Numerical investigations of joints with different surface roughness under shear and normal loads

S Xiao¹, X Li ², Y Zhou³, W Dang³*, Y Wang¹ and D Li⁴

¹ Zhuhai Da Heng Qin Company Limited, Zhuhai 519000, China
² China Railway 18th Bureau Group CO., LTD., Zhuhai 519000, China
³ School of Civil Engineering, Sun Yat-sen University, Zhuhai 519000, China
⁴ Zhuhai Institute of Urban Planning & Design, Zhuhai 519000, China

*E-mail: dangwg@mail.sysu.edu.cn, Orcid ID: 0000-0002-3397-8481

Abstract. A large number of discontinuities and weak planes exist in the natural system of rock masses. The presence of these discontinuities and weak planes reduces the strength of the rock masses. Thus, a thorough understanding of the shear behavior of jointed rocks is very important for many engineering projects. In this study, multistage normal loading (30, 60, 90, 180, and 360 kN) direct shear tests were conducted on a smooth planar joint using a large shear box device. Four numerical models with different joint asperities were built in parallel using Fast Lagrangian Analysis of Continua in three dimensions (FLAC3D), and the shear behavior was numerically analyzed. According to the experimental and numerical simulation results, joint roughness and normal force are the two most important factors that influence the shear behavior. The peak shear force increased as the normal load and joint asperity increased, but the normal displacement increased as the joint asperity increased and the normal load decreased. For the plane joint surface or joint surface with small asperity, the vertical displacement on the applied shear force side tended to go down, whereas it tended to go up on the opposite side. For the joint surface with large asperity, the vertical displacement on both sides went up. However, the value in the applied shear force side for the joint surface with large asperity was lower than that for the joint with smaller asperity. During shearing, the inclination of the upper box of the specimen is an important characteristic that causes the nonuniform distribution of normal stress, shear stress, and contact area of the interface. Furthermore, we developed a method for calculating the aperture size during shearing and discovered that the aperture size increased as the joint asperity increased. This research provides insight into the shear behavior of rock joints with various asperities.

1. Introduction
Many engineering projects deal with rock masses that are frequently cut by discontinuities and weak planes [1-3]. The strength of the rocks is weakened by the presence of these discontinuities and weak planes. Understanding the shear behavior of jointed rocks is essential for many engineering projects (e.g., surface and underground excavations, dam foundations, and geothermal reservoirs) and for preventing geological hazards [4-7]. Therefore, direct shear box tests have become increasingly popular in recent years [1, 8-14]. Presently, direct shear box tests are performed under constant normal load and constant normal stiffness conditions. Furthermore, dynamic cyclic loading shear tests are widely used to explore the dynamic shear behavior of jointed rocks [10-15].
Joint roughness is an important characteristic that influences the shear behavior of jointed rocks [16, 17]. Many methods have been proposed for investigating the roughness of rock discontinuities [9, 18-22]. Nguyen [9] used a three-dimensional (3D) optical scanning equipment to investigate the joint surface. Babanouri [20] proposed a 3D approach for modeling the spatial structure of rock fracture surfaces before and after conducting shear tests. These advanced techniques have aided in the analysis of surface behavior during shearing.

In the past, during the direct shear test, the dilation behavior was always evaluated using the average normal displacement of the upper specimen [8-10, 14, 23]. However, the movement behavior of the upper sample is complicated, and vertical deformation varies at different points along the sample. Therefore, evaluating the dilation behavior with only the average settlement value is insufficient. In fact, for the plane joint under the direct shear box test, the applied shear force side has a positive dilation, whereas the other side has a negative dilation. In laboratory direct shear tests, it is difficult to draw general conclusions based on data obtained from real rock samples because of the complex morphology of the joint surface, i.e., the joint asperity differed for different specimens. Artificial materials (e.g., cement and gypsum) are becoming increasingly popular as a means of overcoming the aforementioned problems [10-13, 24, 25]. The specimen used in this study was made of artificial materials with the desired geometry and discontinuity shapes (e.g., plane joints or saw tooth joints with a certain angle). In addition, joint surfaces can have diverse forms.

This study aims to investigate the shear behavior of specimens with different joint asperities under different normal loads. Cement replicas of the plane joint samples were prepared, and multistage normal loading direct shear box tests were conducted using the GS-1000 shear box apparatus. Thereafter, the laboratory tests [13] were evaluated using the numerical Fast Lagrangian Analysis of Continua in three dimensions (FLAC3D) software [26]. The numerical simulation model and the laboratory test results were in good agreement. In addition, four numerical models with different surface asperities were created. The joint aperture size was analyzed. The results of this study can aid in understanding the shear behavior of rock joints with different asperities.

2. Laboratory test

![Figure 1. Overview of the GS-1000 direct shear test apparatus [27]](image-url)
The shear tests were performed using the GS-1000 shear box device (Figure 1). Shear displacement was measured using a horizontal linear variable displacement transducer (LVDT), which was attached to the lower part of the shear box. The normal displacement was measured using four vertical LVDTs with high accuracy (+/- 0.001 mm). These LVDTs are positioned at the four corners of the upper part of the shear box. Normal and shear loads were measured using load cells integrated into the vertical and horizontal loading pistons.

The sample size was 300 × 160 × 150 mm (length × width × height). The sample was made using a weight ratio of 1:3 of the 32.5 cement grade and Hohenpockaer glass sand. The physical properties of the material after 28 d were 2.5 MPa tensile strength, 19.1 MPa compression strength, 30 GPa Young’s modulus, 0.2 Poisson’s ratio, 7.2 MPa cohesion, 30° internal friction angle, 10° dilation angle, and 2.50 g/cm³ density. The direct shear tests were performed under multistage normal loading (30, 60, 90, 180, and 360 kN) with a constant shear velocity of 3 mm/min. The maximum shear displacement was 20 mm.

Figure 2 depicts the laboratory test results. As shown in Figure 2a, the shear force increases as the normal force increases. During each direct shear stage, the shear forces increase linearly as the shear displacement increases until the peak shear forces are reached. Unloading causes elastic recovery of the displacement. After the peak shear force is reached, frictional sliding is observed at a residual shear stress level nearly identical to the peak value. Figure 2b shows a bilinear inclination (rotation) behavior.

![Figure 2](image-url)

*Figure 2.* (a) Shear displacement versus shear stresses under different normal stresses and (b) shear displacement versus normal displacement.

### 3. Numerical simulation

The FLAC3D software is a numerical modeling code for advanced geotechnical analyses of soil, rock, and structural support in three dimensions. As shown in Figure 3, the entire model consists of a loading plate, lower shear box, upper shear box, lower and upper parts of the specimen, and corresponding interfaces. The loading plane was subject to a constant normal load that was applied vertically. The outside surfaces of the shear box were fixed. In the lower shear box, a horizontal velocity was applied. The numerical parameters are documented in section 2. The constitutive model for the matrix and interface was selected as the Mohr–Coulomb model. Furthermore, four additional numerical models with different joint asperities were set up (Figures 3a, b, c, and d) to investigate the influence of the joint asperities of the contact surface on the shear behavior. The roughness was defined using a self-designed code that randomly changes the grid point coordinates in both the upper and lower contact surfaces (equation 1).

\[
\Delta u = (U_{rand} - 0.5) \times f,
\]

where \(\Delta u\) is the amount of grid point movement in the \(Z\) direction, “\(U_{rand}\)” is the FLAC3D keyword for changing the grid point coordinates, and \(f\) is the changing coefficient. The amounts of grid point
movement in the Z direction for models A, B, C, and D were ±0.25 mm, ±0.5 mm, ±1.0 mm, and ±1.5 mm, respectively.

Figure 3. FLAC3D numerical model set up. Models with different interface roughness: (a) ±0.25 mm, (b) ±0.5 mm, (c) ±1.0 mm, and (d) ±1.5 mm.

Figure 4. (a) Numerical simulation results and (b) shear force as a function of shear
Figures 4a and 4b show that the shear forces increase as the normal forces increase. The peak shear forces for models A, B, C, and D were about 30, 40, 85, and 115 kN, respectively, under a normal load of 30 kN. However, the residual shear forces were nearly identical (fluctuating between 20 kN and 30 kN). Under normal forces of 90 kN, they both had a similar changing pattern except that the maximum peak shear forces and residual shear forces increased. Figures 4c and 4d also show the relationship between the normal displacement and shear displacement. In the upper specimen, the absolute value of the normal displacement increased as the normal forces increased. The model went down on the left side and up on the right side, indicating that the top specimen rotated during shearing. The rotation is also a bilinear inclination behavior of the rough surface. Large joint asperity promotes dilation and large normal force inhibits dilation. Joint surface morphology and normal force are the two most important factors that influence joint shear behavior.

Nguyen [9] proposed a method for calculating the micro-slope angle. The specimen was sheared by moving the bottom part in a shear direction parallel to the X-axis, i.e., the shear direction plane is the XOZ plane (Figure 5a). The shear plane is the plane that includes the X-axis and Y-axis. \(A(x_{ij}, y_{ij}, z_{ij})\), \(B(x_{i+1,j}, y_{i+1,j}, z_{i+1,j})\), and \(C(x_{i,j+1}, y_{i,j+1}, z_{i,j+1})\) are the coordinates of triangle ABC. The true dip angle (\(\alpha\)) of the ABC plane in space is the angle between the ABC plane and the XOY plane and it is calculated as

\[
\cos(\alpha) = \frac{n_{ABC} \cdot n_{XOY}}{|n_{ABC}| \cdot |n_{XOY}|},
\]

where \(n_{ABC}\) is the normal vector of the ABC plane and \(n_{XOY}\) is the normal vector of the XOY plane. The apparent dip angle or micro-slope angle (\(\theta\)) is the angle between the two vectors (\(\overrightarrow{AB}\) and \(\overrightarrow{OX}\)), and it is calculated as
\[ \cos(\theta) = \frac{\overrightarrow{AB} \cdot \overrightarrow{OX}}{|\overrightarrow{AB}| \cdot |\overrightarrow{OX}|}. \] (3)

Figure 6 shows that the absolute values of the micro-slope angles increased as the joint asperity increased. For model A, the micro-slope angles were mainly below 10°, whereas for model D, the absolute value of the micro-slope angles was up to 30°.

![Figure 6. Contour plots of the micro-slope angles with respect to the relative shear direction of the different models.](image)

To further understand the mechanical and hydraulic behaviors of rock joints, particularly the hydraulic behavior, a good physical model for investigating the void space in rock fractures is required. The void space of a joint is an important parameter to consider when investigating the mechanical and hydraulic behaviors of rock joints. The void space can be evaluated using the aperture size between the upper and lower joint surfaces when they satisfy the noncontact condition. Nguyen et al. [9] and Xia et al. [28] proposed an approach for calculating the aperture size. The three-dimensional joint surface data are digitized on an XYZ grid. Thus, the elevation (Z) of each point on the joint surface is a function of the x and y coordinates, Z(x, y). We assumed that the elevations of the points (x, y) on the lower and upper joint surfaces in the same coordinate system are Z_{low}(x, y) and Z_{up}(x, y), respectively, as shown in Figure 5. The aperture size is estimated as the difference between the two z-coordinates at the upper and lower parts. Consequently, the aperture size at any point can be calculated as follows:

\[ A(x, y) = Z_{up}(x, y) - Z_{low}(x, y) \geq 0, \] (4)

where, \( A(x, y) \) is the aperture size at points (x,y), \( Z_{up}(x, y) \) is the elevation at points (x,y) of the upper joint surface, and \( Z_{low}(x, y) \) is the elevation at points (x,y) of the lower joint surface.

The aperture size of the specimen after shearing was calculated using the above equation for each grid point on the joint surface. Figure 7 shows contour plots of the aperture size determined under a 90 kN normal force at different shear displacements. The maximum aperture size is dependent on the joint surface asperities, normal stress, and shear displacement. The aperture size decreased as the shear displacement increased (Figure 8) and increased as the joint asperity increased (Figure 8a). The aperture size on the right side was larger than that on the left side.
4. Conclusions
The behavior of joints with different asperities under different normal loads was investigated in this study. The shear behavior was influenced by two main factors: joint asperity and applied normal force. The main findings can be summarized as follows:

The shear forces increased as the normal forces increased, the peak asperity forces increased as the joint asperity increased. Rotation of the upper specimen is an important mechanism during shearing. For the plane joint surface or the joint surface with small asperity, the normal displacement tended to go down on the applied shear force side and up on the opposite side. For the joint surface with large asperity, the normal displacement went up on both sides, but the value in the applied shear force side was smaller. The fracture zones in the applied shear force side were more than those on the opposite side. The aperture size increased as the joint asperity increased and decreased as the shear displacement increased.
Acknowledgment
We thank Prof. Heinz Konietzky and Dr. Thomas Frühwirt for help during laboratory testing.

References
[1] Barton N and Choubey V 1977 The shear strength of rock joints in theory and practice. Rock Mech. 10 1–54
[2] Fan X, Kulatilake P H S W and Chen X 2015 Mechanical behavior of rock-like jointed blocks with multi-non-persistent joints under uniaxial loading: A particle mechanics approach. Eng. Geol. 190 17–32
[3] Zhang L 2010 Estimating the strength of jointed rock masses. Rock Mech. Rock Eng. 43 391–402
[4] Hoek E and Brown E T 1980 Underground excavations in rock (London: The Institution of Mining and Metallurgy)
[5] Nima B, Mostafa A and Zahra H-A. 2020 Modeling shear behavior of rock joints: A focus on interaction of influencing parameters. Int. J. Rock Mech. Min. Sci. 134 104449
[6] Li H, Deng J, Yin J, Qi S, Zheng B and Zhu J 2021 An experimental and analytical study of rate-dependent shear behaviour of rough joints. Int. J. Rock Mech. Min. Sci. 142 104702
[7] Tan X, Ren Y, Li T, Zhou S and Zhang J 2021 In-situ direct shear test and numerical simulation of slate structural planes with thick muddy interlayer along bedding slope. Int. J. Rock Mech. Min. Sci. 143 104791
[8] Lee Y K, Park J W and Song J 2014 Model for the shear behavior of rock joints under CNL and CNS conditions. Int. J. Rock Mech. Min. Sci. 70 252-263
[9] Nguyen V H, Konietzky H and Frühwirt T 2014 New methodology to characterize shear behavior of joints by combination of direct shear box testing and numerical simulations. Geot. Geol. Eng. 32 829-46
[10] Dang W, Konietzky H and Frühwirt T 2016 Shear behaviour of a plane joint under dynamic normal load (DNL) conditions. Eng. Geol. 213 133-141
[11] Dang W, Konietzky H and Frühwirt T 2017 Direct shear behavior of planar joints under cyclic normal load conditions: Effect of different cyclic normal force amplitudes. Rock Mech. Rock Eng. 50 1-7
[12] Dang W, Konietzky H, Chang L and Frühwirt T. 2018 Velocity-frequency-amplitude-dependent frictional resistance of planar joints under dynamic normal load (DNL) conditions. Tunn. Undergr. Space Technol. 79 27-34
[13] Dang W, Konietzky H, Frühwirt T and Herbst M 2020 Cyclic Frictional Responses of Planar Joints Under Cyclic Normal Load Conditions: Laboratory Tests and Numerical Simulations. Rock Mech. Rock Eng. 53 337–364
[14] Dang W, Chen J and Huang L 2021 Experimental study on the velocity-dependent frictional resistance of a rough rock fracture exposed to normal load vibrations. Acta Geotech. 16
[15] Cabalar A F, Dulundu K and Tuncay K 2013 Strength of various sands in triaxial and cyclic direct shear tests. Eng. Geol. 156 92-102
[16] Belem T, Souley M and Homand F 2009 Method for quantification of wear of sheared joint walls based on surface morphology. Rock Mech. Rock Eng. 42 883–910
[17] Indraratna B, Thirukumar S, Brown E T, Premadasa W and Gale W 2014 A technique for three-dimensional characterisation of asperity deformation on the surface of sheared rock joints. Int. J. Rock Mech. Min. Sci. 70 483-495
[18] Grasselli G 2006 Manuel Rocha medal recipient shear strength of rock joints based on quantified surface description. Rock Mech. Rock Eng. 39 295–314
[19] Grasselli G, Wirth J and Egger P 2002 Quantitative three-dimensional description of a rough surface and parameter evolution with shearing. Int. J. Rock Mech. Min. Sci. 39 789–800
[20] Babanouri N and Nasab S K 2015 Modeling spatial structure of rock fracture surfaces before and after shear test: A method for estimating morphology of damaged zones. Rock Mech. Rock Eng. 48 1051–1065
[21] Wang C, Wang L and Karakus M 2019 A new spectral analysis method for determining the joint roughness coefficient of rock joints. Int. J. Rock Mech. Min. Sci. 113 72-82
[22] Ban L, Du W, Qi C and Zhu C 2020 Modified 2D roughness parameters for rock joints at two different scales and their correlation with JRC[J]. Int. J. Rock Mech. Min. Sci. 137 104549
[23] Yan Y and Ji S 2010 Discrete element modeling of direct shear tests for a granular material. Int. J. Numerical Anal. Meth. Geomech. 34 978–90
[24] Zhou H, Meng F, Zhang C, Hu D, Lu J and Xu R 2014 Investigation of the acoustic emission characteristics of artificial saw-tooth joints under shearing condition. Acta Geotech. 11 925-939
[25] Qiao Q, Nemcik J, Porter I and Baafi E 2015 Laboratory Tests on Thin Spray-On Liner Penetrated Rock Joints in Direct Shear. Rock Mech. Rock Eng. 48 2173–2177
[26] Itasca Inc. 2012 FLAC3D - Fast Lagrangian Analysis of Continua in 3 Dimensions - Theory and Background (Minnesota: Itasca Consulting Group Inc)
[27] Konietzky H, Frühwirt T and Luge H 2012 A new large dynamic rock mechanical direct shear box device. Rock Mech. Rock Eng. 45 427-32
[28] Xia C C, Gui Y, Wang W and Du S G 2014 Numerical method for estimating void spaces of rock joints and the evolution of void spaces under different contact states. J. Geophys. Eng. 11 065004