STUDY ON THE MESOSCOPIC FAILURE PROCESS OF HETEROGENEOUS ROCK BASED ON THE 3-D GBM MODEL

by

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The rock deformation and failure processes under uniaxial compression are a fundamental issue in rock mechanics. This study constructs a numerical heterogeneous rock specimen composed of Voronoi polyhedral particles using Neper software. It examines the fracture patterns, mechanical behavior, and strength of granular rock through numerical simulations using the 3-D distinct element code. The findings demonstrated that the number of cracks escalates with increasing axial stress. The rate of crack initiation rises significantly when the axial stress is approximately 57.3% of the peak stress, and shear cracks start to appear when the axial stress reaches 73.84% of the peak stress. These heterogeneous rock specimens exhibit significant axial splitting damage under uniaxial compression, transitioning from tensile to shear failure as the axial stress improves. In addition, smaller internal friction angles lead to more severe failures, and the more fully developed the shear zones are, the more pronounced the rock mass's zonal fracturing becomes.

Key words: *rock, heterogeneity, GBM model, uniaxial compression, fracture*

Introduction

Rock specimens' deformation and failure processes under uniaxial compression represent fundamental challenges in rock mechanics. A correct understanding of these processes is crucial for assessing the stability and safety of rock engineering projects [1-8]. Rock heterogeneity primarily influences the initiation and propagation of cracks, which are vital to studying rock's mechanical response and fracture processes [9-16]. Ma *et al*. [17] developed a stress-damage model for heterogeneous rocks and discovered that the fracture mode of rock transitions from plasticity to elastic-brittle as homogeneity increases. Li et al. [18] employed the two-parameter Weibull distribution model the heterogeneity of rock masses. They successfully observed the entire process in sandstone specimens, from the accumulation of microscopic damage to the coalescence of nucleation and fracture propagation until failure. Garza *et al*. [19] constructed a heterogeneous rock model using 3-D distinct element code (3DEC) to examine the mining response of vein-shaped rock masses. Li *et al*. [20] created a segmented damage rock mass model to explore the effects of temperature on the mechanical properties of mudstone specimens. Manouchehrian et al. [21] employed the Abaqus to simulate failure of

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heterogeneous rock, capturing the failure mode of the heterogeneous rock which is dominated by tensile fracture. Li et al. [22] established the heterogeneous rock mass finite difference method model and evaluated the stability of the heterogeneous rock mass tunnel. These studies highlight the significant impact of rock mass heterogeneity in uniaxial compression scenarios.

This study utilizes Neper software to establish a rock particle model with statistical characteristics to explore the compression failure process of rock masses. It develops a 3-D GBM heterogeneous rock model to investigate the mesoscopic failure process by assigning heterogeneity using the FISH function within 3DEC.

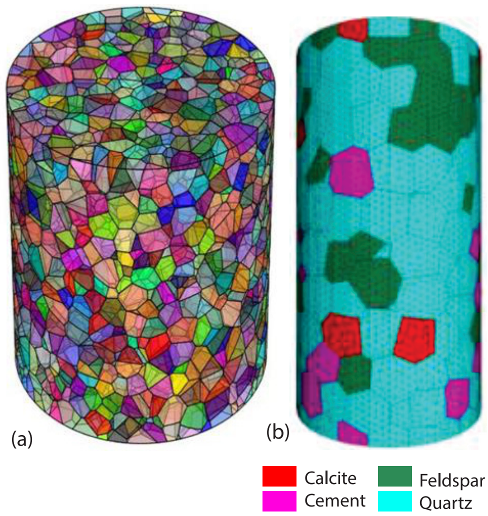

Figure 1. The numerical rock sample model; (a) rock sample generated by Neper and (b) heterogeneous sample model

Model construction

The numerical rock specimen model in this study is constructed using the Neper polycrystal generation software package, as shown in fig. 1. The model's dimensions include a height of 100 mm and a diameter of 50 mm, consisting of 2000 3-D Voronoi polyhedral elements with a grain size of approximately 100-200 μm. The heterogeneity of the model is established based on the statistical parameters of the rock mass and assigned using a custom FISH function after importing into the 3DEC software package. The specimen data are sourced from a feldspar sandstone in Yunnan Province, comprising quartz (60%), feldspar (19%), calcite (8%), and cement (clay minerals) (13%) [23].

The uniaxial compression process in 3DEC is performed by applying a constant displacement rate to the upper and lower surfaces of the specimen along its axis. The displacement rate is set to $4 \cdot 10^{-9}$ m/s. The stress-strain data of rock are obtained by counting the resultant force and total displacement of all elements on the loading surface.

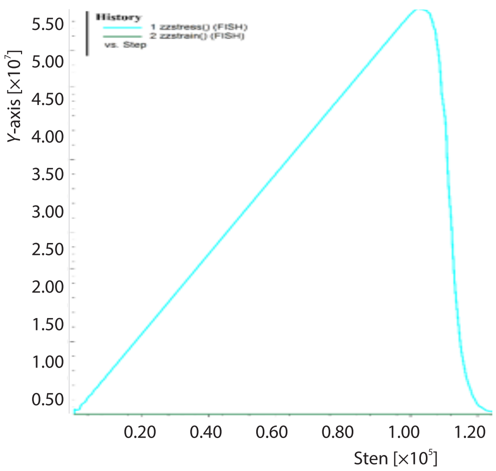

Figure 2. The rock stress-strain relationship

Analysis of rock fracture process

Figure 2 depicts the stress-strain curve for rock specimens under uniaxial compression. It shows that the elastic modulus of the numerical rock specimen is 18.3 MPa, and its peak stress is 55.8 MPa, deviating by 6.7% from the peak stress of 52.3 MPa observed in the actual rock specimen. It proves the accuracy and validity of the model established in this study. Figure 3 illustrates the crack propagation in rock specimens during compression. It demonstrates that at the initial stage of compression, only a few fractures are formed and the damage of rock mass is negligible. As the axial stress reaches 31.99 MPa (57.3% of the peak stress), the rate of tensile crack formation significantly accelerates. When the axial stress rises to 41.2 MPa (73.8% of the peak stress), tensile crack formation intensifies, and shear cracks develop. Then, the rate of crack initiation in the rock specimen improves until complete failure occurs.

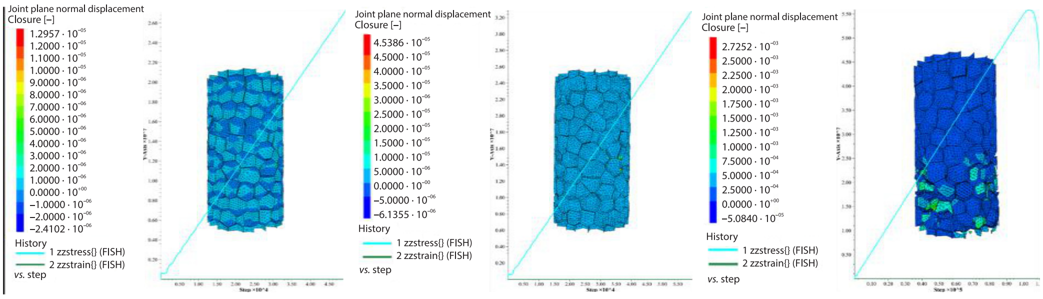

Figure 3. The rock grain contact normal displacement

Figure 4 illustrates the deformation distribution when the rock specimen is in completely failure stage, indicating a transition in the failure mode from an *X-type tensile-shear mixed failure* to shear failure. This failure primarily occurs in the middle and lower sections of the rock specimen, showing a clear pattern of localized failure. In addition, the failure of rock is not the complete crushing of a certain area, formation and penetration of partial cracks. Most shear cracks are found in the cement (clay minerals) sections, which have lower strength than rock units and other contact types. Therefore, after the rock experiences sufficient tensile failure, shear cracks predominantly extend toward these cement sections.

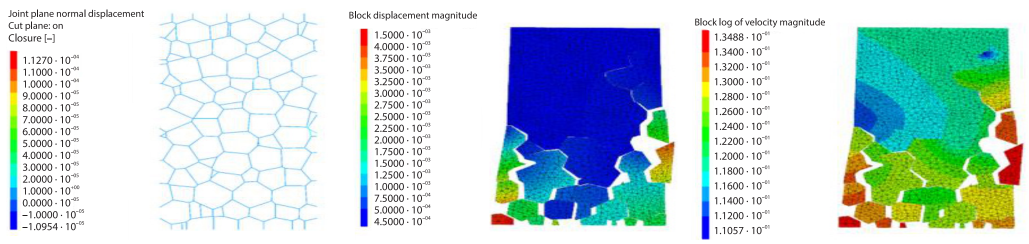

Figure 4. The fracture location when rock breaks

Analysis of influence of internal friction angle on rock failure

Three model sets with differing internal friction angles are created to investigate the impact of mechanical parameters of different joints on the stress-strain curve and rock cracking. The friction angle of the second set is 1.5 times that of the first, and the angle of the third set is three times that of the first, while all other joint parameters remain constant.

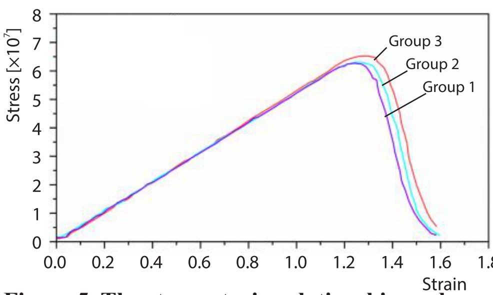

Figure 5. The stress-strain relationship under different internal friction angle

Figure 5 displays the stress-strain curves for three simulations. It reveals that the peak stress of the first set, which has the smallest friction angle, is the lowest at 63.37 MPa, followed by 64.46 MPa for the peak stress of the second set and 65.43 MPa for the third set. The peak stress of the second set exceeds that of the first set by 1.7%, and that of the third set surpasses the second set by 1.5%. Although the increase in the friction angle slightly affects the peak stress, it does not significantly influence the elastic modulus of the entire rock specimen.

Figure 6 presents the fracture images from the three simulations, demonstrating that smaller friction angles result in a broader range of rock fractures, with a more pronounced failure tendency in the middle and lower sections of the specimen. A distinct tensile failure zone forms in the middle section and a shear failure zone develops in the lower section. During rock failure, damage accumulates in the latter sections of the specimen during loading, and tensile cracks emerge in the lower-middle section. As axial stress increases, these tensile cracks in the lower section evolve into tensile-shear cracks until the specimen fails.

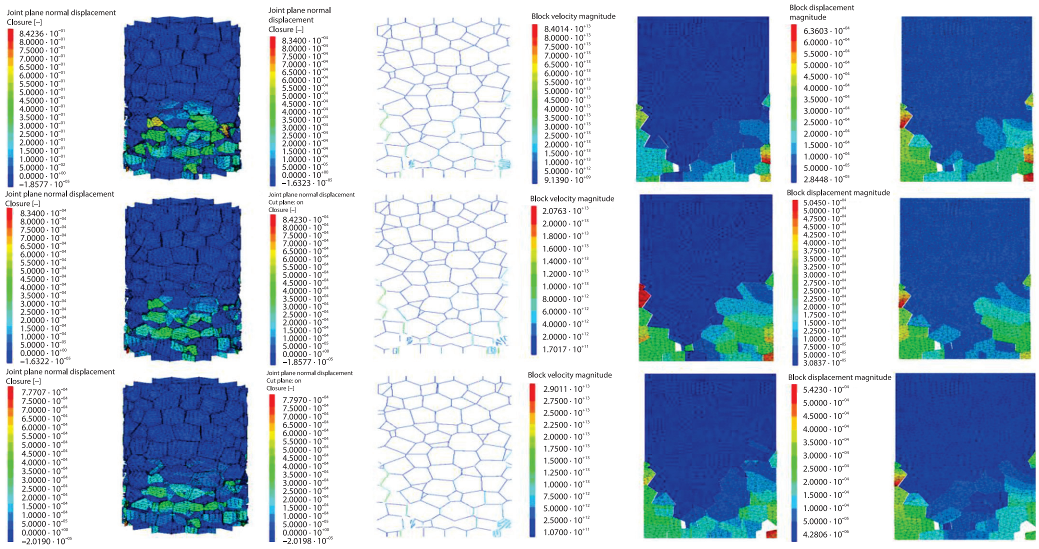

Figure 6. The failure location under different internal friction angle

Conclusion

In the present paper, a numerical model of heterogeneous rock is established and uniaxial compression test is carried out to study the effect of rock internal friction angle on rock fracture process and mechanical behavior. Heterogeneity leads to uneven stress distribution during uniaxial compression of rocks, resulting in localized stress concentration and, ultimately, localized failure. The cement (clay minerals) sections are the primary areas for shear crack propagation due to their lower strength than rock and other contact types. This observation microscopically clarifies the impact of heterogeneity on rock fracture. The greater the angle of friction, the greater the strength of the rock mass. This increase in strength not only manifests in the peak stress but also influences the location and size of the failure zone post-peak.

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