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"Research Note"

NUMERICAL ANALYSIS OF FAULT BEHAVIOR NEAR UNDERGROUND EXCAVATIONS*

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Abstract– In this paper, the behavior of a fault is studied using a constant strain joint model. A combination of slider and spring is used to simulate the shear behavior of faults in the plastic region in contrast to the previous models that have only used an elastic shear spring. Furthermore, the proposed joint element was used to study the behavior of a fault crossing a tunnel regarding the represented shear plastic and dilation behavior of this joint element, and for this purpose a Matlab based program called FEAFB (Finite element analysis of fault behavior) has been developed. The corresponding normal and shear stresses, shear strengths and the factors of safety, for different horizontal to vertical stress ratios and shear stiffness are analyzed and compared to the results of a similar modeling in UDEC program. The analysis indicates that the normal and shear stresses, and the shear strength are increased in the fault elements near the tunnel, and they are decreased in the elements becoming far from the tunnel surface. However, the safety factor can either increase or decrease as it becomes closer to the tunnel surface, depending on the horizontal to vertical stress ratio. Moreover, it is also shown that safety factor depends upon the shear stiffness, i.e., as shear stiffness increases, shear stress increases, and as a result, the safety factor decreases.

Keywords– Fault, joint element, dilation, finite element, tunnel

1. INTRODUCTION

Discontinuities, such as cracks, joints and faults, play a significant role in the behavior of rock masses and can alter the distribution of stresses and deformations. The effect of discontinuities, particularly faults, where passing near a tunnel may influence the stability of the tunnel dramatically; hence, consideration of the fault effects on the stability analysis and design of tunnels is of paramount importance.

In this paper, a joint element, depicted in Fig. 1, is presented which is based on the finite element method, and consists of two double nodal linear elements. This joint element includes a normal spring which models a normal stiffness of K_n, and is connected to a no-tension element,. Moreover, the elastic shear behavior of the fault is modeled by an elastic shear spring with stiffness $K_{1,}$

The main contribution in this study is the modeling of the plastic shear behavior of the fault with combination of an additional shear spring and a slider to represent the shear and dilation behavior of the fault while asperities sheared off in contrast to previous models which have considered only an elastic shear stiffness. This new element is used to analyze the shear and normal stresses, shear strength, and the safety factor of a fault in the vicinity of a tunnel. The analysis is based on the Ladanyi-Archambault failure criterion.

Goodman and Taylor [1] were the first authors who modeled the shear and normal behavior of a discontinuity using a joint element, based on finite element method, but this model is basic and only an elastic shear spring has been applied, however, it has some limitations on the problem geometry and boundary conditions which can result in numerical difficulties.

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Fahimifar [2] used the joint element proposed by Goodman [1] for analysis of jointed rock specimens under triaxial loading condition, numerically. He also studied the effects of schistosity of a typical rock (Isfahan schist) experimentally for various anisotropic angles [3]. The effects of joint orientation on the stress and strain properties of jointed specimens and the time influence on the rock joints were also investigated by Fahimifar [4 and 5].

J. G. Wang et al presented a constitutive model to predict the behavior of rock joints based on limit concept. This interface model employs a non-proportional ellipse yield function that is different from other yield functions adopted in soil mechanics. The shear behavior in this model transfers to residual after elastic stage [6].

More recently, J. H. Wu et al simulated the mechanical behavior of inclined jointed rock masses using Discontinuous Deformation Analysis (DDA) during tunnel construction. In this analysis, the stress distribution and surface subsidence near inclined jointed rock masses are investigated. The inclined rock joints have been modeled using an elastic normal spring and an elastic-residual shear spring [7].

2. MODEL DEFINITION

The model depicted in Fig. 1 is proposed by the authors to study the normal, shear, torsion, and dilation behavior of a discontinuity of length L. The constant strain joint element is composed of two double nodal line elements [8].

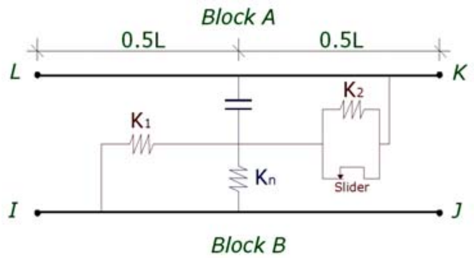

Fig. 1. The proposed joint model [8]

The normal behavior is modeled with a spring in the normal direction that provides normal stiffness (K_n) in compression while having no tension strength. Moreover, an elastic shear spring with stiffness of K_1 is used in combination with another shear spring of stiffness K_2 and a slider (Mandel Model) to model shear behavior of the joint element. Using this combination, the presented joint element is capable of modeling the plastic regime of the shear behavior of a joint to simulate breaking of the asperities, and therefore, the plastic and the residual phases are considered for the shear behavior of a fault in this joint model. It is worthy to mention that in the previous model presented by Goodman, the shear behavior is demonstrated only by a shear spring for the elastic part [1and 8].

This joint element is able to model the plastic behavior of a discontinuity such as a fault by a combined analytical-numerical approach, and based on the fact that the material property matrix does not have any off-diagonal coefficient. So, the possibility of numerical ill-conditioning of stiffness matrix which might occur because of very large off-diagonal terms or very small diagonal terms reduces considerably. Also, dilation is considered in this model in comparison to the previous models (such as Ghaboussi et al. [9]).

3. MECHANICAL BEHAVIOR OF THE JOINT

Normal, shear, dilational behavior and failure criteria of a joint play a significant role in its numerical analysis. Therefore these are explained in this section and the related formulas are presented. Figure 2 represents the normal, shear and dilational behavior of a joint.

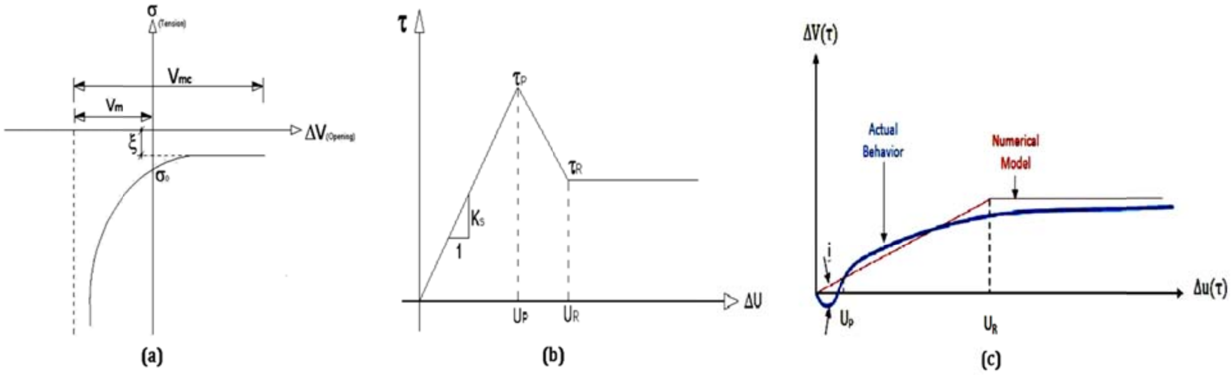

Fig. 2. Mechanical behavior of a joint element (a) Normal Behavior
(b) Shear behavior (c) Dilational Behavior [10]

The joint behavior diagram under vertical stress is shown in Fig. 2a. The normal stress σ_n, the seating pressure ξ defining the initial condition for measuring the normal deformation, the joint vertical displacement ΔV, and the maximum value of joint closing V_m due to initial stress are related according to Eq. (1). Meanwhile, normal stiffness is computed according to Eq. (2), and depends on the initial normal stress σ_0 and the maximum closing of the joint V_{mc} [10].

$$\sigma_n = \left(\frac{\Delta V}{V_m - \Delta V} - 1\right)\xi \tag{1}$$

$$K_n = \frac{-\sigma_0{}^2}{\xi \times V_{mc}} \tag{2}$$

The idealized model for shear behavior is as shown in Fig. 2b [10]. The model includes an elastic stage with slope K_s. When shear stress reaches its peak value τ_P, the asperities on the fault surface start to shear off. As displacement increases, the roughness of the fault surface reduces until the shear stress drops to the residual stress called τ_R. Beyond that point, the shear stress remains constant as displacement increases [11].

To consider the shear behavior of the fault, a composition of two springs and a prefect plastic slider is used in which the slider ultimate strength is defined equal to the peak shear stress of the fault (τ_P). The stiffness of the spring 1 is equal to K_s, and the stiffness of spring 2 is calculated using equation 3, where $K_{P\text{-}R}$ is the gradient of the plastic part of shear behavior diagram in accordance with Eq. (4). In the proposed combination, the slider has a solid behavior before reaching the peak shear stress (τ_P); consequently, the spring 2 does not affect the model; and so the overall stiffness of the joint element in the elastic part is equal to the stiffness of spring 1. In the proposed joint model, after reaching the peak shear stress, the indicated slider becomes plastic and starts to displace. As a result, the shear stiffness equal to $K_{P\text{-}R}$ is applied to the system by both springs in the presented combination and in this way, the plastic regime of the shear behavior is simulated. [8]

$$K_2 = \frac{K_s \times K_{P-R}}{K_s - K_{P-R}} \tag{3}$$

$$K_{P-R} = \frac{\tau_P - \tau_R}{U_R - U_P} \tag{4}$$

The peak shear stress (τ_P) and the residual shear stress (τ_R) are calculated according to Eqs. (9) and (5), respectively, where B_0 is the ratio of peak shear stress to residual shear stress at low normal stresses. Moreover, U_P is the relevant displacement for the peak shear stress and U_R is the relevant displacement for the residual stress that was defined earlier. U_R is calculated using Eq. (6), where M is the ratio of the displacement corresponding to the peak shear stress (U_P) to the displacement relevant to residual stress (U_R). The magnitudes B_0 and M were selected 0.6 (according to Goodmans's suggestion [10]) and 1.5 (according to Indraratna & Haque [12]), respectively.

$$\tau_R = \tau_P \left(B_0 + \frac{1-B_0}{q_0} \sigma \right) \tag{5}$$

$$U_R = M \times U_P \tag{6}$$

The dilation behavior of the joint must be defined based on the relations (7) and (8). These equations are based on the simplifications being made in Fig. 2c, where σ_n is normal stress, q_u is unconfined compressive strength, i is dilation angle, ΔU is shear displacement, U_R is the displacement relevant to the residual stress τ_R, τ and K_s are shear stress and shear stiffness, respectively [10].

$$\Delta V_i(\tau) = \left(\frac{\sigma_n}{q_u} - 1\right)^4 \tan i \left(|\Delta U| + \left|\frac{\tau}{k_s}\right| \right) \quad \text{for} \quad u_R(-) \le \Delta U \le u_R(+) \tag{7}$$

$$\Delta V_i(\tau) = \left(\frac{\sigma_n}{q_u} - 1\right)^4 \tan i \left(u_R(+) + \left|\frac{\tau}{k_s}\right| \right) \quad \text{for} \quad u_R(-) \ge \Delta U\,,\ \Delta U \ge u_R(+) \tag{8}$$

It is assumed that sliding along the fault will begin at the peak shear strength of the fault. Therefore, accurate definition and determination of this parameter is very important. For this purpose, a non-linear failure criterion presented by Ladanyi-Archambault is chosen according to Eq. (9):

$$\tau_P = \frac{\sigma(1\text{-}a_s)\cdot(\dot{V} + \tan\varphi) + a_s \cdot S_R}{1\text{-}(1\text{-}a_s) \times \dot{V} \times \tan\varphi} \tag{9}$$

In this equation, σ is the initial normal stress of the fault, a_s is the proportion of joint area sheared through the asperities, $\dot{V}$ is the dilation rate at the peak shear stress, φ is the friction angle and S_R is shear strength of the rock material [13].

4. APPLICATION OF THE PROPOSED MODEL IN ANALYSIS OF FAULT BEHAVIOR CROSSING A TUNNEL

In this section, the model described above is applied to study fault behavior passing through a tunnel (see Fig. 3a). A computer program was developed using MATLAB software called FEAFB (Finite Element Analysis of Fault Behavior) based on the finite element method. This program performs the analysis on the basis of the joint model presented in Fig. 1. However, it is required to input the geometry of the model, number of elements and nodes, type of elements and their initial stresses. This process is prepared in a pre-modeling using ABAQUS program and is linked to FEAFB.

a) Material properties

Rock properties were selected as presented in Table 1, whereas the fault properties were presented in Table 2. It should be noted that rock mass is assumed elastic and isotropic since analysis of rock behavior is not the major purpose in this paper.

Table 1. Geotechnical properties of the intact rock surrounding the tunnel

Density (Kg/m^3)	Modulus of elasticity , E (GPa)	Poisson `s ratio, υ	Tensile strength (MPa)	Friction Angle, φ (degree)	Cohesion, C (MPa)
2600	20	0.25	3	45	8

Table 2. Geotechnical properties of the fault

q_u (MPa)	Tensile Strength (MPa)	Shear Stiffness, K_s, (GPa)	Dilation angle, i (degree)	Friction Angle, φ (degree)	Cohesion, C (MPa)	V_{mc} (m)	ξ (MPa)
100	0	0.2	9	35	0	0.01	0.05

b) Geometry and model description

The angle of the fault in this model is equal to 75 degrees to the horizontal. Moreover, the radius of the tunnel is equal to 5 meters, while it is located in the center of a 100×100 meter block. Subsequently, the horizontal displacement of the block has been constrained on the left and right sides. It is interesting to note that the center of the tunnel is located at a depth of 380 meters, where the vertical stress is almost 10 MPa and the ratio of horizontal to vertical stresses (K) is considered 0.5,1 and 2(Fig. 3).

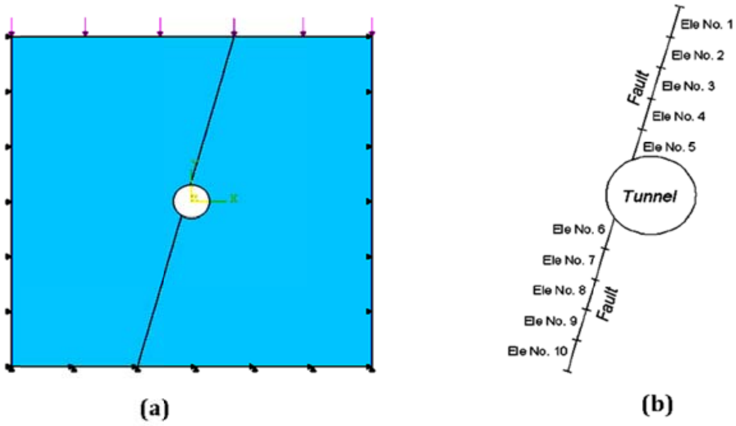

Fig. 3. (a) Fault model crossing the tunnel (b) Element numbers of the fault crossing the tunnel

5. NUMERICAL RESULTS

For the purpose of studying the effect of a fault crossing a tunnel using the proposed model, normal stress (σ), shear stress (τ), shear strength (τ_p) and factor of safety (Ratio of τ_p to τ which named safety factor) corresponding to 10 elements (Fig. 3b) were calculated using FEAFB program. The results obtained were compared with the results using UDEC program (Version 4.00).

Figure 4 shows the calculated parameters with shear stiffness equal to 0.2 GPa, and for horizontal to vertical stress ratios (K) equal to 0.5, 1 and 2, respectively, through the analyses performed using the FEAFB program and UDEC code. As it is observed, the results are similar. The difference between the results is mostly due to the difference of joint lengths in UDEC and FEAFB. Furthermore, Mohr-Coulomb failure criterion was used in UDEC, whereas in FEAFB program, Ladanyi-Archambault relation was used as the failure criterion.

It is observed that the magnitude of normal stress in the elements nearer to the tunnel surface is higher than that in the far elements. It may be due to the decrease in the confinement effect and lack of triaxial condition nearer the tunnel surface. Furthermore, the calculated normal stress increases with increase in K, because the horizontal stress affecting on the fault elements increases. However, it depends on the fault angle and will be different in various angles.

Meanwhile, the shear stress in the top of the tunnel decreases in the elements near the tunnel surface and increases in the bottom of tunnel in the similar elements. The direction of shear stress changes with increase in K since the greater stress will be vertical for K=0.5, and when K is equal to 2, the greater component will be horizontal. It is important to mention that while the horizontal and vertical stresses are equal, the shear stress behavior in the elements on the top and bottom of the tunnel is the same, and even the corresponding shear stress values are approximately equal.

It is also observed that the shear strength magnitudes obtained through the FEAFB program are greater than the corresponding values in UDEC program. It is implied that Ladanyi-Archambault criterion leads to higher values in contrast to Mohr-coulomb criterion. Moreover, it is seen that normal stress increases considerably as K increases, however, they decrease by becoming far from the tunnel surface and then approach a constant value.

When K is equal to 0.5 and 2, safety factors in the fault elements near the tunnel surface have higher values than the elements that are far from the tunnel surface; however, for the case of equal horizontal to vertical stresses (K=1), safety factor reduces as it approaches to the tunnel surface and there are lower safety factors near the tunnel. But, the safety factor is generally higher for values of K=1 in comparison to the values of K opposite to unity. It should be noticed that, the elements near the tunnel surface (elements 5 & 6) have minimum safety factors for the condition of K=1 but these safety factors are still greater than the safety factors for the condition of K opposite to unity. This may be attributed to the fact that for the condition of K=1, deviatoric stresses tend to zero.

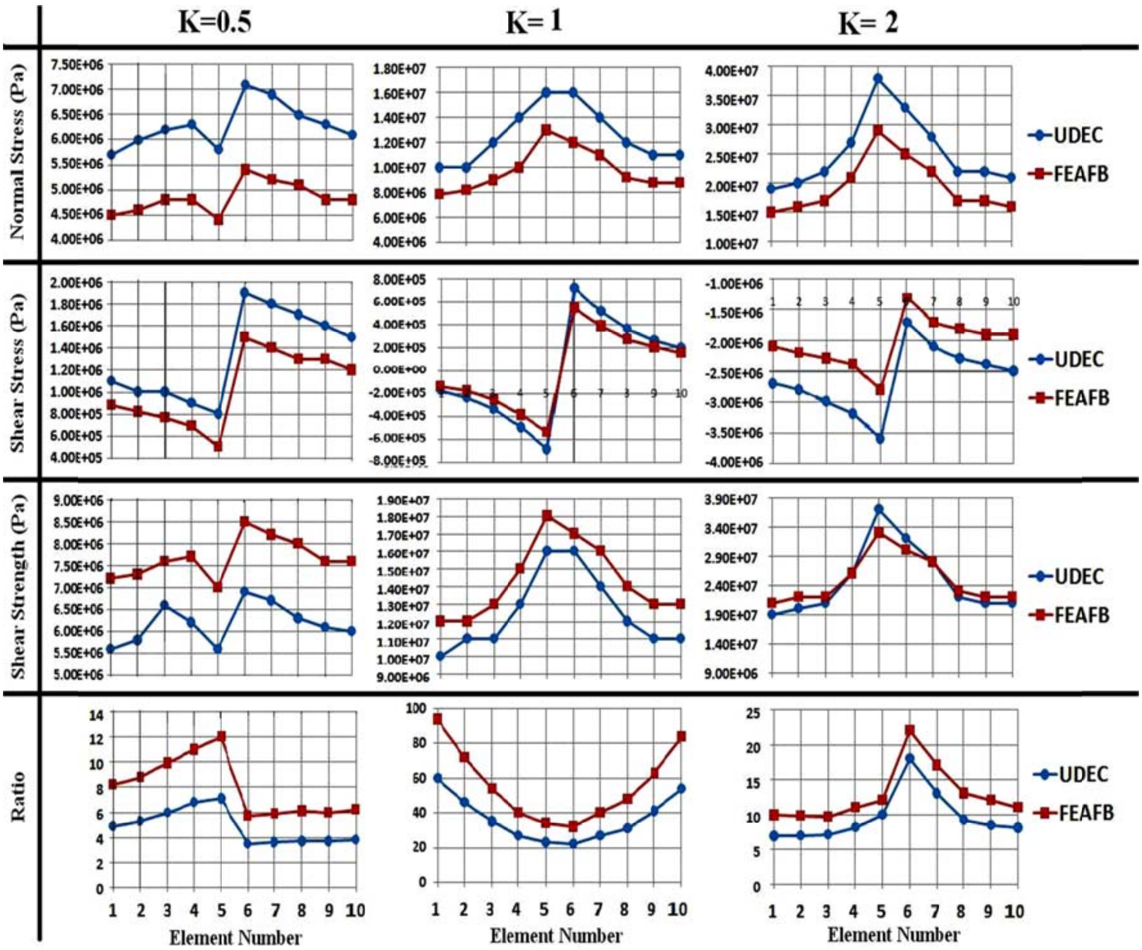

Fig. 4. Results of analyses for a fault with shear stiffness of 0.2 GPa

6. SUMMARY & CONCLUSIONS

A new joint model was presented for fault analysis. This constant strain joint element uses a combination of a slider and a shear spring to model the shear behavior in the plastic region regarding shearing of the asperities. Furthermore, the effect of dilation is considered in the proposed joint element. A computational efficient software was developed for the numerical analysis based on the proposed model, and the behavior of a fault crossing a tunnel was analyzed for different horizontal to vertical stress ratios. The results are consistent with a similar modeling in UDEC. The results reveal that the combination of a slider and a shear spring provides more accurate results for the plastic region compared to the other joint models which only use an elastic shear spring.

The normal and shear stresses and shear strength have higher values in the fault elements near the tunnel surface. This is because of the uniaxial condition of the fault elements adjacent to the tunnel surface, while there is a triaxial condition in the other points. It is interesting that shear stress is higher where the in-situ horizontal to vertical stress ratios are equal. But safety factor depends on the horizontal to vertical stress ratio and decreases as it becomes far from the tunnel surface, however, the horizontal to vertical stress ratio is not equal to unity. Nevertheless, its values generally are higher than the relevant values, where the horizontal to vertical stress ratio is not equal to 1.

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