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Numerical simulation of a direct shear test on rock joint based on finite difference code

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ABSTRACT

The presence of discontinuities in a rock mass may have a significant influence on shear strength. The most popular method currently used to determine the joint shear strength is a direct shear test which can be performed by using a direct shear apparatus. In this article, the direct shear tests on jointed rock under constant normal load condition are carried out using the code $FLAC^{3D}$. A rough joint of rock sample is simulated via using 3D-scanned data. The shear behaviour of rock joint at a given different normal stresses corresponded well to those observed in laboratory tests. The numerical simulation results also show that the normal stress concentration at contact areas, especially at the tips of asperities, is higher in comparison to initial applied normal stress and can lead to failure of these parts.

1. Introduction

The shear strength and deformation of the rock mass are obviously influenced by the presence of discontinuities in rock mass such as joints, fractures, faults, bedding planes and other geological structures. The shear behaviour of jointed rock is a combination of complicated phenomena and interactions, such as normal dilation, surface roughness, asperity failure and contact area. The difference of the joint characteristics will lead to the different mechanical properties of the rock mass.

The most popular method currently used to investigate the shear strength of rock joints is a direct shear test. Patton (Patton, 1966) carried out shear tests on saw-tooth specimens and from which the shear strength of the joint can be established based on the angle of the saw-tooth face. The surface roughness of natural rock joints is an extremely important parameter, which has influence on the shear strength of joints, especially in the case of unfilled joints. Generally, the shear strength of the joint surface increases with increasing surface roughness. Based upon the results of experimental investigation, Barton (Barton, 1973) suggests the relationship between the shear strength of rough rock joint and JRC (Joint Roughness Coefficient) value. In recent years, many methods to determine rock joint surface roughness with high accuracy in the laboratory and in-situ such as laser profilometry (Milne et al., 1966), digital photogrammetric systems (Nilsson et al., 2012), and stereo-topometric scanners (Tatone and Grasselli, 2009) were developed. All these methods provide "cloud points" that need to be mathematically treated to describe the surface in a synthetic way (Haneberg, 2007).

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Numerical simulation methods have been used to simulate direct shear tests by several researchers. Indraratna and Haque (Indraratna and Haque, 2000) have used a discrete element method (DEM) to simulate artificial regular rock joints. Park and Song (Park and Song, 2013) have simulated direct shear tests on rock joints applying particle simulation technique. (Lin et al., 2012) have used a continuum approach to simulate direct shear tests on flat and wave-like rock joints. Shrivastava and Rao (Shrivastava et al., 2012) have also used a 2-dimensional DEM-approach to simulate direct shear tests on rock joints with asperity inclinations of 15° and 30° at different normal stresses. FLAC^{3D} (Fast Lagrangian Analysis of Continua in 3 Dimensions) has been successfully used to investigate the shear behaviour of rock joints under constant normal load boundary conditions (Itasca, 2012). However, these studies, which have focused mainly on smooth or regular saw-tooth joint surfaces. A detailed consideration of joint roughness is necessary to get deeper inside into the shearing process. In this study the behaviour of rough rock joint surfaces under constant normal load boundary condition and considering the joint roughness at the microscopic scale was simulated using FLAC^{3D}.

2. Finite difference code simulation of the direct shear tests

FLAC^{3D} is developed by Itasca and is based on an explicit finite difference scheme was used to simulate the direct shear tests. Joint surface between top and bottom part of the specimen in direct shear tests is modelled with interfaces elements in FLAC^{3D}. Interface elements are represented by a collection of triangular elements, each of which is defined by three nodes (interface nodes). Each interface element distributes its area to its nodes in a weighted fashion. Each interface node has an associated representative area. The entire interface is thus divided into active interface nodes representing the total area of the interface. Figure 1 illustrates the relation between interface elements and interface nodes, and the representative area associated with an individual node (Itasca, 2012).

Interfaces in FLAC^{3D} are simulated by Coulomb sliding and/or tensile and shear bonding. Interfaces have the properties of friction, cohesion, dilation, normal stiffness, shear stiffness, tensile and shear bond strength.

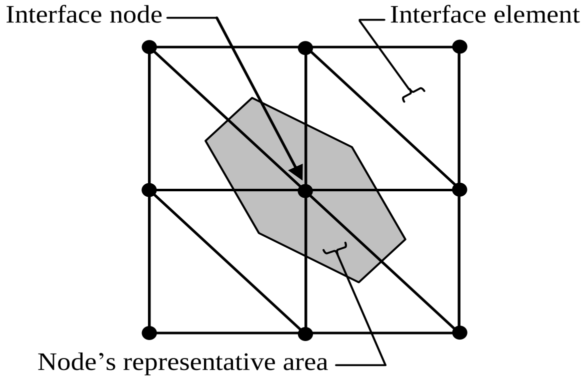


Figure 1. Distribution of representative areas to interface nodes

2.1. Surface Roughness Simulation

In this study, 3D-scanner (named Zsnapper from ViALUX) was used to measure the joints surface roughness of jointed rock specimen. The apparatus consists of an optical monochromatic projector and separately digital camera which are mounted on a horizontal bar and placed on a tripod as shown in Figure 2.

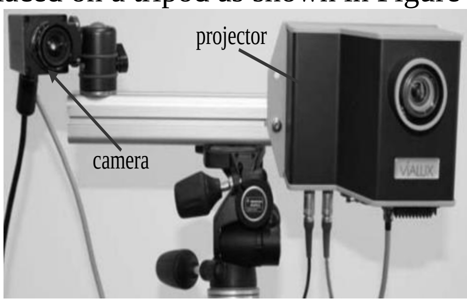


Figure 2. 3D-scanner zSnapper (ViALUX, 2010)

The 3D-scanning results were used to set-up numerical models. Surface roughness of a sample was simulated in FLAC^{3D} by using the 3D-scanner data. The 3D-scanner data were converted into ASCII format and finally used to manipulate the mesh in FLAC^{3D}, so that the joint topography was duplicated. It is assumed that the upper joint and lower joint surfaces are completely matched at the initial stage. Geometry and size of the models are identical to the laboratory samples. The surface mesh is generated by 50 x 100 elements. This means that each mesh element has area of around

3mm x 3mm. The surface roughness was generated by manipulation of the Z elevation of the grid points of the flat surface according to the 3D-scanner data. FISH code (FISH is a programming language embedded within $FLAC^{3D}$) was developed to perform these manipulations. Figure 3 illustrates the results of the procedure.

The geometry of the model is divided into two parts: the upper part and lower part. The interface is assigned on the joint face of the lower part. A uniform mesh is generated for each part on the model as shown in Figure 4.

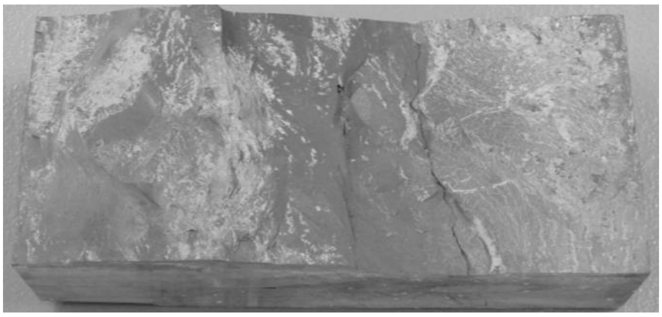
2.2. Direct Shear Tests Simulation

The direct shear test was modelled under constant normal load boundary condition. The lower part of model is fixed in the vertical direction at the bottom face (z-axis). The upper part of model is fixed in the horizontal direction (x-axis) at two faces: left and right boundary. The initial normal stress is applied at the upper boundary of the model and calculation is performed until equilibrium is reached. After that, a horizontal velocity is applied to the lower part of specimen to produce the required shear displacement compatible with laboratory shear rate. The shear and normal stresses along the joint were calculated via FISH functions. The peak shear stress for the applied normal stress can be determined from the shear stress versus shear displacement plot. The shear displacement was determined by multiplying the shear velocity with time steps. Linear Mohr-Coulomb criterion is taken to describe the behaviour of rock mass. The rock properties are set to be 27.8 kN/m^3 for unit weight, 71.0 GPa for Young's modulus, 0.3 for Poisson's ratio, 2.5MPa for cohesion, 29.5° for friction angle and 1.0MPa for tensile strength. The parameters of the joint are set to be, 0.7MPa for cohesion, 18.0° for friction angle, 3.3 GPa/m for normal stiffness and 4.9GPa/m for shear stiffness. The direct shear test was carried out with three normal stress levels of 5, 10 and 15 MPa according to the normal stress applied in the laboratory test.

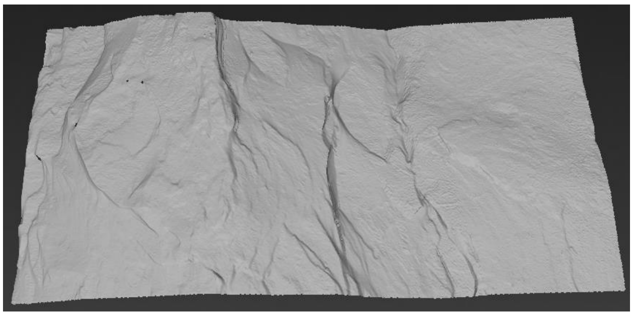
Figure 5 shows the shear stress versus shear displacement at difference normal stress levels. It can be seen that the shear behaviour of joint obtained from numerical simulations are in good agreement with experimental results. The shear stress increases to a peak value and then slightly decreases due to asperity degradation. It can be noted that the peak is reached after 0.5 mm of shear displacement. The peak shear strengths were 2.0MPa, 3.8MPa and 5.5MPa. The ratio of peak shear stress to applied normal stress was higher at lower normal stresses: 0.4, 0.38 and 0.36 at 5MPa, 10 MPa and 15MPa applied normal stresses, respectively. The peak shear stress increases with increasing applied normal stress.

The normal load applied on the specimen is constant during the constant normal load tests. However, there is only a part of the lower joint surface area in contact to the opposite joint surface during the shearing process. As a consequence, the normal stresses at these contact areas can be much higher than applied normal stress. Therefore, the stress concentrations at certain contact areas, especially at the tips of asperities, can reach the limit state and lead to failure - breakage of asperities (Barton and Choubey, 1977). The normal stress distributions on the joint surface under different applied normal stresses of 5 MPa, 10 MPa and 15 MPa after shear displacement of 10 mm are illustrated in Figures 6 to 8, respectively.

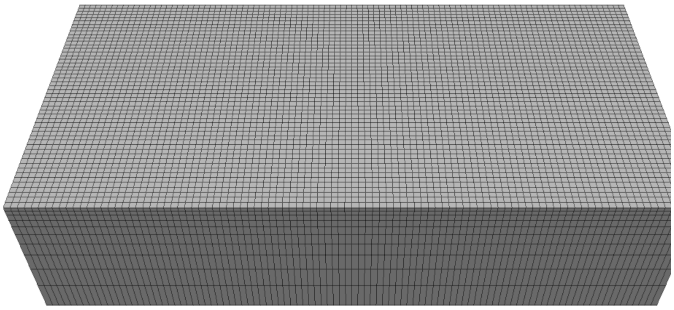
The distributions of local normal stress under variation of initial normal stress are shown in Figure 9. This figure indicates that the local normal stress distribution on the joint surface varies in a wide range. However, the distribution is still centered at the initial normal stress. The ratio of maximum normal stress to initial normal stress of 5 MPa, 10 MPa and 15 MPa on the joint surface is 4.3, 4.2 and 4.0, respectively. The results show that local maximum normal stress is more than four time in comparison to applied normal stress. This means that the normal stress at the tips of asperities (especially at contact area) is higher in comparison to initial normal stress and can lead to failure of these parts.



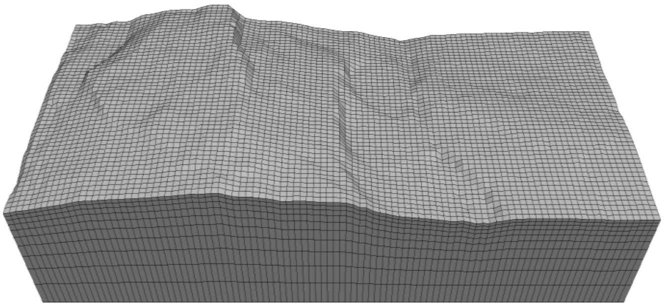
a) Rock sample



b) 3D-scanner data



c) FLAC^{3D} flat surface mesh



d) FLAC^{3D} manipulated surface mesh

Figure 3. Simulation of surface roughness using FLAC^{3D}

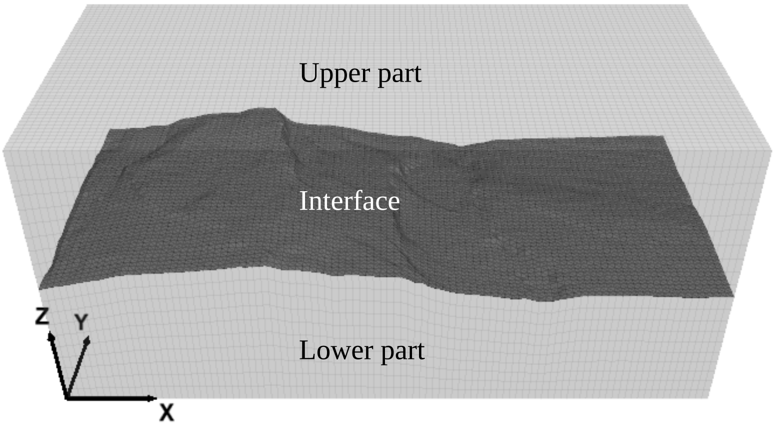


Figure 4. General model for simulating the direct shear test in FLAC^{3D}

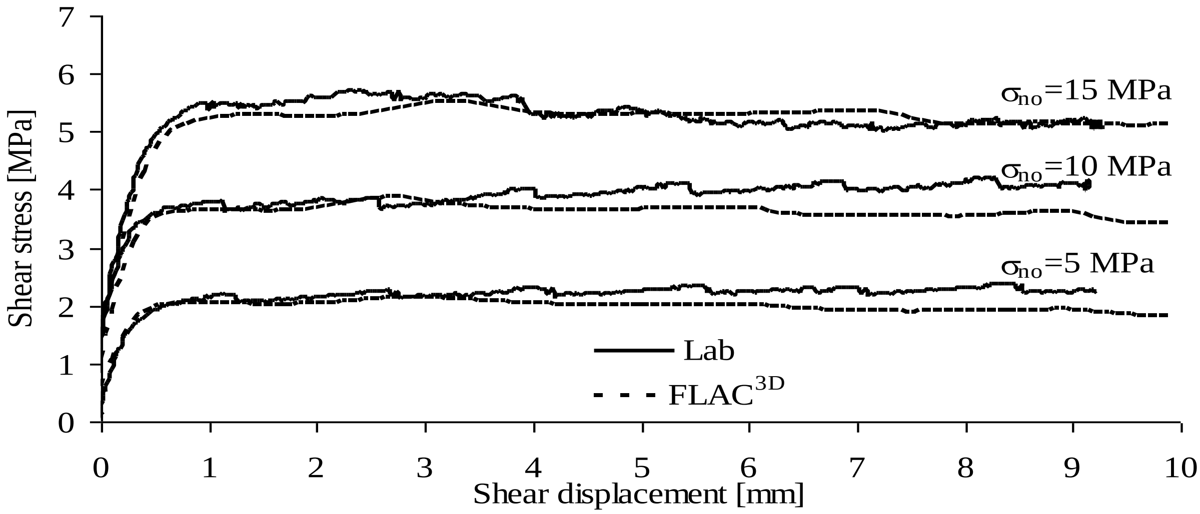


Figure 5. Shear stress versus shear displacement for different normal stress levels

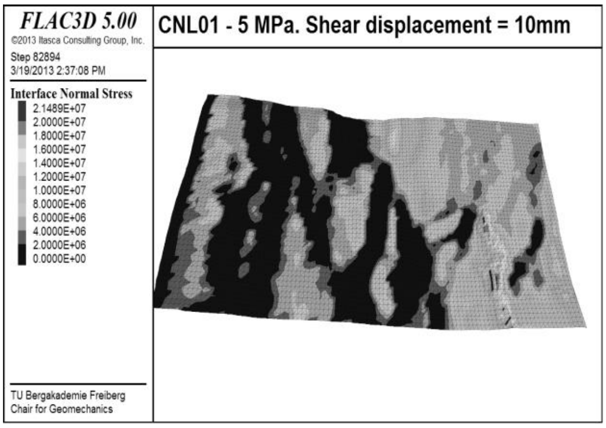


Figure 6. Distribution of normal stress [Pa] across the joint surface under applied normal stress of 5 MPa at shear displacement of 10 mm

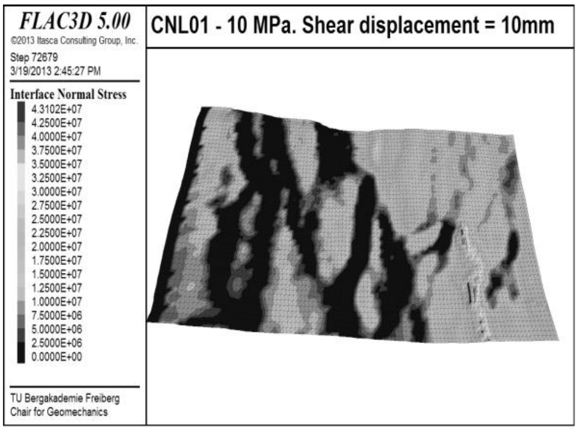


Figure 7. Distribution of normal stress [Pa] across the joint surface under applied normal stress of 10 MPa at shear displacement of 10 mm

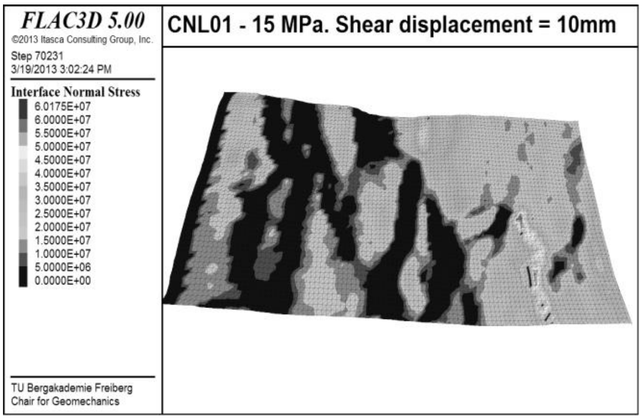


Figure 8. Distribution of normal stress [Pa] across the joint surface under applied normal stress of 15 MPa at shear displacement of 10 mm

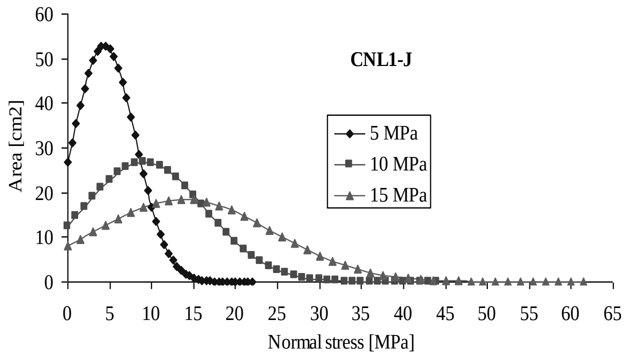


Figure 9. Distribution of local normal stress at the joint for different applied normal stresses

3. Conclusion

This paper presented the simulation of the direct shear tests under constant normal stress by using finite difference code. The roughness joint surface was simulated with $FLAC^{3D}$ software by using the 3D-scanner data. The shear behaviour of rock joint at a given different normal stresses is corresponded well to those observed in laboratory tests. The shear strength of rough rock joints under constant normal load boundary conditions increases with increasing applied normal stress. Local normal stresses vary within a wide range, but concentrate at the initial applied value. The local normal stresses values can reach up several times to the initial applied value. The numerical simulation results also indicated that the normal stress concentration at contact areas, and is higher in comparison to initial applied normal stress and can lead to failure of these parts.

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