Shale Brazilian split test and numerical simulation of the discrete element method

Jiong Wang\(^1\), Yang Wang\(^1\)*, Weili Gong\(^1\) and Zhaoxuan Wang\(^1\)

\(^1\)State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

Corresponding author. E-mail: 18810000685@163.com

Abstract. This study performs a shale Brazilian split test by setting the loading and bedding directions at different angles to study the effect of anisotropy caused by the bedding structure and heterogeneity caused by different particles on the mechanical properties of shale. The results indicate that the cracks of the specimens splitting and breaking at 0° and 90° all extend vertically through the disk. A combination of Neper and 3DEC software is applied to the numerical simulation study of the shale splitting process through the discrete element method. The shale splitting failure modes are divided into three categories. At 0° and 90°, the cracks extend linearly through the loading ends, and the models show bedding and particle tensile failures, respectively. At 15°, the cracks run diagonally through the rock sample from the end of the upper loading section, parallel to the bedding direction. At 30° to 75°, the cracks propagate from the loading end along the parallel bedding direction. The experiments and numerical simulations verify that bedding influences the shale splitting failure mode and the mechanical behavior. Therefore, the investigation of the mechanical problems caused by the destruction of shale gas mining has a far-reaching significance.

1. Introduction
The development of unconventional resources, such as shale, is becoming increasingly important with the decrease in conventional oil and gas resources. The mechanical properties of shale are an important basis for evaluating the mining effect. Moreover, internal structures, such as micro cracks inside the rock, affect the safety and stability of rock engineering [1]. Therefore, an in-depth research on the influence of shale anisotropy and heterogeneity on its mechanical properties must be conducted. Rock layering has a significant influence on the progressive failure process under load. Yang et al. [2] used the rock failure process analysis to perform a numerical simulation of the uniaxial compression of the heterogeneous bedding shale. Consequently, they found that the direction and the homogeneity of shale influenced the change in its failure form and compressive strength. Heng et al. [3] performed a three-point bending test of shale and found that the weak cementation of the shale bedding significantly affects the hydraulic crack propagation. Ye et al. [4] conducted a direct shear test on a layered slate and found that the slate failure mode differs with the different directions of the bedding and shear planes.
Meanwhile, Cao et al. [5] pointed out in a uniaxial compression experiment that detecting all new
cracks, which appear when the rock is destroyed, is difficult when using only the naked eye. A numerical simulation greatly facilitates the study of the rock mechanical behavior. Wang et al. [6] used Neper [7] to generate a non-uniform particle model, analyzed the contact and grain properties of rigid, elastic, and fragile particles, and found that both affect the macroscopic mechanical behavior of rocks. Moreover, Ghazvinian et al. [8] used a combination of 3DEC and Neper to simulate the crack formation in rocks and analyzed the anisotropic behavior of rocks with bedding. Li et al. [9] presented different constitutive relationships in different rocks in 3DEC to simulate the bearing response of artificial pillars in stopes. Meanwhile, Tan et al. [10] divided gneiss into different mineral particles and contacts, used UDEC to perform a numerical simulation of the Brazilian split test of gneiss, and compared it with the test results to verify that the gneiss crack growth under load is a self-organizing process from disorder to order.

In the previous literature, the Brazilian split test was conducted on shales in different bedding directions. Furthermore, transverse isotropic and other continuous media were used for the simulation analysis. However, the impact of shale anisotropy and heterogeneity on its mechanical behaviors was rarely considered. This study analyzes and compares the Brazilian split test and the corresponding numerical simulation of shale with different bedding angles. The failure mechanism of the shale specimen under the influence of the bedding and block composition is revealed based on the tensile strength and failure form.

2. Experimental research
Black shale was divided into two groups (I and II) herein and processed into disk specimens with 50 mm diameter and 25 mm height. The two end faces of each disk were polished on a sander. The end face parallelism was controlled within ±0.05 mm. The surface flatness was within ±0.01 mm. The samples were allowed to dry naturally. The shale samples were then loaded onto a platform. A thin line with a gravity block was hung at the contact point between the loading block and the disk [11], such that the thin line coincided with the loading line, to ensure that the loading line passes through the center of the disk. The lower end of the disk was fixed. A vertical downwards loading speed of 0.01 mm/min was applied at the upper end. Figure 1 shows the samples obtained before and after shale splitting.
Figure 1. Splitting failure diagram of the shale Brazilian test: a) before splitting; (b) Group I after splitting (0°, 45°, and 90°); (c) Group II 0° specimen after splitting; and (d) Group II 90° specimen after splitting.

The split strength analysis of the sample was performed according to the classic Brazilian split formula:

$$\sigma_t = \frac{2P}{\pi Dt}$$

where, P is the specimen split load (i.e., maximum load corresponding to the load–displacement curve of the rock sample); D is the disk specimen diameter; and t is the disk thickness. The samples used for the experimental data were obtained from the Schlumberger and Kouzidong mines. Group I shale fracturing specimens with 0°, 45°, and 90° bedding angles were obtained and displayed in Figure 1(b). Considered together with Group II specimens having 0° and 90° angles, the split cracks for the 0° and 90° specimens extended straight through the upper and lower loading ends, and the 45° specimen was affected by the bedding angle to produce a certain angle of inclination (Figures 1(c) and (d)). The measured splitting strengths at the center point of the shale disks with 0°, 45°, and 90° bedding in Group I were 2.07, 2.92, and 7.87 MPa, respectively, while those of Group II with 0° and 90° bedding were 4.50 MPa and 6.50 MPa, respectively. The ratio of the splitting strength of the 90° specimen to the 0° specimen was used to define the shale anisotropy [12]. The ratios of the two groups were 3.80 and 1.44, respectively, indicating that bedding has a significant effect on shale.

3. Numerical simulation of discrete element

The well-developed shale formation and the heterogeneity of the mineral composition disqualify the continuous media modeling method from being suitable to an in-depth study of anisotropy and other related aspects. The discrete element method can effectively solve the problem of discontinuous media with the basic idea of treating the rock mass as a series of rigid bodies or deformable blocks cut from joints, cracks, and other structural planes. The contact between the rigid bodies or blocks is defined by a relevant mechanical analysis to further simulate the deformation process of the discontinuous medium under load [10]. The 3DEC modeling code can simulate and analyze the shale Brazilian split test process.

3.1. Establishing a shale Brazilian split model

Shale materials are divided into two parts: a mineral matrix block and an interface contact. The mineral block parameters were used herein to characterize shale heterogeneity, while the interface contact parameters were used to characterize shale anisotropy.
Figure 2. Shale: (a) Voronoi disk; (b) bedding surface; (c) joint diagram of the split model; and (d) observation points.

Neper open-source software was used to build a \( \Phi 50 \times 1 \text{ mm} \) Voronoi disk (Figure 2). Considering the computer performance, the disk contained 500 particles with an average particle volume of 3.93 mm\(^3\). Subsequently, the code was imported into 3DEC. The loading and fixed blocks were set at the upper and lower ends of the disk. The weak surface of the structure was inserted in seven different directions (i.e., 0°, 15°, 30°, 45°, 60°, 75°, and 90°) in the disk to simulate the bedding and form a Brazilian split loading model of shale after meshing. Figure 2(c) depicts the disk joint diagram. No bedding plane was established near the upper and lower loading ends to avoid the concentrated stress formation at the loading end. The contact surface was set by a Mohr Coulomb slip model. The shale particles were set as Variable Block 1, while the upper and lower loading blocks were set as Rigid Body 2. Only the necessary density, bulk modulus, and shear modulus were assigned herein. In addition, the three parameters of the rigid body were assumed to be very large. The contact interface between the upper and lower loading blocks and the disk was assumed as Contact 1; the layering surface was Contact 2; and the contact surface between particles was Contact 3. Tables 1 and 2 show the characterization parameters of each block and contact.

### Table 1 Block parameters.

|          | Density (kg/m\(^3\)) | Bulk modulus (GPa) | Shear modulus (GPa) | Elastic modulus (10\(^6\) kPa) | Poisson's ratio | Cohesion (10\(^4\) kN) | Friction angle (°) | Tensile strength (10\(^3\) kPa) |
|----------|----------------------|-------------------|---------------------|-------------------------------|----------------|------------------------|-------------------|------------------------|
| Mat 1    | 2700                 | 38.9              | 13.0                | 4.21                          | 0.25           | 1.62                   | 14.4              | 2.6                    |
| Mat 2    | 650000               | 1000              | 333                 | 0                             | 0              | 0                      | 0                 | 0                      |

### Table 2 Contact parameters.

|          | Normal stiffness (10\(^{14}\) Pa/mm) | Tangential stiffness (10\(^{14}\) Pa/mm) | Friction angle (°) | Cohesion (MPa) | Tensile strength (MPa) |
|----------|--------------------------------------|------------------------------------------|--------------------|----------------|------------------------|
| Contact 1| 2.26                                 | 0.76                                     | 366                | 25             | 20                     |
| Contact 2| 2.26                                 | 0.76                                     | 13                 | 10             | 9                      |
| Contact 3| 2.26                                 | 0.76                                     | 34                 | 24             | 19                     |

The upper loading block was given a larger loading speed during the loading process to increase the calculation efficiency. Moreover, the direction was along the negative direction of the Z-axis. The lower loading block speed was fixed at 0. Five units were set at the center line of the disk as
observation points (Figure 2(d)). The corresponding load change, displacement change, and corresponding load–displacement relationship at each point were recorded.

3.2. Numerical simulation results

Figure 3. Split vertical displacement cloud diagrams of the bedding shale models with different angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60°; (f) 75°; and (g) 90°.
Figure 3 shows that for the 0° and 90° models, the cracks propagated vertically from the upper and lower loading ends to the center of the circle during the split failure. For the 15° model, the cracks extended diagonally from the upper loading end to the lower loading end, and the inclination direction was parallel to the bedding direction. Meanwhile, for the 30° to 60° models, the splitting cracks extended from the two loading ends parallel to the bedding direction, while the 75° model split only at the upper loading end, generated with oblique cracks in parallel bedding directions.
Figure 4. Split transverse stress cloud diagrams of the underlying bedding shale models with different angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°; (e) 60°; (f) 75°; and (g) 90°.

Figure 4 illustrates that the lateral stress of the center area of the 0° shale model was greater than that of the other regions. For the 15° model, the lateral stress was greater at the cleavage crack formed. For the 30° to 75° models, a diamond-shaped large transverse stress region was formed along the crack propagation direction. Meanwhile, for the 90° model, the direction of the connecting line at the upper and lower loading ends penetrated the larger transverse stress. Combined with the displacement and stress cloud analysis, the 0° model was split by tensile failure; the 90° model was split by the tensile failure of particles; and the 15° to 75° models were split by the tensile shear failure while tensile and shear failures occurred between the shale minerals.

Figure 5. Split stress–displacement cloud image of the recorded point of the bedding shale model with different angles.
The lateral stress and the vertical displacement of the model during the splitting process were recorded (Figure 5). The stress–displacement curves of the model during the splitting process were similar at different angles. The displacement gradually increased during the loading process, that is, from the lowermost to the uppermost recording points. The splitting stress also showed an increasing trend.

![Figure 5](image1)

**Figure 6.** Tensile strength of the central point of the underlying shale model with different angles: (a) stress–displacement curves; (b) splitting strength at the center points; and (c) comparison of the split strengths between the test and simulated shales.

The splitting strength at the center point was approximated to the model tensile strength [10]. Figure 6(a) shows that the model stress and the displacement had a linear relationship before the splitting failure, and the curve change trend was similar at different angles. The stress sharply increased during the splitting failure and suddenly dropped after reaching the maximum splitting point. Figure 6(b) presents that the tensile strength of the bedding–bearing shale model increased from 0° to 90° because the splitting strength obtained at 0° approximated the tensile strength of the weak layer of the middle layer of shale, and the splitting strength obtained at 90° approximated the tensile strength of the shale particles. The ratio of the tensile strengths between the 90° and 0° models was 3.98. Figure 6(c) shows that the splitting strengths at the center points of the shale disks with 90° and 0° bedding obtained by the two sets of experiments and numerical models were quite different. The shale with different bedding angles showed anisotropy, which further verified the influence of the bedding angle on the mechanical properties of shale.

### 4. Conclusions

Through a comprehensive comparison of the shale Brazilian split test and the shale disk model split simulation, we found that the angle of the shale middle bedding plane significantly affect the rock split failure mode and mechanical properties. The following conclusions are obtained:

1. In the Brazilian splitting test, the shale with bedding planes of different angles can be divided into
three types of crack propagation failure modes during cracking. First, at 0° and 90°, the crack extended linearly through the upper and lower loading ends. Second, at 15°, the crack was oblique through the rock sample parallel to the bedding direction from the end of the upper loading section. Third, at 30° to 75°, the cracks propagated from the loading end in the parallel bedding direction. When the 0° model was split, the shale failure was found to be a tensile failure of the bedding surface. When the 90° model was destroyed, the shale failure was found as a tensile failure of the particles. Meanwhile, when the 15° to 75° models were destroyed, the shale showed a tensile shear failure.

(2) During the loading process, the displacement of each point from the bottom to the top of the vertical center line of the model gradually increased, and the cleavage stress showed an increasing trend. The lateral stress and the vertical displacement of the center point before shale splitting were approximately linear. Furthermore, the change trends of the stress–displacement curve at different angles were similar. The splitting instantaneous stress suddenly increased and decreased.

(3) The tensile strength of the bedding–bearing shale model increased in the 0° to 90° specimens. The tensile strength ratios of the 90° and 0° specimens obtained by the test and the numerical simulation were both greater than 1, indicating that the shale anisotropy affected the mechanical properties.

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