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Research Paper

Numerical study on the influence of cross-sectional shape on strength and deformation behaviors of rocks under uniaxial compression

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ABSTRACT

Cross-sectional shape effect, which has not been well studied, is one of the geometry effects that influence rock laboratory test results. In order to investigate the influence of cross-sectional shape on the strength and deformation behaviors of rocks, a comprehensive numerical experiment is carried out to simulate the deformation responses of circular, square, and rectangular cross-sectionally shaped specimens in uniaxial compression. The validity of the numerical model is first examined by comparing the uniaxial compressive strengths (UCS) of cylinder and square prism specimens obtained from the numerical modeling with these obtained in laboratory tests. Both the numerical modeling and laboratory test results show that the cross-sectional shape has a very small influence on the UCS of rocks. However, the numerical results show that the cross-sectional shape affects the post-peak behaviors of rocks considerably. It is also concluded that hoop tension contributes little to affecting rock strength. It is revealed through the numerical study that in the laboratory tests because the square prism specimens with a slenderness (defined by specimen height divided by specimen width) the same as that of a cylinder specimen have an equivalent diameter larger than that of the cylinder specimens, a slightly higher strength of the square prism specimens is thus observed. It is suggested to use the equivalent diameter of a non-circular cross-section to define the slenderness of a specimen to present laboratory test and numerical simulation results consistently.

1. Introduction

Laboratory test results of rocks depend on many factors. Test results have shown that compared with smaller specimens larger specimens of the same slenderness (height to width or diameter ratio) tend to have a lower rock strength [1], and this is known as size effect. Aside from specimen size, the shape of specimens can affect laboratory test results. The shape effect includes the influence of the slenderness and the cross-sectional shape (circular or square) of a rock specimen on its uniaxial compressive strength (UCS) and post-peak stress–strain curve. It is documented that due to the end effect caused by friction at the specimen-platen contacts, the UCS of rocks increases with the decrease of the slenderness of the specimens [2,3]. However, the influence of cross-sectional shape on UCS of rocks is not well studied because circular rather than square cross-sectionally shaped specimens are often used in rock mechanical property testing, as suggested by the International Society for Rock Mechanics (ISRM) [4]. True triaxial testing has become popular in recent years and prismatic (square or rectangular cross-sectionally shaped) specimens are routinely employed in true triaxial testing [5–10]. Unfortunately, the influence of specimen's cross-sectional shape on rock's peak strength under true triaxial loading is again not well studied.

The importance of obtaining not only the peak strength but also the complete stress–strain curve of rocks from laboratory tests has been recognized because the post-peak behavior of rocks affects rock stability [11–14]. For instance, a good knowledge of the post-peak behavior of rocks is needed to estimate the depth of failure accurately for rock support design [15] and to avoid violent pillar failure [16,17]. Thus, it is also important to study the influence of cross-sectional shape on the post-peak behavior of rocks.

Few systematic studies focused on the cross-sectional shape effect. Hoop tension [18–21] can be induced by the geometry of a cylinder specimen in compression (Fig. 1b) and it may influence crack propagation and hence the strengths of rocks in laboratory and in-situ. Hoop tension also exists in square prism specimens but due to the shape difference, it would be less than that in cylinder specimens. For a rectangular prism specimen, hoop tension

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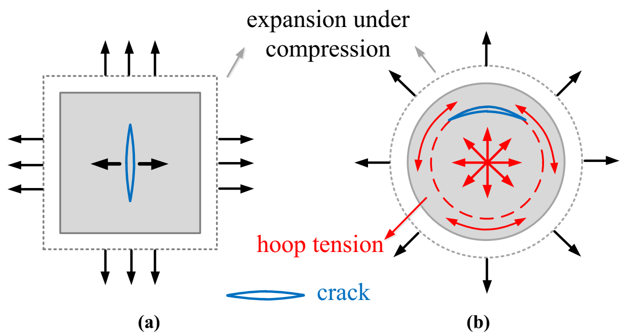

Fig. 1. Illustrations of hoop tension and its influence on crack propagation: (a) crack propagation on a non-circular shaped cross section (e.g., near an excavation boundary); (b) crack propagation on a circular shaped cross section (e.g., in a cylinder specimen).

would be even less. If hoop tension does influence rock strength, it can be hypothesized that the strength of a cylinder specimen should be higher than the strength of a square or a rectangular prism specimen.

Uniaxial compression tests using cylinder and square prism specimens, sampled from a large block of Beishan granite, were conducted by Zhao et al. [22] and the test results indicate that there is no significant cross-sectional shape effect on the UCS of the rock. Due to the difficulty in preparing and conducting UCS tests using rectangular prism specimens, the conclusion on the hoop tension effect was inclusive. Furthermore, the post-peak deformation behavior of the rocks was not investigated in the laboratory tests.

Inspired by the laboratory test conducted by Zhao et al. [22], we plan to use numerical experimental approach to study the cross-sectional shape effect in the present study. First, the strength parameters of Beishan granite [22,23] are obtained for the numerical modeling through a detailed model calibration. Rock strengths of cylinder and square prism specimens are then obtained from the numerical modeling and compared with the laboratory results [22]. Subsequently, more numerical experiments are conducted to investigate the influence of cross-sectional shape on the UCS by adding results of rectangular prism specimens with different slenderness. Finally, the influence of cross-sectional shape on the post-peak behavior of rocks is studied.

2. Influence of cross-sectional shape on UCS of rocks

2.1. Numerical model and model parameters

A numerical experiment using the ABAQUS/Explicit FEM tool is carried out to study the cross-sectional shape effect in uniaxial compression tests. ABAQUS/Explicit is a powerful tool in solving highly nonlinear structure system problems under transient loads by employing the explicit numerical scheme. It is also robust to solve problems involving complex boundary conditions with efficient contact convergence and oscillation control.

The material properties of Beishan granite are calibrated first to simulate the uniaxial compression tests. The pre-peak behavior of the rock specimens in compression is simplified as linear elastic, and the elastic properties (Poisson's ratio and Young's modulus), obtained from the uniaxial compression test results, are summarized in Table 1. The peak strength and the post-peak behavior of the rock specimens are governed by strength parameters. Mohr-Coulomb failure criterion with a tension cut-off is employed. Based on the fitting equation for the triaxial compression test results of Beishan granite under low confinement (0–5 MPa) [23], the frictional strength parameter of the rock is obtained (Table 1). Then, based on the UCS of Beishan granite [22], cohesive strength parameters of the rock (Table 2) are calibrated and used in this numerical experiment. Tensile strength was not provided in the test results of Beishan granite; thus the calibration for tension cut-off was based on the data compiled in [24,25], and the strength ratio of UCS to tensile strength was taken as 20.

Steel loading platens used to apply a constant loading velocity onto the ends of the specimen are modeled to honor laboratory test conditions; steel property (E = 200 GPa, ν = 0.3) is assigned to the platens. 3D simulation models of the specimens with standard slenderness (H/W = 2 or H/D = 2, where H is the height of the specimens, W is the width of the square prism specimen, and D is the diameter of the cylinder specimen) subjected to uniaxial compression by two steel platens are shown in Fig. 2. The geometry of the cylinder specimen is 50 mm in diameter and 100 mm in height (Fig. 2a), and that of the square prism specimen is 50 mm in width and 100 mm in height (Fig. 2b), which are same as the dimensions of the laboratory test specimens [22].

In the laboratory tests, the ends of the specimens were lubricated with a thin layer of Vaseline to reduce the end effect. A coefficient of friction (μ) of 0.1, recommended from some researchers [26,27], is used for the specimen-platen contacts in the numerical modeling. In addition to the simulation of the cylinder and square prism specimens used in the laboratory tests, a rectangular prism specimen is considered in our numerical modeling to study the shape effect. The cross-section of the rectangular prism specimen is 70 mm in length and 35 mm in width, with a cross-sectional area of 2450 mm^2, which is very close to the cross-sectional area of the square prism specimen (2500 mm^2). The height of the rectangular prism specimen is 100 mm, which is the same as that of the cylinder and the square prism specimens.

2.2. Modeling results

Fig. 3 presents the modeling results of the UCS of the cylinder, square prism, and rectangular prism specimens with different slenderness varying from 1.0 to 2.5, along with the UCS obtained from the laboratory tests for a slenderness of 2.0 [22]. Because there is no agreed definition of the slenderness of a rectangular prism specimen, the slenderness of the rectangular prism specimens presented in the figure is defined by the specimen height divided by the specimen's equivalent width that results in the same cross-section area as the square prism specimen. Due to the end effect that can activate confined zones near the specimen ends (Fig. 4), the UCS of the specimens increases as the slenderness decreases. It is seen that there is no significant difference of UCS among different cross-sectionally shaped specimens with the same slenderness. The UCS of the square prism specimens is, in fact, slightly higher than that of the cylinder specimens of the same slenderness. The difference of the UCS between the cylinder and the square prism specimens increases with the decrease of the slenderness due to the increased end effect.

The numerical simulation results are in good agreement with the laboratory results of Zhao et al. [22]. In their laboratory tests, eight specimens of each shape with a slenderness of 2.0 were tested and the mean UCS and the standard deviations of the cylinder and the square prism specimens were 132.1 MPa, 4.58 MPa, and 135.8 MPa, 7.20 MPa, respectively. The laboratory results showed that using carefully prepared specimens for testing, the average UCS of the cylinder and the square prism specimens were close to each other. In fact, the average UCS of the square prism specimens is 2.7% higher than that of the cylinder specimens, and our numerical modeling result is in good agreement with the test result. Therefore, it is proven both experimentally and numerically that the cross-sectional shape has a limited influence on the UCS of rocks.