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Anisotropic shear behavior of closely jointed rock masses

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ABSTRACT

In-situ shear tests on a closely jointed rock mass containing two sets of joints, one continuous and another staggered, were conducted. A series of laboratory shear tests with varying combinations of loading conditions and geometrical characteristics of rock joints were also carried out. A Discrete Element Method (DEM) was used to numerically simulate the in-situ and laboratory shear tests. The in-situ tests, laboratory tests and numerical modeling were aimed at evaluating the anisotropic shear behavior of closely jointed rock masses. Comparison between the test and simulation results of this study with the results of similar laboratory tests was completed. The simulation results agreed well with the laboratory test results and provided slightly higher shear stresses comparing to the results of in-situ shear tests. The test and simulation results showed that the jointed rock masses exhibited a strong anisotropic shear behavior, the significance of which depended on the orientation of the continuous joint set. Different failure mechanisms were confirmed in the tested and simulated rock mass models with different geometrical characteristics of rock joints, which resulted in the anisotropic shear behavior.

1. Introduction

The shear behavior of jointed rock masses is an important issue in rock engineering, especially for the stability of slopes and dam foundations. However, limited cases of in-situ shear tests have been conducted, mainly due to their high costs and technical challenges in implementation [1–5]. The shear behavior of closely jointed rock masses is governed by the mechanical properties of intact rock matrix and mechanical and geometrical characteristics of rock joint systems, such as the orientations of the joint sets and direction of the shear loading. Different geometrical characteristics will induce different failure mechanisms of rock masses during shear processes, resulting in different shear behaviors [6].

Since in-situ tests are expensive, laboratory tests are typically conducted to give insight into the deformation behavior and failure mechanisms of jointed rock masses subjected to unconfined compression [7], biaxial compression [8] and triaxial compression [9]. Such laboratory test results show that the strength of a jointed rock mass increases with the increase of confining stress and decrease of joint density, decreasing to the lowest value at a critical joint orientation. Different failure modes, such as splitting and shearing through intact rock and sliding along rock joints, can be observed on the models with different geometrical characteristics of rock joints. Hayashi and Fujiwara [10] conducted a series of direct shear tests on jointed rock mass models with one continuous joint set and reported that higher shear strengths could be observed in most orientations of a positive joint orientation system than that in a negative joint orientation system (see Fig. 1). His results showed that the compaction of rock mass increased the normal stress acting on rock joints, resulting in the increase of the strength of rock mass in the positive joint orientation system, while the dilation of rock mass reduced the strength of negative joint orientation system. Kawamoto [11] conducted shear tests on similar mass models, and found that in the positive joint orientation system, cracking initiated in the position underneath the toe of the face of the loading block subjected to shear loading, which propagated and connected with pre-existing joints and finally formed the failure plane. In the negative joint orientation system, opening of joints firstly happened in the same position, which then induced tensile cracks accompanied by the rotation of the rock mass, leading to the ultimate failure (see Fig. 9 presented later). Nagayama et al. [12,13] also conducted shear tests on jointed rock mass models, emphasizing on the influence of rock joint orientation on the shear strength of rock mass. They reported that the strength of a jointed rock mass could be governed by the strength of intact rock, rock joints, or the mix of both depending on the orientation of the continuous joint set.

Besides the laboratory tests, numerical simulations using Discrete Element Method (DEM), which more realistically models the mechanical behavior (compression, sliding, opening etc.) and

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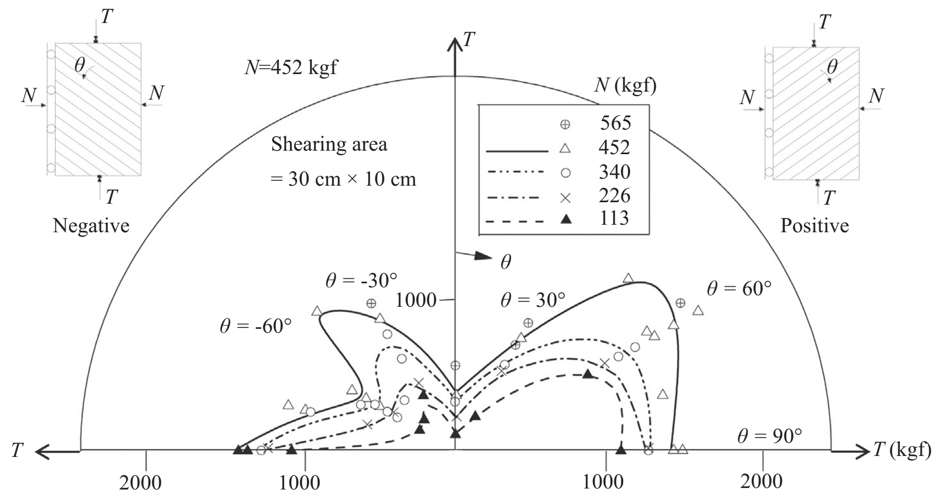

Fig. 1. Results of shear tests conducted by Hayashi and Fujiwara [10] on jointed rock masses with positive and negative joint orientation systems.

geometrical characteristics (orientation, gap, spacing etc.) of rock joints, have achieved tremendous success in helping understand the mechanical behavior of jointed rock masses [14]. Although jointed rock masses subjected to unconfined, biaxial, and triaxial normal compressions have been modeled in numerical simulations, no attention has been paid to modeling jointed rock masses subjected to the combined normal and shear loadings. In addition, many numerical studies lacked support from measured data from laboratory tests or in-situ tests, thus caused difficulties for justifications of validity and applicability of the numerical models.

To overcome the above mentioned shortcomings, combined research of numerical simulations and in-situ shear tests on a closely jointed rock mass, supported further by a series of laboratory shear tests, were conducted. Laboratory test models containing a set of continuous joints intersected by a set of staggered joints orthogonal to the continuous joint set were reproduced at a 1/3 scale using artificial rock materials. A series of shear tests on these laboratory test models were carried out, taking into account the influence of loading conditions (lateral restraint stress and initial normal stress) and the geometrical characteristics of the rock joints (dip angle and spacing), in order to investigate the anisotropic shear behavior of closely jointed rock masses. The mechanical properties of the in-situ intact rock and rock joints, and the artificial rock materials and joints for laboratory tests were measured through a well-planned laboratory testing procedure, which were then adopted in the numerical simulations of the shear tests using a DEM. The influence of the orientation of continuous joint set on the anisotropic shear behavior of rock masses was further studied with numerical models containing varying dip angles of the continuous joint set. The test and simulation results were verified through comparisons with the results of similar laboratory tests reported in the literature.

2. Setup of in-situ and laboratory shear tests

2.1. Characteristics of the prototype rock mass

The site for the in-situ shear tests is located on Kyushu Island, Japan (a possible site for a foundation of a nuclear power plant). The rock mass in this site is constituted by Mesozoic clay slate, sandstone, and conglomerate, covered by a shallow layer of Cenozoic igneous rock. The rock mass is slightly weathered, and closely jointed by three sets of rock joints. The geometrical characteristics of rock joints and the mechanical properties of intact rocks and rock joints at two locations in this site with different rock types (location A: clay slate; location B: conglomerate) were investigated. The rock mass at location A was chosen as the prototype rock mass for the laboratory tests, and in-situ shear tests were conducted at location B. From a cross-sectional view, two sets of joints can be identified in the field, orthogonal to each other with different spacings. The joints of Set 1 are continuous with good persistence, serving as the major rock structure; the joints of Set 2 are less persistent and staggered, and are oriented perpendicular to the joints of Set 1. Fig. 2 shows an example of the core specimen sketch, the statistical orientation distribution of the rock joints and a cross-sectional view of the distribution of joints in the field. The sketches show a set of sub-vertical persistent rock joints (Set 1), intersecting with several parallel sub-horizontal rock joints (Set 2). The lower hemisphere stereographic projection of joint poles shows that most of the rock joints of Set 1 in the field have moderate to steep dip angles ranging from 50° to 90°. Through the analysis of 34 boreholes with a maximum length of 230 m and field investigation by trench and tunnel excavations (Fig. 2c), the approximate cross-sectional profiles of the geometrical distribution of joints for the two locations were then obtained, as shown in Fig. 3.

According to the survey results, the spacing of Set 1 is 30–60 mm, and that of Set 2 is 90–180 mm at location A. The mean spacing of joints of Set 1 is 50 mm with a standard deviation of 30 mm, and 100 mm with a standard deviation of 60 mm for Set 2, at location B. Set 1 dips at mean angles of 70° and 75° at the locations A and B, with standard deviations of 9.9° and 8.2°, respectively.

Note that there is a third set of joints on the site with orientation normal to both set 1 and set 2 and in the out-of-plane direction in Fig. 2, which has a mean spacing larger than 1 m. Its influence on the in-situ shear tests with a sheared area of 600 mm × 600 mm is therefore negligible. This information also made a 2D numerical model for the site, a reasonable simplification.

The physico-mechanical properties of the intact rocks and the mechanical properties of rock joints in the two locations are shown in Tables 1 and 2, respectively. The properties of intact rocks were estimated through standard laboratory unconfined compression tests and triaxial compression tests, and the properties of rock joints were estimated through laboratory direct shear tests. Core specimens were used for all tests. A servo-controlled direct shear apparatus was used in this study to accurately estimate the shear behavior of relevant rock joints, which is important since the deformation and failure of rock joints govern the total performance of the jointed rock masses. The testing procedure and some results are presented in detail in Refs. [15,16].