Post-peak roughness degradation model based on Barton-Bandis criterion for rock joint

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Abstract Based on the non-linear shear behaviour obtained by many researchers’ direct shear test, an exponential degradation model about the joint roughness is introduced into Barton-Bandis shear strength criterion to describe the non-linear post-peak shear behaviour. In the degradation model, the joint roughness coefficient ($JRC$) gradually decreases with the shear displacement to account for asperity degradation during shear process, and the decay rate decreases. Finally the $JRC$ falls to a constant value that corresponds to the residual shear resistance of the joint and the decay rate decreases to zero. At last, the model is used to fit experimental data for different materials of joints, and the high fitting accuracy shows its validity.

1. Introduction

Rock mass is composed of rock and discontinuity networks. Discontinuities usually contain bedding planes, faults, fractures, joints and other mechanical defects. Mechanical properties of rock masses are sharply influenced by their discontinuity shear strength. So, it has great theory significance and engineering application value to study the shear strength criterion of rock discontinuities, especially the joints between rocks. Direct shear test is usually adopted to research the shear properties of the rock joints.

Under constant and static load conditions, there have been several joint constitutive models describing the relationship between the shear stress and shear displacement. According to the direct shear test, Bandis(1983) and Kana(1996) proposed shear constitutive models about the relationship between the shear stress and shear displacement before the post peak strength. For the first time, Saeb and Amadei(1992) used piecewise linear functions to describe the shear stress-displacement relationship in the whole shear process, while this linear model can’t express the nonlinear mechanical behaviour of the joint deformation. Simon(1999) proposed a CSDS model(complete stress-displacement surface model) to describe the shear stress-displacement relationship with a simple exponential function in the whole shear process, which describes the piecewise discussion, but the parameters are hard to calculate and it’s not applicable in the engineering. Grasselli (2003) presented that hyperbolic function can well fit the post-peak strength attenuation curve based on the actual shear test.

Barton (1973) presented an empirical non-linear criterion of peak shear strength; in this criterion, the joint roughness was adopted to study the shear behaviour of the joint between rocks. In his later research, he recommended the use of mobilized roughness in the shear strength criterion and the value
of $JRC$ was gradually decreased to account for asperity degradation during shear process. In this paper, an exponential function is used to describe the joint roughness degradation, so as to describe the non-linear post-peak shear behaviour of rock joint.

2. The roughness degradation model based on Barton-Bandis criterion

Based on the direct shear tests, Barton (1973) proposed an empirical non-linear criterion of peak shear strength

$$\tau = \sigma_n \tan \left[ JRC \log_{10} \left( \frac{JCS}{\sigma_n} \right) + \phi_r \right]$$

(1)

Where $\sigma_n$ denotes the effective normal stress acting on the joint, $\phi_r$ denotes the residual friction angle of the joint, which equals to the base friction, $JRC$ is the joint roughness coefficient which varies from approximately 0 to 20 from the smoothest to the roughest end of the spectrum, $JCS$ denotes the effective joint wall compressive strength, $\tau$ is the peak shear strength.

Barton and Bandis (1982) suggested the concept of roughness mobilization, recommended the use of mobilized roughness $JRC_m$ in Eq. (1), and derived an expression for the mobilized shear strength

$$\tau_m = \sigma_n \tan \left[ JRC_m \log_{10} \left( \frac{JCS}{\sigma_n} \right) + \phi_r \right]$$

(2)

The value of $JRC_m$ is gradually decreased to account for asperity degradation during the shear process. Barton presented that the ratio of $JRC_m/JRC_p$ is a function of the ratio of current shear displacement to peak shear displacement, $d_s/d_{s,p}$, which means $JRC_m$ can be expressed as a function of the current shear displacement $d_s$. Here, $JRC_p$ is the peak joint roughness value before asperity degradation.

Yerro et al. (2016) introduced a strain-softening Mohr–Coulomb model to examine the stability conditions and the post-failure behavior of a compound landslide, in this model, the state parameters (cohesion $c$ and friction angle $\phi$) decrease exponentially with the accumulated deviatoric plastic stain invariant. In this work, we employ the softening rules to describe the joint roughness degradation

$$JRC_m = JRC_r + \left( JRC_p - JRC_r \right) e^{-\eta(d_s - d_{s,p})}$$

(3)

where $JRC_r$ is the residual joint roughness, $\eta$ is a shape factor to control the rate of $JRC_m$ decrease. This model requires the specification of peak and residual joint roughness ($JRC_p$, $JRC_r$) and a shape factor $\eta$ in calculation.

Before the sliding of the rock joint, a small linear elastic deformation stage is considered normally, in the stage, the shear stress can be expressed as

$$\tau = k_s d_s$$

(4)

and the elastic shear stiffness of the joint is derived

$$k_s = \frac{\tau_{s,p}}{d_{s,p}}$$

(5)

where $d_{s,p}$ denotes the peak shear displacement when the shear force reaches the peak shear strength, $\tau_{s,p}$. When the shear force grows and becomes larger than the peak shear strength ($\tau > \tau_{s,p}$), the joint starts to slide. The shear force of the joint will be computed by the improved Barton-Bandis model in which the exponentially displacement dependent $JRC_m$ is used. The typical shear stress-displacement curve with the $JRC$ degradation model is shown in Fig. 1. Comparing the curves 1, 5 and 6, with the same $JRC_p$, $JRC_r$ and $\eta > \eta_i > \eta_6$, the higher the shape factor, the larger the loss in strength, the stress will reach the residual shear strength more fast. Comparing the curves 1 and 2, the higher the elastic shear stiffness $k_s$, the smaller the peak shear displacement $d_{s,p}$ when $JRC_p = JRC_r$, that is the roughness degradation is not considered, this model is equivalent to the traditional B-B shear strength criterion,
as plotted with curve 4. When the degradation is small, the stress-displacement curve is shown like curve 3, the shape of the curve is relatively flat.

3. Validation of the roughness degradation Model

Lee et al. (2001)’s direct shear test model for rock joints under shear loading and constant normal stress is employed in this study. Two tests are selected from Lee et al. (2001)’s study to examine the validity of the proposed model, one test is granite joint under the normal stress of 1 MPa, the other test is marble joint under the normal stress of 0.5 MPa. The parameters used in the calculation are listed in Table 1, referring to the Ma et al. (2017)’s paper.

| Rock type  | JCS(MPa) | JRCp | ϕr(°) | σn(MPa) | τp(MPa) | ds,p(mm) | Rn(N)  | ks(N/m) |
|------------|---------|------|-------|---------|---------|---------|--------|---------|
| Granite    | 151     | 12.8 | 34.6  | 1       | 1.92    | 1.25    | 1e5    | 7.68e7  |
| Marble     | 72      | 12.9 | 72    | 0.5     | 1.13    | 0.3     | 5e4    | 1.888e8 |

3.1 Validation against shear behaviors of rough granite joint

Lee et al. (2001)’s test results for granite joints under the normal stress of 1MPa is presented in Figure 2. According to the experimental data, the mobilized joint roughness $JRC_m$ after sliding is back-calculated by the Eq. (2), which are shown as the red triangular marks in Figure 3. Then based on the exponentially degradation model proposed in Eq. (3), $JRC_m$ is derived as a function of the current shear displacement $d_s$, see in Eq. (6), which is fitted by the test results and is plotted in Figure 3 with blue line. The correlation coefficient $R$ is 0.909.

$$JRC_m = JRC_r + \left( JRC_p - JRC_r \right) e^{-\eta(d_s - d_{s,r})}$$

$$=2.656 + (12.8 - 2.656) e^{-0.788(d_s - 1.27)}$$

$$R=0.909$$

Then the fitting function $JRC_m$ is substituted into the Barton-Bandis shear strength model in Eq. (2), the shear stress related to shear displacement is obtained, as shown in Figure 4 in blue line. Figure 4 shows that a very good agreement is presented between the numerical simulation results and the experimental results, the proposed model successfully reproduces the peak shear stress and the residual shear stress, and the mobilized shear stress variations are quite consistent.
Figure 2. Experimental shear stress versus shear displacement curves for the granite joint (Lee et al., 2001).

Figure 3. Experimental and fitting joint roughness versus shear displacement curves for the granite joint.

Figure 4. Shear stress versus shear displacement curves for the granite joint.
3.2 Validation against shear behaviors of rough marble joint

Figure 5. Experimental shear stress versus shear displacement curves for the marble joint (Lee et al., 2001)

Figure 6. Experimental and fitting joint roughness versus shear displacement curves for the marble joint.

Lee et al. (2001)’s test results for marble joints under the normal stress of 0.5MPa is presented in Figure 5. According to the experimental data, the mobilized joint roughness $JRC_m$ of the marble joint after sliding is back-calculated by the Eq. (2), which are shown as the red triangular marks in Figure 6. Then based on the exponentially degradation model proposed in Eq. (3), $JRC_m$ is expressed as a function of the current shear displacement $d_s$, see in Eq. (8), which is fitted by the experimental results and is plotted in Figure 6 with blue line. The correlation coefficient $R$ is 0.9595.

The shear stress versus shear displacement curves obtained by the numerical simulation and shear test are also compared, as shown in Figure 7. It can be seen that a very good agreement is presented between the results calculated by the proposed model and the experimental results as well.

$$JRC_m = JRC_r + (JRC_p - JRC_r) e^{-pd_s}$$

$$= 3.575 + (12.9 - 3.575) e^{-0.4164(d_s - 0.268)}$$

$$R=0.9595$$
4. Conclusions
According to the experimental results of the direct shear test to the rock joint, the non-linear shear behaviour after the peak shear strength is usually observed, and the shear stress will fall to a constant value. Based on the non-linear shear behaviour, an exponential degradation model about the joint roughness is introduced into Barton-Bandis shear strength criterion to describe the non-linear post-peak shear behaviour. Two test results of the rock joint are employed to validate the proposed model and a very good agreement is obtained between the numerical results and the experimental results, which verifies the effectiveness of the roughness degradation model in describing the joints’ non-linear post-peak shear behaviour.

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