, limy shale and shaly limestone. Table 1 presents a summary of the rock properties obtained from laboratory testing on core samples from the tunnel site.

During the tunnelling operation, changes in rock quality were frequent, with rock mass quality ranging from fair to very good. The stress ratio along the tunnel has been estimated to be about 0.5. The support system of the tunnel is precast concrete segments. For ground load distribution evenly, the pea gravel and cement grout are usually injected through the holes inside the segments to fill in the gap between the segment and the surrounding rock mass.

Gurpi formation with compacted shales has a very low permeability, whereas Ilam formation is highly permeable, therefore, in the contact zones of these two formations the water being transmitted from Ilam formation can increase the swelling potential in Gurpi. Figure 1 shows an outcrop of Gurpi formation and a shale sample after the swelling test.

Table 1 Gurpi formation rock mass mechanical properties

Parameters	Minimum	Maximum	Average
Geological Strength Index (GSI)	30	44	38
Hoek-Brown criterion m_i Index	6	8	7
Cohesion (MPa)	0.7	2.1	1.37
Friction angle (°)	20	26	24
Tensile strength (MPa)	0.021	0.092	0.051
Compressive strength (MPa)	0.43	2.1	1.1
Young's modulus (GPa)	1.58	5.01	3.09
Poisson's ratio		0.27	

(a) An outcrop of the formation

(b) A shale sample after performing a swelling test

Fig. 1 Gurpi formation

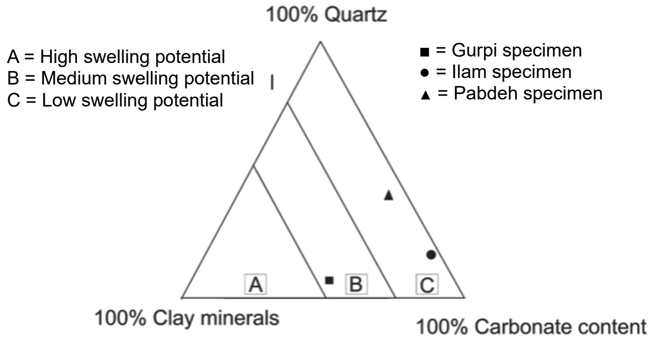


Fig. 2 Diagram of the swelling potential for Zagros Tunnel formation

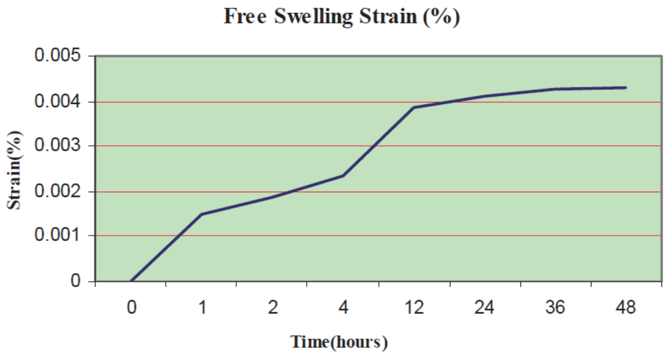


Fig. 3 Free swelling strain experiment carried out on shale specimen from Gurpi formation

Figure 3 shows the plot of strain versus time for one of the samples from Gurpi formation. The results indicate that the sample levels off to a constant strain of approximately 4.3×10^{-5} after 48 hours of swelling strain taking place. Assuming identical strains in three different directions leads to a total volume strain of 12.9×10^{-5}. This shows that the rock has a high potential for swelling in the tunnel if it exposed to groundwater.

3. STUDY ON SWELLING POTENTIAL OF GEOLOGICAL FORMATIONS

Samples obtained from Gurpi, Pabdeh and Ilam formations were used to estimate their swelling potential when they are in contact with water. In the laboratory, the XRD test is used to analyse the mineralogy of the rock samples. The laboratory observations indicated that all samples have calcite, quartz and clay minerals. All samples appeared to have at least 10% Illite, with high swelling potential but lesser than Montmorillonite.

To investigate the likelihood of swelling potential of rocks, the XRD data was plotted on the swelling potential diagram shown in Fig. 2 (Barla 1999). Each point in the diagram defines a rock with different percentage of carbonate, clay and quartz content depending on its distance from three corners of the triangle. The data presented in this figure confirms that Shale sample from Gurpi formation exhibits a medium to high swelling potential.

An estimate of the swelling pressure is essential as an input to numerical models. The swelling pressure was estimated by performing free swelling strain tests in the lab on some samples. For this test, the samples obtained from Gurpi formation were placed in a cell where the rocks exposed to water to generate swelling. Unlike the conventional oedometer, radial deformation is not prevented in this test. Axial displacement was measured and recorded to determine axial swelling versus time.

4. A NUMERICAL APPROACH TO APPLYING SWELLING STRESS

As the swelling problem is very critical in Gurpi formation, numerical modelling is undertaken in this geological formation. Table 1 demonstrates the mechanical properties of Gurpi formation rock mass (Bayati 2007). Tables 2 and 3 present the properties of concrete segmental lining and the filling material which are incorporated into numerical modelling.

Table 2 Properties of concrete segmental lining

Parameter	Value
Eurocode 2 class	C35/45
Uniaxial compressive strength (MPa)	35
Tensile strength (MPa)	2.2
Young's modulus (GPa)	20
Poisson's ratio	0.25
Cohesion (MPa)	2.74
Internal friction angle (°)	60

Table 3 Properties of the filling material

Parameter	Value
Density (kg/m^3)	1,600
Young's modulus (GPa)	40
Poisson's ratio	0.25

Figure 4 explains the approach for answering the first question, and the amount of swelling stress and Fig. 5 explains the approach for the swelling zone around the tunnel, which answer the second major question in swelling ground. Laboratory tests were performed to determine the magnitude of swelling stress, and then the stress path method was utilised to determine where the swelling pressure is applied in the tunnel. Figure 4 schematically shows the steps followed in this study to determine the magnitude of swelling stresses. Laboratory approach and free swelling strain test used to measure the maximum swelling stress which the sample submerged into water and swelling stress will be recorded, and the effect of the water presence and physicochemical behaviour of swelling will be evaluated. Figure 5 shows the methodology used to determine the location of applying the swelling stresses.

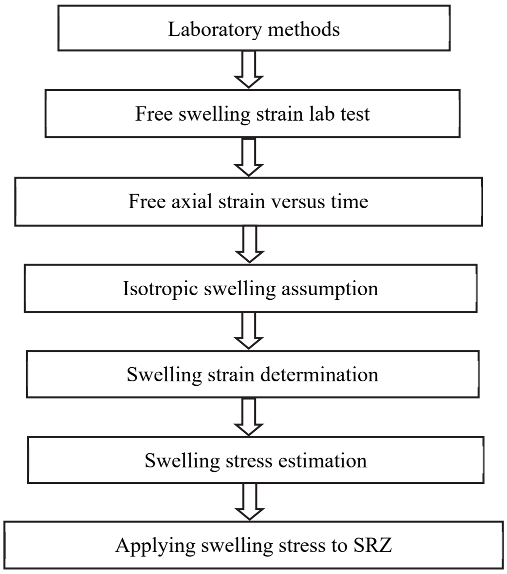


Fig. 4 Swelling stress estimation approach

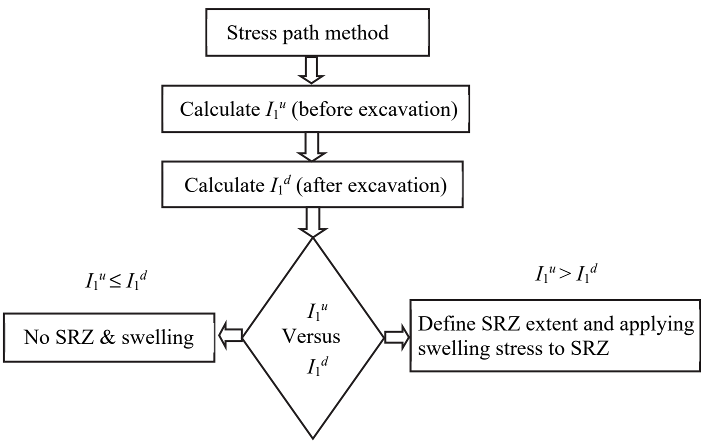


Fig. 5 Determination of SRZ which is the locations swelling stress apply

In order to apply swelling stress in the numerical model, we need to know the amount and location of swelling stress.

Amount of swelling stress is obtained from ISRM free swelling test and then Noorany (1999) approach is used to convert swelling strain to stress tensor. Besides, swelling stress is located by locating the stress relief zone following the approach suggested by Einstein (2000).

FLAC2D was used to run several models to simulate the swelling related stresses and study their effect on existing concrete segments. Comparing to other similar numerical codes available, FLAC was found to be advantageous in the sense that the user can write and change the code to perform a particular simulation (Itasca 2002). This is essential in this approach to apply pre-defined swelling stresses in the SRZ around the tunnel.

The objective of numerical simulations is first to determine the SRZ around the excavated section of the tunnel. The swelling strains estimated from the laboratory experiments in the previous section are then applied to the SRZ, to assess the corresponding increased stresses which may be applied to the support system.

Different methods can be used to apply the swelling stress on the stress relief zones. For instance, the total stress magnitude can be divided by the total number of numerical time-steps to obtain the portion of stress magnitude that should be applied at each time-step. This can be done using the Whilestepping FISH command in FLAC software. The other method is to divide the total computational time into a series of equal intervals, and then apply the proportional swelling stress magnitude on the model in each corresponding numerical interval. Also, when the swelling stress level is low, it can be applied to the model at the initial numerical step immediately after the excavation of the tunnel. The most crucial point that should be considered in all of these methods is that when the swelling stress magnitude is high, it is necessary to apply the incremental stresses gradually; and the incremental value should not exceed the strength yield limit of the rock mass. In order to dissipate the unbalanced forces caused by the stress increment from the numerical model, it should be cycled sufficiently to achieve a static equilibrium state. Also, in order to prevent any change in the stress relief zone, it is required to store its grid-points in a temporary file (called "Relief" in the codes) before applying the stress increments. This file can be restored later during the simulation to calculate the equivalent stresses from the volumetric swelling strains, and use them on the model.

4.1 SRZ Determination Using Stress Invariants

The microscopic analysis of the structure of swelling rocks before and after they undergo an increased volume indicates that the applied stress has a significant impact on swelling extent (Wong and Wang 1997).

The physicochemical swelling around a tunnel occurs in unloaded zones, *i.e.,* zones with relaxed stresses. The stress path, as introduced earlier, indicates the stress changes within the rock mass during an engineering activity (Barla 1999). The criteria which can be used to determine the SRZ is the stress invariants. The first stress invariant is defined as the sum of the normal stresses or three principal stresses, *i.e.*:

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \quad (1)$$

The SRZ is where I_1^d calculated from induced stresses (*i.e.,* after excavation) is lesser than that of calculated from stresses corresponding to the in-situ stresses, I_1^u, (*i.e.,* before excavation). Figure 6(a) shows the contours of I_1^u corresponding to an undisturbed zone, as an example. Swelling starts after excavation and as soon as a SRZ is developed around the tunnel. A proper simulation to investigate the effects of advancement of the tunnel face on SRZ and swelling requires the use of 3D models but 2D models can also be implemented with a reasonable accuracy. For example, Panet (2001) method can be implemented to study the effect of tunnel face advancement on swelling.

The developed code for FLAC simulation can estimate the extent of the SRZ and then apply the swelling strains to this zone. The Mohr-Coulomb failure criterion with tension cut-off was employed for the stability analyses. This failure criterion has been widely used to assess the stability of underground structures (Su *et al.* 2019). In this failure criterion, the yield envelope is $f(\sigma_1, \sigma_2) = 0$, and the following shear failure criterion characterizes the model behavior:

$$f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} \quad (2)$$

The tension cut-off ($f^t = 0$) is defined as follows:

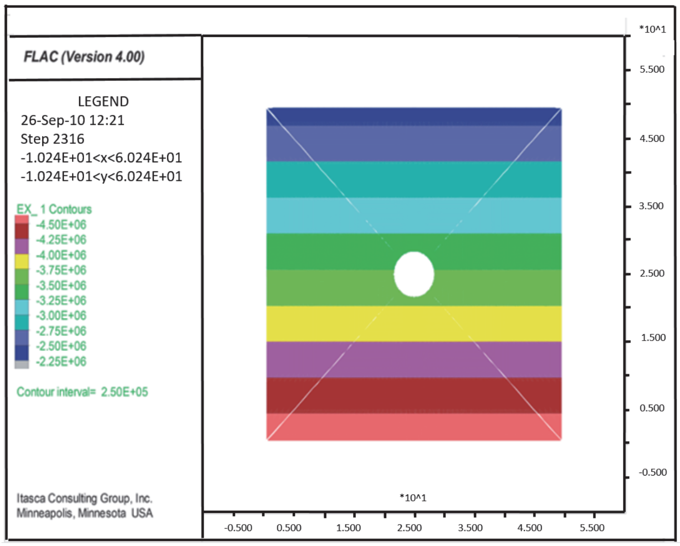
$$f^t = \sigma_3 - \sigma^t \quad (3)$$

where σ_1 and σ_3 are the first and third principle stresses, respectively; c and σ^t represent the cohesive and tensile strength of material, respectively; φ is friction angle; and N_φ is a constant value which can be obtained as follows:

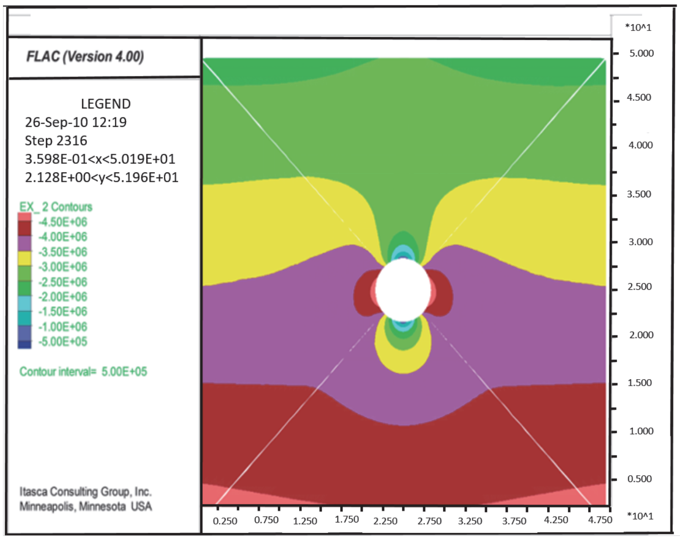
$$N_\varphi = \frac{1 + \sin\varphi}{1 - \sin\varphi} \quad (4)$$

For this purpose, at an in-situ state of stresses, the first stress invariant (I_1^u) is calculated and stored as variable Ex_1. The stress in each element of the model would be the summation of in-situ stresses along x, y, z axes. I_1^d will be calculated after excavation and when the model becomes stable (*i.e.,* the stresses are redistributed) and it is stored as variable Ex_2. The ID number of those elements which undergo stress relaxation is stored in a text file. This file will be called on when the stress difference corresponding to the swelling stresses are to be applied to the SRZ. The numerical results are illustrated in Fig. 6. Figure 6(a) illustrated the model state before excavation of the tunnel. In Fig. 6(b) the SRZ corresponding to a stress ratio of $K = 0.5$ is shown. This figure shows lesser values for the first stress invariant corresponding to the top and bottom of the tunnel section comparing to the sides.

Parameter Ex_3 is the ratio of Ex_2/Ex_1 and is an indication of the percentage of stress relaxation. Figure 7(a) shows the values of Ex_3 for the above example. It is important to note that as the volumetric strain obtained from free swelling strain is the strain calculated in the presence of no stresses, equally applying the stresses corresponding to this maximum strain to the entire SRZ is incorrect. Therefore, in this study, the swelling stress applied to each element was weighted based on the percentage of stress relaxation (Ex_3) in that zone. An elasto-plastic constitutive model is employed in this study. The swelling stress was applied to SRZ, which is the area around the tunnel with platic deformation. Notice that the magnitude of applied stress should not exceed the yield limit of the elements in SRZ. This was necessary to avoid abrupt failure of elements which were still in elastic state.



(a) Before excavation



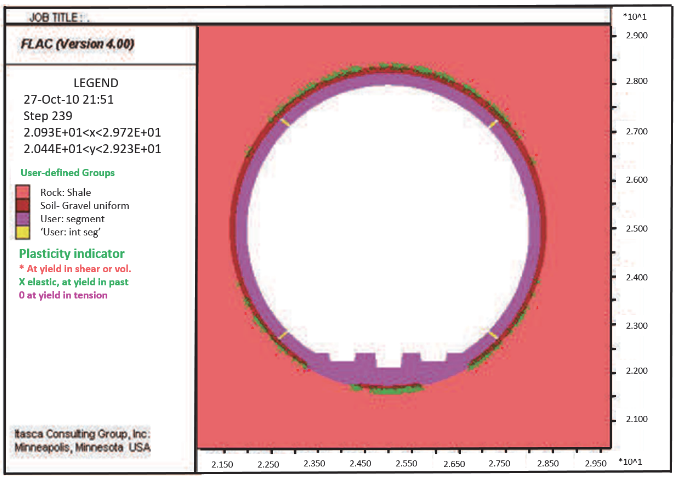
(b) After excavation

Fig. 6 The first invariant of stress

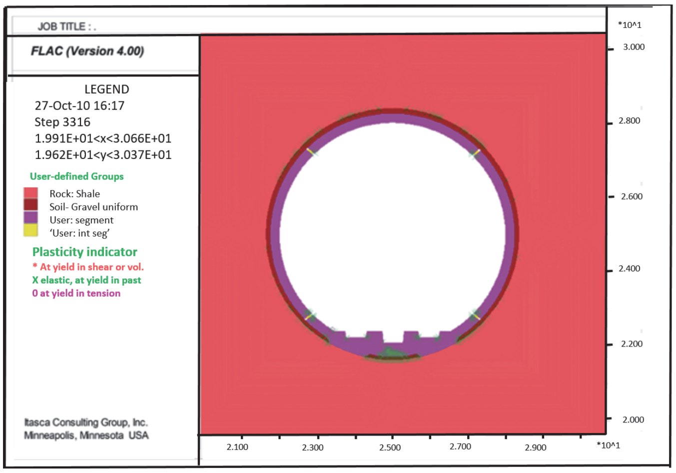
The swelling stress can be applied to the SRZ in one step when the stress level is low or in some steps if the load is large. Regardless of which approach is used, the high-stress levels should be applied gradually and must not exceed the yield strength of the rock mass.

4.2 Applying Swelling Strains in SRZ

As mentioned earlier, the ID of elements which are in the SRZ are stored in the text file, and they are recalled at this stage to subject them to stresses corresponding to the volumetric strains that these elements are exposed to. In doing so, the approach proposed



(a) After applying swelling stress



(b) After applying swelling stresses until failure

Fig. 7 Support system

by Noorany *et al.* (1999) was utilized in this study. To apply this method, an increase in volumetric strain in a certain region of the model will be simulated by changing the stress level within this region. To gain a volumetric strain (ε_{vol}) in a single element, the total stresses σ_x, σ_y, σ_z are to be increased as follows:

$$\Delta\sigma_x = -\left[K + \frac{G}{3}\right]\varepsilon_{vol} \tag{5}$$

$$\Delta\sigma_y = -\left[K + \frac{G}{3}\right]\varepsilon_{vol} \tag{6}$$

$$\Delta\sigma_z = -\left[K - \frac{G}{3}\right]\varepsilon_{vol} \tag{7}$$

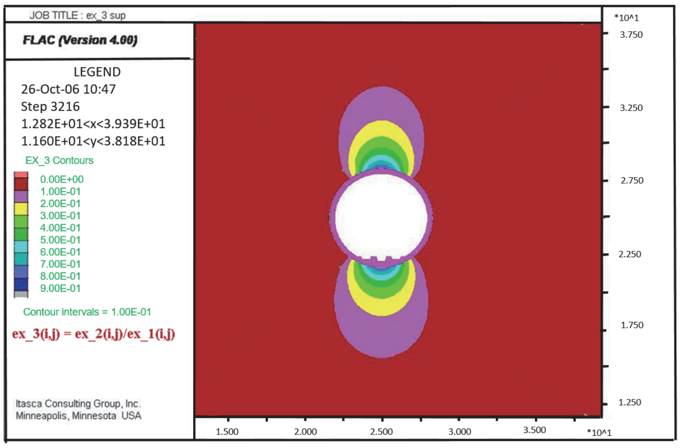
In these equations, K and G are the volumetric and shear modulus, respectively. The volumetric strain (ε_{vol}) estimated from free swelling strain test is 13×10^{-5}, which results in following stress increments: $\Delta\sigma_x = -2.8 \times 10^5$ Pa, $\Delta\sigma_y = -2.8 \times 10^5$ Pa, and $\Delta\sigma_z = -1.12 \times 10^5$ Pa.

As can be seen from Fig. 7(b), the support system is stable when it is subjected to these additional loads and, no plastic deformation is expected in the support material.

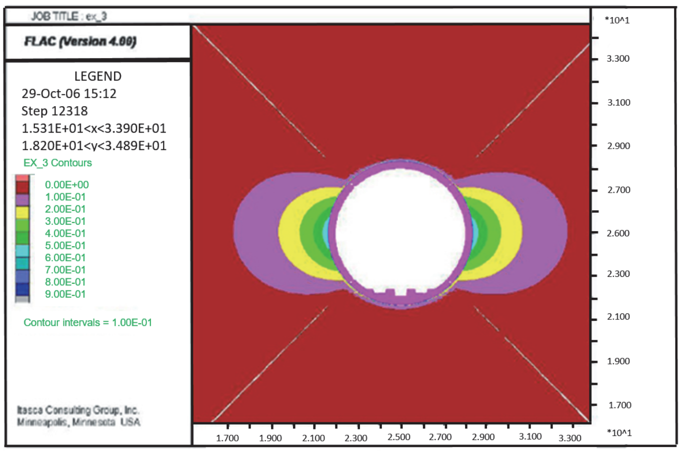
In the next step, to obtain an idea of the maximum swelling stresses that the support system can carry, the volumetric swelling strains were increased, and the stress concentration around the tunnel was monitored. It was observed, as shown in Fig. 8(a), that when the volumetric strains exceed 50×10^{-5}, plastic zones developed around the tunnel, and hence the swelling stresses corresponding to this strain could be considered as a limit for carrying capacity of the existing concrete segments in the Zagros tunnel. The stress increments corresponding to volumetric strains of 50×10^{-5} are calculated as: $\Delta\sigma_x = -10.7 \times 10^5$ Pa, $\Delta\sigma_y = -10.7 \times 10^5$ Pa, and $\Delta\sigma_z = -4.3 \times 10^5$ Pa.

4.3 Effect of Stress Ratio on Swelling

As mentioned before, the stress ratio in Zagros tunnel is around 0.5 and with this approach, the swelling pressures can be predicted around the top and invert of the tunnel (Fig. 8(a)). In this study, the swelling released stresses were assumed to be a function of the extent and location of the SRZ. However, this could be influenced significantly when the stress ratio (K) changes. To demonstrate this, in Fig. 8(b) the SRZ corresponding to $K = 2.0$ are plotted. Comparing this figure with Fig. 8(a) for $K = 0.5$, it may be seen that the strains are more likely to be applied to the concrete segments at the top and bottom of the section for $K = 0.5$ whereas it is the sides of the segment which will be more prone to swelling



(a) $K = 0.5$



(b) $K = 2.0$

Fig. 8 Stress relief zone after excavation

stress concentration when $K = 2.0$. Also, the displacements at the top and bottom of the support system due to swelling stresses become lesser when the stress ratio increases.

The increased pressure in invert and roof segment in Gurpi and Ilam contact zone with consideration of $K = 0.5$ may be related to SRZ in floor and roof of the tunnel section. This is mainly because when $K = 0.5$, stress concentration mainly happens in roof and floor and tunnel walls may experience relaxation (*i.e.,* stress relief) and, therefore, swelling stresses can be generated in tunnel sides. On the other way, when $K = 2.0$, swelling pressure can be built up on the roof and floor as these areas are likely to experience stress relaxation.

This outcome has been confirmed with field observation during the excavation of the tunnel with TBM. In Gurpi and Ilam contact zone, where the rock is easily exposed to groundwater, jamming of TBM was occurred due to heavy swelling pressure. As shown in Fig. 9, to rescue the TBM, the stresses around the TBM were released by manual excavation. The extreme swelling pressure was observed in TBM roof and floor. This is consistent with the results of numerical modelling since generally K value in the tunnel is equal to 0.5.

Fig. 9 Swelling pressure encountered at the top and bottom of the tunnel cross section ($K = 0.5$)

5. CONCLUSIONS

In this paper, the swelling stresses induced in shale formations in Zagros tunnel is studied. Free swelling strain lab experiments were carried out to estimate maximum expected swelling strains. It was discussed that the physicochemical swelling is related to the swelling minerals content, water absorption, and stress path around the tunnel: and therefore, the first stress invariant (I_1) was used as a criterion to identify the areas that stress relaxation has taken place. The SRZ was also considered as those points where I_1 after excavation is lesser than that of before excavation. The swelling induced stresses estimated in Zagros tunnel at specific sections where it intersects swelling layers of Gurpi formation was applied to the estimated SRZ. The results indicated that the swelling pressure in K ratio equals 0.5 occur at the top and bottom, and it is consistent with the field observations of swelling in Zagros tunnel at the contact of Gurpi and Pabdeh formations.

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DATA AVAILABILITY

This study does not generate new data and/or new computer codes.

CONFLICT OF INTEREST STATEMENT

The authors certify that there is no conflict of interest.

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