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The influence of bedding plane orientation on rock breakages in biaxial states

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ABSTRACT

Bedding planes are weak structural planes in rock masses, significantly affecting rock properties. In the present article, the indentation and morphology scanning tests have been conducted to investigate the influence of the bedding plane orientation on rock breakages in biaxial states. First, the indentation tests show that the increase in δ restrained the propagation of both internal and surface cracks. Then, the theoretical analysis properly validated this conclusion. In addition, the morphological scanning tests show that these restraints on crack propagation directly led to the shrinkage of grooves. It is believed that the crack propagation is responsible for the chip formation when δ is low, whereas chips frequently form by shear failure for higher δ. Furthermore, the recorded AE, reflecting the crack propagation level, also indicates that fiercer crack propagation occurred for lower δ. Simultaneously, the sharp drops of the indentation force frequently were accompanied with promoted AE. With the consumed energy and the groove volume, it can be concluded that the increase in δ restrains the crack propagation and further leads to the decrease in indentation efficiency.

1. Introduction

Many internal or external factors of rock, such as structural planes, rock brittleness and the ratio of spacing to penetration, directly affect the rock breakages induced by excavation tools and influence the excavation performance. Thus, many researchers have investigated the rock breakage mechanism for various conditions. For instance, the indentation tests conducted by Innaurato et al. [1] indicated that the chipping level characterized by crack propagation is promoted by the increased confinement, and some other laboratory tests have verified this conclusion [2,3]. In addition, Gong and Zhao [4] proposed that high rock brittleness frequently leads to more efficient chipping because of the promoted crack propagation. Furthermore, Liu et al. [3] proposed that the increase in the s/p ratio restrains the surface crack propagation and thus affects the indentation efficiency. With other studies on rock breakages generated by excavation tools [5–11], it has been widely recognized that crack propagation plays a vital role in rock breakages.

Discontinuities in rock may significantly affect crack propagation [12–16]. Thus, bedding planes, the typical structural planes in sedimentary rock, are also supposed to affect the rock breakages caused by excavation tools. Indeed, extensive numerical and laboratory tests have verified this speculation. First, the inclination angle, θ, determined by the tunnel axis and joint plane in Fig. 1(a), significantly affects rock breakages. Gong and Zhao [17] proposed in a field investigation that the penetration rate first increases and subsequently decreases with the increase in θ. The numerical studies by Gong et al. [18], and the laboratory tests by Wanner and Aeberli [19] and Sanio [20] agree well with this conclusion. In addition, the numerical investigation of Gong et al. [21] by conducting single indentation tests indicated that the joint spacing, s, also affects the fracture mode. Bejari and Hamidi [22] also proposed that the spacing and orientation of the joint plane determines crack propagation induced by indentations.

The above studies have greatly contributed to understanding the effect of the structural plane on the internal crack propagation on the ABC plane (Fig. 1(b)). However, in the practical field, the excavated rock usually locates in biaxial states (Fig. 1(a)). In addition, chips are spatial objects with several facets. Thus, the connection of the internal cracks from adjacent crushed zones only partially forms the chips. The incision by the surface cracks between adjacent cutters is the other

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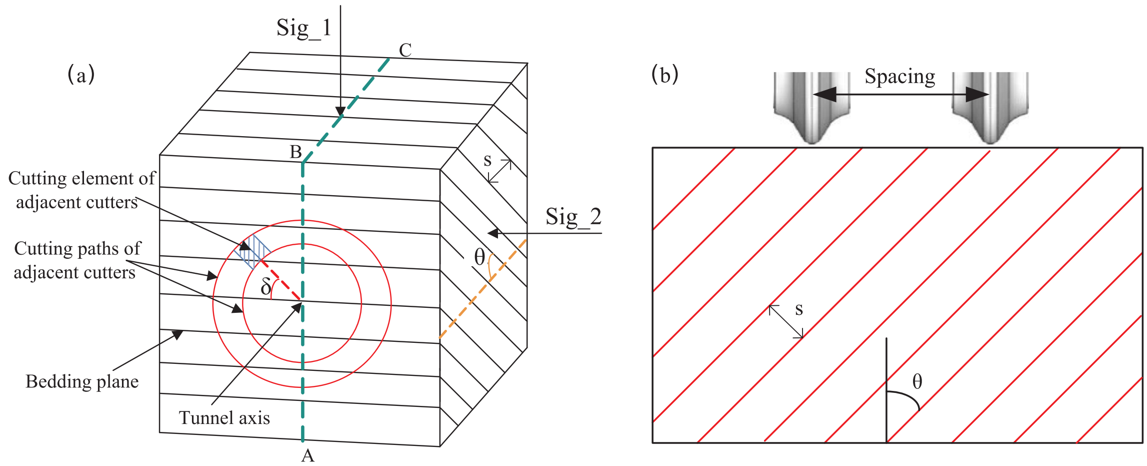

Fig. 1. Field and laboratory models: (a) a tunnel face in field; (b) previous studies of the chip formation in the ABC plane.

essential factor determining chip formation. Therefore, the incision by surface cracks deserves detailed investigation. Furthermore, for different rotation angles in Fig. 1(a), δ, the crack propagation may be affected. However, the effect of the rotation angle of the crack propagation induced by excavation tools, especially on the surface crack propagation, remains unknown.

Thus, this paper aims to investigate the effect of δ on rock breakages that may be induced by crack propagation or shear failure. First, to simulate the practical rock breakages, indentation tests, used to investigate the rock breakages by excavation tools, were conducted in biaxial states. Simultaneously, acoustic events were recorded in the indentations to characterize crack propagation degree. Second, grooves were measured by a morphology machine to analyze the chip formation and to obtain groove volumes. Finally, the effect of δ on indentation efficiency will be analyzed.

2. Test methodology

2.1. Rock specimen preparation and test apparatus

Discontinuities widely exist in rock masses, especially for the sediment rock. In the present article, sandstone specimens, the typical sediment rock, containing bedding planes with the bed thickness of about 1 mm, were adopted to investigate the influence of bedding plane orientation on rock breakages by indentations. Table 1 lists the main mechanical parameters obtained by conducting uniaxial compressive tests, shear tests and Brazilian tensile tests. The cubic specimens were 250 mm, 200 mm and 100 mm in length, width and height, respectively. According to the previous study and the mechanical properties in Table 1, the ratio of the plastic zone to the minimum length of the sample was much less than 1/6 and, therefore, the specimen size is reasonable [2].

Practically, rocks on a workface are in biaxial states. Thus, the indentation tests, widely used to simulate the excavation process [1–3], were performed on a triaxial testing platform reported by Li et al. [23] (Fig. 2(a)). The horizontal and vertical loading systems can be independently operated in a displacement-controlled or a force-controlled manner. Simultaneously, the indentation force can be precisely recorded every few seconds. The maximum loading forces, up to 3000 kN in the vertical direction and 2000 kN in the horizontal direction, can satisfy the requirements of indentation force and confinements provisions. The heat-treated loading frame with large stiffness keeps the indentation result reliable. In addition, the indenter containing two semi-sized TBM blades with a spacing of 70 mm was also heat-treated [24]. Moreover, in order to investigate the crack propagation degree in the indentation process, the PC-II AE system consisting of the AE sensor, the amplifier, the recording and analysis system was used to dynamically monitor the AE event. The AE sensor was the R6a sensor with a frequency range of 20–100 kHz. Then, the sensor was connected to an amplifier with a gain of 40 dB. The AE signals were processed by the recording and analysis system with a sampling frequency of 1MSPS. To eliminate the background noise, the trigger level was set to 40 dB (Fig. 2(b)). Furthermore, to precisely measure the groove volume and analyze the formation of the groove after indentations, a high-resolution morphology scanning machine with a precision up to 0.5 μm was applied [25,26].

2.2. Test design and procedure

Considering the confinements in the field conditions (Fig. 1(a)), two vertical confinements (5 MPa and 15 MPa) were analyzed in the present article. The rotation angle, δ, is determined by the bedding plane and the plane determined by two indentation axis (Fig. 1(a)). The inclination angle (θ) was 90°. According to the different match ups between confinements and bedding planes (Fig. 2(b)), two series of indentation tests, named Series A and Series B, were conducted as shown in Table 2. It is noted that another Series C, in which the specimens were cast in concrete without external confinements, was conducted in order to test and fix the boundary condition.

A complete test on a specimen consisted of the indentation test, the morphological scanning test, and the internal crack observation by incising the specimen perpendicular to the nicks. Thus, the laboratory tests include the following procedures:

(1) Indentation tests: first, to ensure the even contact and eliminate the stress concentration between loading plates and sample surfaces, lateral surfaces of the sample were grinded and lubricated. Second, the location of the indenter was marked to ensure the specific rotation angle, and then the sample was put in the center of the loading chamber of the triaxial testing platform. Subsequently, the

Table 1
Mechanical parameters of rock samples.

Mechanical properties	Elastic modulus, (GPa)	Poisson's ratio	Uniaxial compressive strength, (Mpa)	Tensile strength, (Mpa)	Friction angle, (°)	Density (g/cm^3)
Sandstone	17.1	0.25	29.5	9.2	41.6	2.5