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The effect of indentation sequence on rock breakages: A study based on laboratory and numerical tests

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ABSTRACT

Rock may response differently to external loads applied in different sequences. Thus, we conducted indentation tests to investigate the effect of the indentation sequence on rock breakages. Sequential indentations, consuming less indentation energy, usually resulted in larger and deeper grooves and then led to lower specific energies. Thus, we conclude that sequential indentations occur instead of simultaneous indentations form larger grooves with the same indentation energy. To further validate this conclusion, we performed a series of numerical tests. The numerical analysis of stress evolution shows that, for simultaneous indentations, the propagation of an internal crack from an inner rim restrained the propagation of the other internal crack from the other inner rim. However, the chipping pattern varied for sequential indentations. In the first indentation process, an internal crack, initiating from an inner rim, is usually connected with an internal crack caused by the second indentation. The deflection angles of the internal cracks for the sequential indentations were smaller because of the lower compressive stress in the horizontal direction. Then, these smaller deflection angles led to larger chips.

1. Introduction

Indentation tests have been extensively applied to investigate the rock breakages that significantly affect indentation efficiency [1–3]. Specific energy (SE), determined by the chipping volume between indentations and the consumed indentation energy, is a critical index of cutting efficiency. Thus, extensive studies, applying single or multi indentations, have reported many important characteristics of chipping and indentation force. For the single indentation tests, Huang's theoretical investigation in plane conditions indicated that the initiation and deflection angles increase with the increase in confinements [4]. Simultaneously, the increase in confinements usually leads to increases in both indentation force and energy. In addition, the repeated indentations, conducted by a single TBM cutter on a soft rock, indicated that the preset indentation depth significantly affects rock breakages [5]. Then, the most unfavorable depth was obtained by analyzing the consumed energy and the chipping volume. Another numerical study, using single indentations, showed that shear failure occurs for small indentation depths, whereas tensile failure frequently occurs for larger depths [6]. Moreover, the numerical indentations by Gong indicated that joint spacing and orientation affect rock breakages, and thus further influence indentation efficiency [7,8]. Other studies, based on single indentations, have significantly contributed to understanding rock breakages [9,10]. However,

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Table 1
Main mechanical parameters of the rock samples.

Mechanical parameters	Density (g/cm^3)	Elastic modulus (GPa)	Poisson's ratio	Uniaxial compression strength (MPa)	Tensile strength (MPa)	Friction angle (°)
Value	2.5	17.1	0.25	29.5	9.2	41.6

chips usually form between adjacent indentations; thus, rock breakages between indentations might be more representative. To investigate the rock breakages between indentations, extensive numerical tests in plane conditions have been conducted because of the analytic feasibility. Similarly, previous researchers investigated the effects of confinement, joint distribution and spacing–penetration (s/p) ratio on rock breakages. For instance, Ma proposed that the chipping level increases with an increase in confinement, when the confinement is higher than a critical value [11]. In addition, Bejari stated that indentation efficiency decreases with an increase in joint spacing for a specific orientation [1]. Moreover, based on the analysis of the consumed energy and of the chipping area, Moon proposed that the optimal s/p ratio is about 10 [12]. With other numerical studies [13,14], it has been concluded that crack propagation between adjacent indentations determines chip formation and thus further influences cutting efficiency. Accordingly, recent laboratory indentation tests have verified this conclusion. For example, simultaneous indentation tests showed that increased confinements may promote internal crack propagation between indentations [15]. Additionally, Liu's sequential indentation tests indicated that effective connections of the internal cracks are fundamental to the formation of deeper grooves between indentations, whereas insufficient connections of internal crack or poor incisions by surface cracks frequently result in shallow grooves with thin chips [16].

The above investigations show that many factors, such as confinements and s/p ratio, significantly affect crack propagation. However, the effect of the loading history, a factor affecting rock breakages, on crack propagation by indentations remains unknown. Thus, in the present article, we conducted simultaneous and sequential indentation tests on sandstone specimens for various s/p ratios and confinements. Additionally, we measured the groove morphology to study the rock breakage characteristics. To further investigate crack propagation between indentations, we conducted a numerical study based on PFC 2D.

2. Laboratory test

2.1. Test preparation

2.1.1. Rock sample preparation

Cubic sandstone specimens, whose length, thickness, and height were 25 cm, 20 cm, and 10 cm, were adopted in the present tests. According to the suggestions by the International Society of Rock Mechanics, the mechanical parameters in Table 1 were obtained by conducting uniaxial compressive, shear, and Brazilian tensile tests. Based on the classification by Yagiz [17] (Yagiz 2009), these specimens were of low brittleness. Specimens were incised from a big intact sandstone block; thus, the mechanical properties of the specimens are close. In addition, to ensure the even contact between rock surfaces and loading plates, the specimen surfaces were ground and lubricated before loading.

2.1.2. Test apparatus and design

To conduct simultaneous and sequential indentations, two kinds of indenters were adopted. Indenters (Indenter A), consisting of two semi-sized TBM blades with various spacings, were applied in the simultaneous indentation tests (Fig. 1(a)), whereas the indenter (Indenter B), containing a single semi-sized TBM blade, was applied in the sequential indentation tests (Fig. 1(b)). These indenters (high-temperature treated) were made of high-stiffness steel. In addition, the indenters were much stiffer than the specimens, thus, the deformation of the indenters in indentations is negligible. In addition, the same geometrical shape of each blade made the laboratory results comparable.

To practically simulate field indentations, these sandstone specimens were indented in biaxial states, achieved on a triaxial testing platform in Fig. 2(a). This platform consisted of a loading system, a controlling system, and a computer system. The high-stiffness loading frame made the indentation results reliable. Fig. 2(b) shows the free-body diagram of the rock specimen, placed in the loading chamber. Before indentation, the lateral surfaces of the specimen were compressed by servo-controlled horizontal forces to achieve specific confinements. The maximum and minimum confinements are denoted by <sigma>2 and <sigma>1, respectively. The differential stress that may significantly affect rock breakage is defined as <sigma>2-<sigma>1. Simultaneous and sequential indentations were conducted by applying the indenters in Figs. 1(a) and (b), respectively. In the indentation processes, the constant indentation rate (servo-controlled) was 0.5 mm/min; simultaneously, the computer system recorded and restored the indentation force and depth every few seconds. Then, the indentation energy was obtained by integrating the indentation depth and force. After indentation tests, to accurately measure the groove volumes formed between simultaneous or sequential indentations, the morphological measurement machine reported by Chen and Zhao was used [18,19]. Then, the groove morphology and volume were obtained by conducting the corresponding analyses.

Table 2 lists the specifications of two series of indentation tests. According to various s/p ratios and stress levels, the first and second series involved 6 and 8 indentation tests, respectively.

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