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Rock fails in shearing as a tuned critical system

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ABSTRACT

Shearing is the most widely exploited method to fracture and remove rock formations in many man-made rock-opening activities. During shearing, rock breaks into chips due to the periodic nucleation, propagation, and coalescence of numerous micro-cracks. The crack interactions along with the rock's complex physical properties lead to extreme challenges in reaching a consensus on the rock's failure behavior in shearing. In this paper, force-drop events, as a quantitative measure of the global rock breakage occurrence, were recorded and analyzed. A power-law distribution with a tunable cut-off between the frequency of the force-drop events and their magnitudes is shown. The obtained results, for the first time, reveal the rock's tuned critical behavior in shearing which is intrinsically similar to its failure behavior widely observed in earthquakes.

1. Introduction

Rock shearing processes illustrated in Fig. 1 in which a tool is dragged either along a straight path or a complex trajectory to fracture and remove rock formations layer-by-layer, since their first introduction in the early 1900s,[1] have been widely exploited in many man-made rock opening activities such as oil and gas exploration, underground excavation, stone mining and land bulldozing. Due to its extremely high energy efficiency and penetration rate,[2] rock shearing has been applied in more than 65% of the global oil well drilling footage since 2012.[3] However, the rock's inhomogeneous microstructure, unpredictable internal defects/cracks and its scale-dependent material properties pose numerous difficulties in accurately estimating its failure behavior and preventing catastrophic damage to the drill bits used. Hence, many bit failure phenomena such as bit wear, balling, and fracturing are frequently being observed in daily oil drilling practices[4].

Since the late 1950s, tremendous efforts have been devoted to obtaining insights into the rock's failure behavior in shearing. Rock is widely believed to fail in two fragmentation modes, i.e., crushing and chipping.[5] Crushing creates highly fractured small rock fragments in the form of powder-like chips, while chipping initiates and propagates cracks to form big rock fragments, i.e., chunk-like rock chips. Some researchers believe that the crushing and chipping modes work independently,[6,7] while others agree that the crushing mode initiates cracks first which then triggers the chipping mode.[8,9] According to fracture mechanics, the chipping and crushing modes have been attributed to different reasons, e.g., tensile,[10] shear,[11] or tensile-shear hybrid fractures.[12]

Recent studies suggest that rock breaks due to the complex interactions of many micro-cracks generated under tensile stresses,[13,14] indicating that the crushing and chipping modes are identical in principle but different in the geometry of the formed chips as illustrated in Fig. 2. When the cutter first contacts with the rock, micro-crack nucleation in a compact damage zone beneath the cutter's front face is generated, as shown in Fig. 2a. Then in the crushing process, the compact damage zone grows with the growth of micro-cracks into macro-cracks. At this stage, some of the macro-cracks first reach the free surface of the virgin rock to form many highly fractured small rock fragments in the form of powder-like rock chips, as demonstrated in Fig. 2b. After crushing, the rock failure further develops into chipping, in which macro-cracks in the compact damage zone continue to grow and coalesce with each other. Big rock fragments, namely chunk-like chips are ultimately generated when a combined group of macro-cracks reach the free surface of the virgin rock, as shown in Fig. 2c. Those cracks which are not able to propagate to the rock's free surface remain in the virgin rock as residual cracks. It can be concluded from above that crushing and chipping are initiated based on the same principle. However, a scientific consensus on how numerous micro-cracks interact, coalesce and lead to global rock breakage is still missing. In addition, the rock's mechanical properties such as internal friction have been found to change with loading conditions,[15] which makes the understanding of the failure process even more ambiguous.

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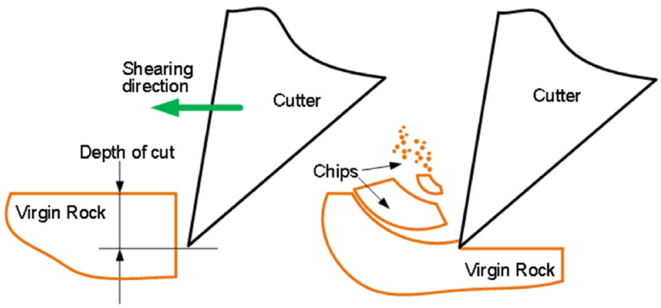

Fig. 1. Schematic of a typical rock shearing process.

In this paper, we postulate that rock fails as a dynamical system and attempt to correlate local micro-fractures and global rock breakage in a statistical way, an approach that is generally used in studying the scaling behaviors of intermittent slips of geological materials or the Earth under slowly applied loads. In fact, the complex sliding and/or brittle fracture of the Earth's crust along local faults results in global avalanche events, i.e., earthquakes, which are, in principle, quite similar to the aforementioned rock shearing processes. According to Green's research,[16] the Earth's crust, as a complex dynamical system, displays a self-organized critical (SOC) behavior in earthquake events. The SOC concept, first proposed by Bak et al,[17] describes a property by which complex dynamical systems self-organize into certain critical states.[18] Since its introduction, SOC phenomena have been universally observed in earthquakes,[19] glacier calving,[20] forest fires,[21] neural networks,[22] crystal plasticity,[23] brittle fragmentation,[24] micro-fracturing in inhomogeneous materials,[25] etc. Recently, the distributions of intermittent slips occurring in the deformation of many materials such as bulk metallic glasses,[26] single crystals,[27] granular materials[28] and even the Earth were found to universally follow a power-law with an exponential cut-off rather than a pure power-law.[29] The change of the exponential cut-off with the loading conditions indicates that a tunable critical behavior rather than the typical SOC behavior exists in these complex dynamical systems. This paper, for the first time, illustrates that rock also fails as a tunable critical system in shearing. The experimental evidence to be presented below illustrates a scale-free similarity between the rock's failure behavior in nature and those in man-made rock opening practices.

2. Experimental method

2.1. Testbed setup

We developed a linear rock shearing testbed (LRST) to perform the aforementioned linear rock shearing tests under accurately adjusted loading conditions. As shown in Fig. 3, the LRST is built based on a commercial CNC milling center (Cincinnati Milacron Sabre EV-750). A dynamometer (Kislter 9255A) was used to measure the three components of the force applied to the rock by the cutter during shearing tests. The charge signals generated by the dynamometer were amplified through a charge amplifier (Kistler 5010) and recorded by a data acquisition (DAQ) system (NI PXI-1036 chassis with PXI-6123 DAQ card). Moreover, three accelerometers (PCB 308B15) were attached to the vice to capture the dynamic vibrations occurring at the rock-cutter interface. The voltage signals generated by the accelerometers were amplified by a voltage amplifier (PCB 480C02) and passed to the abovementioned DAQ system. A high speed high resolution camera (Photron Fastcam Mini UX100) was used to visualize the rock chip formation process. The moving stage of the CNC milling center was used to drive the rock towards the cutter, as shown in Fig. 4, at cutting speeds ranging from 3 to 12,000 mm/min. The travel ranges in the x-, y-, and z-directions are 762, 381, and 508 mm respectively. The linear shearing motion in the reported tests is driven along the x-direction shown in Fig. 5A. In this testbed, the rake angle γ is defined as the angle between the cutter's front face and the vertical direction y (perpendicular to v_c), while the depth of cut d_c is defined as the depth between the rock's free surface and the tool's cutting tip. A tool holder with multiple levels of the rake angle γ, i.e., 10°, 15°, 20°, 25°, and 30°, was manufactured and fixed to the top structure of the milling center. For the tests reported in this paper, the cutting speed, v_c was set to 4.2 mm/s. The tool is a polycrystalline diamond compact cutter identical to those applied in oil drilling, as demonstrated in Fig. 6. The cutter consists two layers, i.e., a diamond layer and a tungsten carbide layer. The cutting edge, as indicated in red was ground to a nearly straight shape with an approximately 19 mm width in order to ensure a simple orthogonal cutting condition in which the cutting edge is always perpendicular to the cutting speed direction. Two types of sedimentary rocks, i.e., Indiana limestone and Austin chalk were selected for the tests, as demonstrated in Fig. 7. The physical properties of the rock samples are listed in Table 1. The cutting force F_c, i.e., the force component along the x-direction shown in Fig. 5A was measured by a piezoelectric dynamometer (Kislter 9255 A) and recorded at a 20 kHz sampling rate. The rock fragmentation phenomena were visualized by a high speed camera (Photron Fastcam Mini UX100) at a 4000 fps sampling speed and a 1280 × 1024 resolution. One example of the high speed camera photos for cutting of Indiana limestone with v_c = 4.2 mm/s, γ = 15° and d_c = 1.4 mm is illustrated in Fig. 5B-G; in (B) the cutter starts to engage with the rock, at the time of (C) a small volume of powder-like rock chips starts to separate from the virgin rock, when the cutting further develops to (D-F) more chips are formed and accumulating in front of the cutter, finally at (G) a big chunk-like chip is suddenly formed with many other powder-like chips. To further reduce the environmental noise, the force responses were filtered through a digital low-pass filter with a cut-off frequency of 300 Hz.

2.2. Force event characterization

Cutting force rapidly increases right after the test starts and oscillates rapidly along the linear trajectory during the whole shearing process until the end of the test. To keep the sampling condition consistent, the sampling of the force data was controlled to start 4.5 s after the shearing test started and last for 22.5 s for all the repeated tests. During the tests, the rake angle γ, was adjustable between two levels, i.e., 15° and 25°. The depth of cut d_c, was also set at two levels, i.e., 0.6 and 1.4 mm for Indiana limestone and 0.8 and 2.4 mm for Austin chalk, respectively. For each test set, i.e., a combination of rock type, rake angle and depth of cut, three repeated cutting tests were conducted with the cutting force and time being recorded, as the example demonstrated in Fig. 8. The detailed loading conditions for all the reported tests can be found in Table 2.

Fig. 9A is an example of the real-time cutting force F_c response obtained in shearing Indiana limestone with v_c = 4.2 mm/s, γ = 15° and d_c = 0.6 mm. A small region of the cutting force response is enlarged in Fig. 9B. A force-drop event is defined as the process of the cutting force change from the moment that a local maximal force is reached to the moment that a local minimum force adjacent to it is reached. The magnitude of a force-drop event can be obtained by subtracting the local minimal force from the preceding local maximal force, as demonstrated in Fig. 9B. We searched and determined all the local maximal and minimal forces from the previously sampled force data by using a user-defined data processing program. The sampled force data is discrete with a constant time interval of 0.05 ms between two adjacent data points. The fundamental algorithm is to compare the force value at a candidate data point with twenty points in its neighborhood. The program will regard a force value at the candidate data point as a local maximal (or minimal) force if it is larger (or smaller) than those at all the adjacent points. A demonstration of this algorithm realization is indicated in Fig. 10: C_0 is considered as the local maximum since it is larger than the 10 points before it and the 10 points