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NUMERICAL MODELLING OF CYCLIC SHEAR BEHAVIOUR OF ROCK JOINTS UNDER CONSTANT NORMAL STIFFNESS CONDITION

Ali Mirzaghorbanali and Jan Nemcik

ABSTRACT: The cyclic shear behaviour of rock joints was investigated in the laboratory under constant normal stiffness condition for low and high values of initial normal stress and asperity angle. The Universal Distinct Element Code was applied (UDEC) to simulate the laboratory behaviour using two available models. The predicted shear stress, normal stress, and dilation with shear displacement were compared with experimental results. It was observed that the change in the shear strength and recovery of dilation upon load reversal are simulated using the Coulomb Slip model for low values of initial normal stress and asperity angle when the shearing mechanism was sliding over asperities. However, the Continuously Yielding model replicated better cyclic shear behaviour of rock joints under breaking mechanism (i.e. high levels of initial normal stress and asperity angle), as this model represents progressive damage of asperities during shearing and approaching to the residual friction angle when asperities are fully degraded.

INTRODUCTION

Designing of open cast and underground mining, construction of dams, and slope movements can be strongly influenced by the presence of joints within a rock mass. In this sense, a correct evaluation of the mechanical behaviour of joints and discontinuities including the stress-displacement relationship is imperative to simulate behaviour of a rock mass.

Patton (1966) was among the first researchers to systematically study the effect of joint asperity on the shear behaviour of rock joints and proposed a bilinear shear strength criterion. Jaeger (1971) replaced the bilinear form of Patton's with a non-linear function and introduced a new failure criterion. Barton (1973) performed an extensive number of laboratory tests on three dimensional joints and introduced a peak shear strength criterion incorporating the concept of joint roughness coefficient.

Barton (1976) modified the concept of joint roughness coefficient and introduced the mobilized roughness coefficient to capture the effect of asperity damage as a function of the normalized shear displacement. The continuously yielding model was proposed by Itasca Consulting Group (Cundall and Hart, 1984) to provide a coherent and unified discontinuity deformation and strength model for joints undergoing both elastic and plastic deformations. An effective mechanical model was introduced by Plesha (1987) who assumed sliding occurs along an inclined asperity angle degraded exponentially due to the plastic shear work. Gens et al. (1990) developed an elasto-plastic constitutive model for rock joints considering a hyperbolic yield function. In another study of shear behaviour of rock joints, Roosta et al. (2006) introduced an elasto-plastic constitutive model in a multi laminate framework.


Among the above mentioned models, the Continuously Yielding (CY) model along with the conventional Coulomb Slip (CS) criterion are extensively applied to simulate the shear behaviour of rock joints within the rock mass due to their simplicity and availability in Universal Distinct Element Code (UDEC). This study is an attempt to investigate the capabilities of CS and CY models in simulating the cyclic shear behaviour of rock joints under CNS conditions. Firstly, the results of large scale cyclic direct shear tests conducted on artificial rock joints for low and high values of initial normal stress and asperity angle under...
constant normal stiffness condition are presented. Subsequently, the UDEC code is applied to model the observed laboratory behaviour using CS and CY constitutive models.

SPECIMENS, TEST APPARATUS, AND EXPERIMENTAL PLAN

The joint surface was prepared based on a regular triangular saw tooth shape with inclination angles equal to 9.5° and 26.5°. The joint surface area for the prepared samples was 187.45 cm² (250 x 75 mm) with a total of 8 asperities (30 mm long) in the direction of shearing. A close view of the prepared sample with initial asperity angle equals to 26.5° is shown in Figure 1.

In this study, high strength Gypsum plaster (CaSO₄.H₂O hemihydrates, fraction of CaSO₄ to H₂O = 3.5:1) was used to mould the artificial rock joints. This material can take any desired shape when mixed with water and the long term strength is independent of time once the chemical hydration is complete. The initial setting time of plaster is about 25 min. Furthermore, the cured plaster mix shows a repeatable uniaxial compressive strength in the range of 60 MPa which is comparable to many sedimentary rocks. Testing on planar joints with the Gypsum Plaster showed a basic friction angle of approximately 35°.

The large scale cyclic direct shear tests were conducted at the rock mechanics laboratory of University of Wollongong. The CNS direct shear apparatus (Figure 2) consists of two boxes, one of size of 250 mm in length, 75 mm in width and 150 mm in height, at the top and the other of size 250×75×100 mm, at the bottom. The bottom box is fixed on a rigid base by bearings and can only move horizontally. The top box can only move in the vertical direction along which the stiffness is kept constant by a set of springs simulating the normal stiffness of surrounding rocks. The desired initial normal stress is applied via a hydraulic jack located at the top of the apparatus where the applied load is measured via a calibrated load cell. The cyclic shear load is applied via a hydraulic actuator which is connected to the controller unit. The applied cyclic shear load is recorded via strain meters fitted to a load cell. Finally, the desired rate of cyclic displacement can be set by the controller unit.

Low and high values of initial normal stress (0.56 and 2.4 MPa) were applied to the samples. The specimens were sheared cyclically at a constant rate of 0.5 mm/min and under a constant normal stiffness of approximately 8 kN/mm. The values of shear load, normal load, and normal displacement were recorded upon the applied shear displacement during each cyclic shear test.

RESULTS OF EXPERIMENTS

Results of cyclic shear tests performed on the prepared samples for low and high values of initial normal stress and asperity angle are shown in Figures 3 (a) and (b). It is observed that for low levels of initial normal stress and asperity angle, the shearing mechanism is sliding over asperities with higher shear strength in forward loading rather than the reverse one. Asperity degradation is evident by reduction of dilation and appeared to be a function of loading cycle and shearing direction such that less damage was observed in reverse loading and further cycles. The shearing mechanism for high values of initial normal stress and asperity angle is breaking of asperities. The shear strength after the initial rapid degradation approaches the residual value and there is no difference in the shear strength between forward and reverse loading (i.e. no contribution of roughness in friction angle). After asperity breaking in first forward loading cycle, contraction may be observed rather than dilation. This might be related to the loss of damaged material from the shearing box when asperities are broken up from the base.
Figure 2 - Schematic diagram of the CNS cyclic shear apparatus

Figure 3 - Cyclic shear test on idealized asperity angle (a) asperity angle = 9.5° and normal stress = 0.56 MPa (b) asperity angle = 26.5° and normal stress = 2.4 MPa
THEORY AND BACKGROUND

The theory and background of applied joint models are concisely described in this section for completeness in discussion of the analysis.

CS model

This criterion provides only a limiting shear strength value for the joint without considering the progressive damage exerted on asperities upon shear displacement:

$$\tau = \sigma_n \tan(\varphi) + c$$  \hspace{1cm} (1)

where, $$\tau$$ is the shear strength along the joint, $$\sigma_n$$ is the applied normal stress, $$c$$ is the cohesion, and $$\varphi$$ is the friction angle.

The dilation starts with a constant angle ($$\psi$$) when the joint begins to slip (i.e. plastic deformation) and can be restricted after attaining a critical shear displacement:

If $$\tau < \tau_r$$ then $$\psi = 0$$ \hspace{1cm} (2)
If $$\tau > \tau_r$$ and $$u < u_{cs}$$ then $$\psi = \psi_r$$ \hspace{1cm} (2a)
If $$\tau > \tau_r$$ and $$u \geq u_{cs}$$ then $$\psi = 0$$ \hspace{1cm} (2b)

where, $$u$$ is the shear displacement, $$u_{cs}$$ is the critical shear displacement, and $$\psi$$ is the dilation angle.

The effective friction angle is obtained by adding the assigned dilation angle to the friction angle and the shear strength becomes equal to the residual value when the critical shear displacement is reached (i.e. no dilation).

CY model

This model is more realistic than the CS model and takes into account the progressive damage of the joint surface during shearing observed in physical tests. In shear, the model considers irreversible, non-linear behaviour from the onset of shearing:

$$\tau = \sigma_n \tan(\varphi_m) \sin\Delta u$$ \hspace{1cm} (3)

where, $$\varphi_m$$ is the friction angle prior to any damage of asperity and $$\Delta u$$ is the increment of shear displacement.

As damage accumulates, the friction angle continuously reduces according to the following equation:

$$\varphi_m = (\varphi_m^i - \varphi_b) \exp\left(-\frac{u_p}{R}\right) + \varphi_b$$ \hspace{1cm} (4)

where, $$\varphi_m^i$$ is the initial friction angle, $$\varphi_b$$ is the basic friction angle, $$R$$ is a parameter with the dimension of length and related to joint roughness, and $$u_p$$ is the plastic shear displacement.

The effective dilation angle in the CY model is obtained by reducing the friction angle from the basic friction angle upon each increment of shear displacement.

$$i = \tan^{-1}\left(\frac{\tau}{\sigma_n}\right) - \varphi_b$$ \hspace{1cm} (5)

UDEC SHEAR MODELING AND SIMPLIFICATION

The CNS cyclic direct shear test was simulated in UDEC as shown in Figure 4. The material properties of block (a) were prescribed as bulk module = 21.3 MPa and shear module = 31.95 MPa in a way to precisely simulate the stiffness of surrounding media (8 kN/mm). The blocks (b) and (c) were discretised according to the laboratory specimen size and assigned properties (bulk module = 1400 MPa and shear module = 792 MPa) of the material prospected.

Firstly, the desired normal stress was subjected to the joint and the model was allowed to reach equilibrium. A periodic horizontal velocity was applied to the block (c) to produce the required cyclic shear displacement. The average normal and shear stresses along the joint were calculated using a FISH function. The associated dilation and shear displacement were also determined via FISH functions.
RESULTS OF NUMERICAL MODELING AND DISCUSSIONS

The CS and CY models were applied separately to replicate the observed experimental behaviour using the simulated CNS direct shear test in UDEC. The relevant model parameters used in the analysis for different conditions are listed in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Normal stress = 0.56 (MPa)</th>
<th>Normal stress = 2.4 (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS</td>
<td>Ψ = 5.2°</td>
<td>Ψ = 4.1°</td>
</tr>
<tr>
<td>CY</td>
<td>ϕ_m = 44.5° and R =0.012 (mm)</td>
<td>ϕ_m = 40.7° and R = 0.005 (mm)</td>
</tr>
</tbody>
</table>

The application of the CS model in simulation of rock joints shear behaviour under cyclic loading for low and high values of applied normal stress and asperity angle is shown in Figures 5 (a) and (b). It is observed that for low levels of initial normal stress and asperity angle when shearing mechanism is sliding over asperities, the CS model can simulate different frictional resistance for forward and backward shearing and recovery of dilation behaviour upon load reversal. However, for the breaking mechanism when asperity is highly degraded at the first forward shear cycle; the CS model cannot represent approaching to the residual shear strength (i.e. no contribution of roughness in shear strength) and the effect of asperity damage in dilation.

The results of cyclic numerical analysis conducted using a CY model for asperity sliding and breaking mechanisms are shown in Figures 6 (a) and (b). In contrast with CS, the CY model cannot represent different frictional behaviour and recovery of dilation upon load reversal (Figure 6a) under sliding mechanism.

As shown in Figure 6 (b), for high values of initial normal stress and roughness, appearance of residual shear strength (i.e. the same shear strength in forward and backward shearing) is reasonably captured by the CY model. Nevertheless, the predicted peak shear strength is underestimated since the additional shear strength provided by asperity breaking is neglected in this model. In addition, the simulated normal displacement shows excessive dilation when shear strength becomes equal to the residual shear strength.
CONCLUSIONS

The cyclic shear behaviour of rock joints was simulated in a simplified manner using two available constitutive models in UDEC under CNS conditions. For a given set of data, the variation of cyclic average shear stress, average normal stress, and dilation with shear displacement were studied and simulated using CS and CY models.

The results indicate that the capabilities of CS and CY models in simulating cyclic shear behaviour of rock joints under CNS condition depends on the governing shearing mechanism. For sliding mechanism observed in low levels of applied normal stress and asperity angle, the CS model can simulate different frictional behaviour and recovery of dilation during load reversal. However, for asperity breaking mechanism, this model excludes the effect of asperity damage on shear resistance and dilation angle. In this condition, the CY model can better represent cyclic shear behaviour of rock joints by considering progressive damage of asperities upon plastic shear displacement.

Figure 5 - CS model predicted results (a) asperity angle = 9.5° and normal stress = 0.56 MPa (b) asperity angle = 26.5° and normal stress = 2.4 MPa
Figure 6 - CY model predicted results (a) asperity angle = 9.5° and normal stress = 0.56 MPa (b) asperity angle = 26.5° and normal stress = 2.4 MPa

REFERENCES


