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Determination of confinement and plastic strain dependent post-peak strength of intact rocks

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ABSTRACT

The post-peak strength behavior of rocks is important for stability analysis of underground excavations. This paper studies the confinement and plastic strain dependent post-peak strength of intact rocks. First, the post-peak behavior of rocks is studied by conducting triaxial compression tests on a coarse marble. The post-peak strengths of the rock under different confining pressures and plastic strains are obtained using the recorded stress–strain curves. A strength degradation index is then proposed to represent the post-peak strength degradation, and a negative exponential function, which includes a shape parameter *n*, is used to describe the relation between the strength degradation index and the confining pressure. Parameter *n* is plastic strain dependent, which decreases with the increase of plastic strain. The proposed strength degradation model can well capture the post-peak strength envelopes of the coarse marble under different plastic strains. Finally, two sets of triaxial compression test data from previous studies are used to further verify the strength degradation model. The peak and post-peak strength behaviors of two marbles are well represented using the proposed model. The approach proposed in this study also provides a simple yet useful method for determining the realistic residual strength of intact rocks.

1. Introduction

The study of strength and deformation behavior of rocks has long been recognized as an important topic in rock mechanics. With the advance of construction technologies, many large geotechnical engineering structures such as deep tunnels for mining, boreholes for oil or gas production, tunnels for storage of radioactive waste, and wells for injection of carbon dioxides, are being constructed at great depth, where the associated geological conditions are very complex. Therefore, it is important for geotechnical engineers to evaluate rock strength under such conditions. A good estimate of rock strength will facilitate cost-effective design and long-term stability of these engineering structures.

The peak strength of rocks represents the maximum loading capacity that a rock can sustain. It is commonly used as an important input parameter in stability analysis of engineering structures. The Hoek-Brown (H-B) model, which considers the nonlinearity of the strength envelope, is widely used to estimate the peak strength of rocks (Hoek and Brown, 1997; Hoek et al., 2002; Cai et al., 2004), and the model has been studied and improved by some researchers (Cai, 2010; Peng et al., 2014; Shen and Karakus, 2014). In the past several decades, the importance of having a correct estimate of the residual strength of rocks is gradually recognized for evaluating stability of geotechnical engineering structures, especially for deep tunnels. This is mainly due to the fact that rocks around a tunnel can still sustain certain levels of load even after they enter into the post-peak deformation stage. Cai et al. (2007) simulated yielding zones around a 6 m wide tunnel with different residual strength parameters and found that the residual strength had a significant influence on the yielding zones. Therefore, the residual strength of rocks should be appropriately determined in order to achieve an optimal excavation design.

Large-scale in-situ tests have been conducted in some engineering projects to directly evaluate rock strengths for design. For example, in-situ block shear tests are generally conducted in large civil projects to obtain shear strength of rock masses. The tested blocks are about a half to 1 m in size, and the obtained peak and residual strengths are usually representative of the strength behavior for a single shear plane in the rock mass. The in-situ block shear tests tend to underestimate the residual strength of rock masses in the high confinement zone because the applied normal pressures are normally low and the interlocking effect is not properly reflected. In addition, large-scale in-situ tests are

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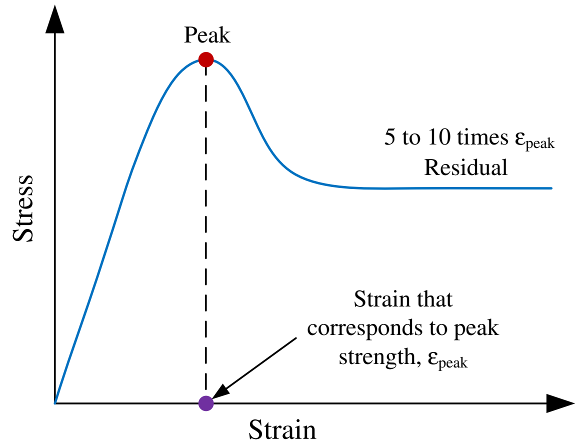

Fig. 1. A typical strain-softening curve of intact rocks (after Cai et al., 2007).

expensive and time-consuming when compared with laboratory testing on rock specimens.

Many researchers had studied the complete stress–strain relations of rocks after the development of stiff servo-controlled test machines (Paterson, 1958; Brace et al., 1966; Mogi, 1966; Bieniawski, 1967; Wawersik and Fairhurst, 1970; Hudson et al., 1972; Wong, 1982; Besuelle et al., 2000; Chang and Lee, 2004; Zhao et al., 2013). The strength of rocks is significantly affected by the applied confining pressure, and the peak and post-peak strengths increase with increasing confining pressure. Under low confining pressures, the loss of the cohesive strength after the peak load leads to strain localization with a stress drop which is traditionally called strain-softening behavior. On the other hand, rock deformation shows a distinct ductile behavior under high confining pressures.

Although the post-peak behavior of rocks has been extensively studied using laboratory testing, there are still no good models for determining post-peak strength of rocks. Traditionally, the models (i.e., H-B model or Mohr-Coulomb (M-C) model) used for estimating peak strength are used to evaluate the residual strength of rocks by replacing the peak strength parameters in these models with residual strength parameters (Cai et al., 2007). This approach is simple but may not provide a comprehensive way to determine the post-peak strength at different deformation stages. Therefore, it is important to study the post-peak strength behavior of rocks and develop a novel model to estimate the residual strength, which is the main scope of this study.

When studying the post-peak strength behavior of rocks in laboratory tests, the residual strength obtained from the stress–strain curve can be questionable. As presented in Fig. 1, the residual strength is usually defined as the plateau after the peak stress, in a strain range of about 5 to 10 times the strain that corresponds to the peak strength (Cai et al., 2007). The remaining load bearing capacity is commonly referred to as the "residual strength" in most civil and mining engineering applications. However, the large strain that corresponds to the residual strength is hard to be attained in a typical laboratory compression test. Tests often have to be stopped at a smaller strain due to insufficient deformation capacity of the test machines or fear of damaging triaxial cells. The obtained "residual strengths", therefore, are not the realistic residual strengths. Depending on the level of plastic straining, they reflect only the post-peak strength of the tested rocks. In the present study, we use the concept of post-peak strength to denote a stress level post peak. The post-peak strength depends on confinement and the amount of plastic deformation. If sufficient plastic deformation is achieved, the post-peak strength approaches the realistic residual strength.

In this paper, confinement and plastic strain dependent post-peak strength is studied by conducting triaxial compression tests on a coarse marble. A model is proposed to represent the post-peak strength envelopes through the introduction of a strength degradation index. The proposed model is further validated by examining two sets of triaxial compression test data from previous studies. The possibility of

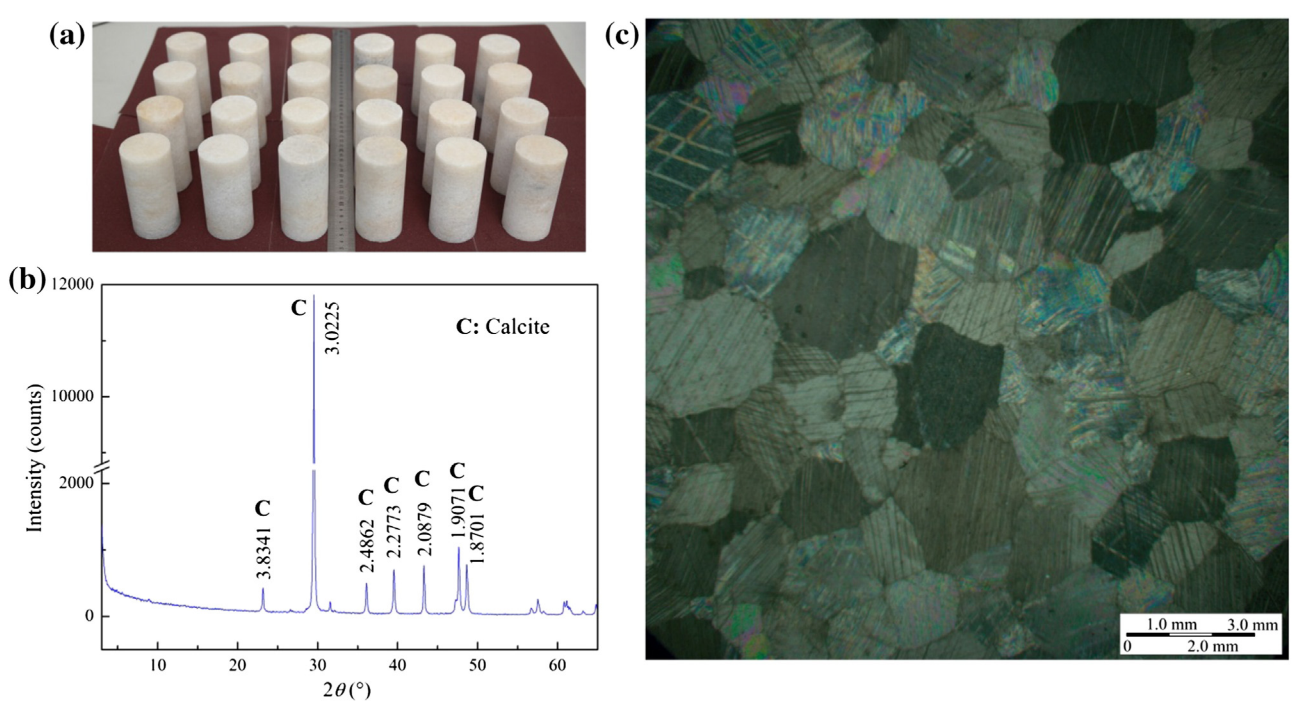

Fig. 2. Prepared coarse marble specimens. (a) Photograph of the specimens; (b) X-ray diffraction pattern of a specimen; (c) optical microscopy observation of a thin section of the specimen.

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