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A new linear cutting machine for assessing the rock-cutting performance of a pick cutter

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ABSTRACT

A small-capacity linear cutting machine (LCM) and a new force measurement method with 1-D load cells were introduced to assess the rock-cutting performance of a low-cost pick cutter. Finite element analysis and LCM tests were implemented to verify the structural stability of the small-capacity LCM and the feasibility of the new force-measurement method. The results of the finite element analysis and the LCM test show that the small-capacity LCM is structurally stable while the new force measurement method is capable of acquiring the cutting forces with an average accuracy of 96.74%. In addition, the small-capacity LCM system for a Roadheader pick cutter was established at a cost of less than 10% of that of a conventional LCM system for a TBM disc cutter.

1. Introduction

The design of the cutting head is one of the most important tasks involved in the manufacturing of rock excavation machines (such as tunnel-boring machines (TBM) and Roadheaders) because the arrangement of the cutters and the design of the cutting head play a dominant role in the rock-cutting ability of these machines. To evaluate the key parameters affecting cutting-head design, tests with large-capacity linear-cutting machines (LCM) have shown them to offer the most reliable and accurate approach because an LCM test is capable of accommodating the full range of cutter forces and rock penetrations. Thus, many researchers have performed large-capacity LCM tests to investigate the cutting performance of a pick or a disc cutter when being applied to the fragmenting of various rock types.[1–20] They could have evaluated the efficiency of rock-cutting machines from the specific energy obtained by measuring the cutting forces and excavated rock volumes resulting from the LCM tests; this enables the prediction of the rock-cutting performance of an excavation machine being designed for a specific type of rock. Hence, it is very important to measure cutting forces accurately when using the LCM test. To ensure the stable operation of machines, the designers and operators should know the cutting forces required by the machine (i.e. thrust force and torque) to cut into a given type of rock. The thrust force and torque can be calculated from the individual cutter's three-dimensional (3D) forces, as obtained from the LCM tests.

To accurately acquire the cutting forces, large-capacity LCMs were designed with frames with large cross-sections to provide a high level of stiffness, with a 3D load cell generally being used to measure the 3D cutting forces, namely, the drag force (F_d), normal force (F_n), and side force (F_s).[4–9] Although the large-capacity tests offer significant advantages, they incur major costs when establishing an LCM system (which includes a high-stiffness frame and a 3D load cell), and also involve time-consuming procedures for preparing the large rock specimens (including the sampling, shaping, transporting, and casting into a steel box). Thus, some researchers have adopted small-capacity tests and have investigated the reliability to economize the high cost of the large-capacity tests.[8,20,21] However, the small-capacity LCM tests, which use a rock core instead of a large rock specimen, still require further study in terms of reliability and feasibility analyses to determine whether the full range of forces can be covered.

Generally, the capacity of a LCM is designed for the disc cutters of a TBM, which incur much higher loads than the pick cutter of a Roadheader.[6–9,12–14,16–19] The mean normal and rolling force (defined as the same direction as F_d) of a disc cutter was found to be 20–250 kN and 2–40 kN,[2,9,12,13,17] whereas the mean normal and drag force of a pick cutter were found to be 0.8–15 kN and 2–10 kN, respectively.[4,5,7,8,16,18,19] Even though these cutting forces could be altered according to the rock types and cutting conditions, a large-capacity LCM will be loaded by a pick cutter to less than 10% of the

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loading capacity. Consequently, the manufacturing of the machine and the shaping of a large specimen inevitably incurs considerable financial loss.

Thus, in this study, we developed a small-capacity, low-cost LCM to validate the reliability of the testing system which can guarantee the stable tests for each pick cutter of a Roadheader. To fabricate a small-capacity LCM testing system, we designed the structures of the developed LCM by referring the existing large-capacity LCMs,[5–9,11–14,16,17,22] while the stability of the system was validated by finite element (FE) analysis. In addition, we proposed a new force measurement method using four 1-D load cells to reduce the cost of using a 3D load cell. This method estimates the 3D cutting force acting on the tip of a pick cutter using simple formulae, which are derived from the force and moment equilibrium. Another FE analysis was also carried out to verify the feasibility of the new force measurement method. Eventually, the small-capacity LCM tests for cement mortar specimens were implemented to check the structural stability and to evaluate the accuracy of the proposed force measurement method.

2. Literature review for LCM tests

Many researchers have addressed large-capacity LCM tests to investigate the cutting performance and efficiency of a pick or a disc cutter. For a large-capacity LCM, a 3D load cell or its assembly have been used to measure the cutting forces. The existing LCM testing systems and the related studies were reviewed, as follows.

Bakar et al.[13,14,16] carried out linear rock cutting tests with a single disc cutter and a chisel-type drag pick on dry and water-saturated sandstone using the LCM at Missouri University of Science & Technology, in the USA. This LCM was equipped with a 3D load cell assembly that consists of four 3D load cells arranged in square diamond patterns, centered over the cutter. According to Gertsch and Summers,[7] this arrangement of the 3D load cells, an alternative to the standard square pattern, is more sensitive to the rolling (or drag) and side forces while continuing to be sensitive to much higher normal forces. Gertsch et al.[9] conducted disc cutting tests to investigate the forces acting on a disc cutter under a series of spacing and penetration conditions. These disc-cutting tests were performed on the LCM at the Earth Mechanics Institute of the Colorado School of Mines. Kim et al.[15] examined the effect of cutting geometry and configuration on bit rotation. Their studies were undertaken on the LCM at Kennametal's rock cutting laboratory in Latrobe PA, USA, and three 3D load cells were used to measure the three cutting force components.

Goktan and Gunes[4] developed prediction equations for the peak and mean cutting forces by analyzing the rock cutting test data using the LCM which was designed and manufactured within the NATO-TU-Excavation Project at Istanbul Technical University. Using identical LCMs, Bilgin et al.[5] carried out rock cutting tests with a conical pick with different depths of cut and cutter spacing values in order to understand the effects of dominant rock properties on cutter performance. In addition, Balci and Bilgin[8] attempted to correlate the small and large capacity rock-cutting tests to select mechanized excavation machines, while Tuncdemir[11] presented rules governing the relationship between specific energy and chip sizes by large-capacity rock cutting tests with the same LCM. This LCM measured the cutting forces acting on a cutter via a single 3D load cell.

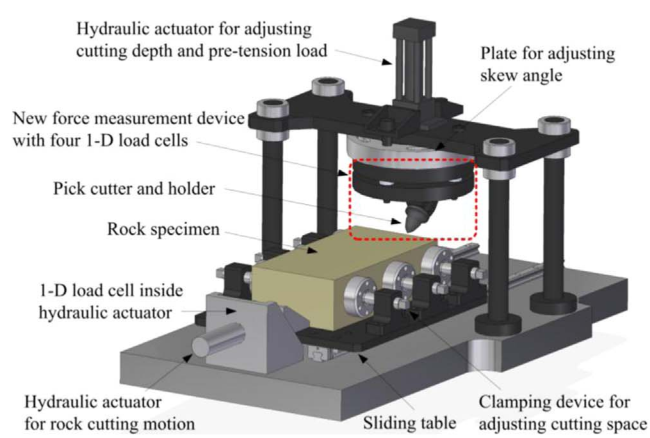
The LCM at the Korea Institute of Construction Technology (KICT) has been used to investigate cutter acting forces and performance. It is able to obtain cutting forces on a cutter using a 3D load cell. Using this LCM, Cho et al.[17] carried out LCM tests under various cutting conditions to access the cutting performance of the TBM disc cutter for granitic rock in Korea. Moreover, Choi et al.[18,19] conducted linear cutting tests to estimate the performance of conical picks under the condition of different attack and skew angles.

Entacher et al.[22,23] developed a novel force measurement technique to determine the 3D loading situation of the disc cutter of a TBM in real-time and then applied it to the three disc cutters of the Koralm tunnel TBM being used in Austria. Structurally, however, it was only suitable for application to the actual TBM disc cutter. Although small-capacity rock-cutting tests were performed with rock core samples,[8,20,21] the correlations between the small and large capacity rock cutting tests were unclear until now.

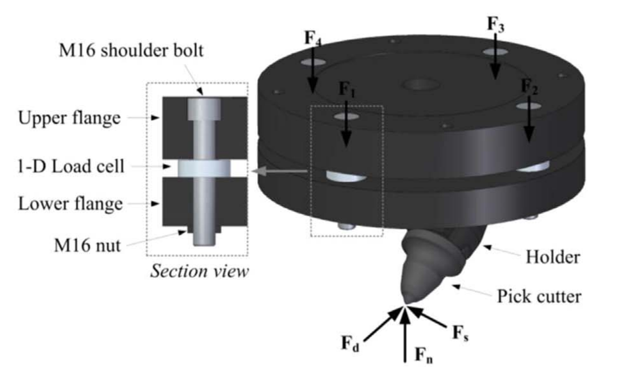
3. Development of linear cutting machine

3.1. New LCM system

A new LCM system appropriate for the small-capacity rock-cutting tests for a pick cutter was proposed as described in Fig. 1 (a). This features four stiff columns to minimize the effects of the structural vibration, which arises from the impact of rock fragmentation between a pick cutter and a rock specimen. A cuboid rock specimen is placed on a sliding table and the rock-cutting motion is controlled by the hydraulic actuator coupled with the sliding table. Moreover, a 1-D load cell was installed to merely monitor the drag force (F_d) at the hydraulic actuator that performs the linear rock cutting. A clamping device firmly holds the rock specimen on the sliding table, while the cutting space is adjusted laterally with six screws. The cutting depth and skew angle can be adjusted by a hydraulic actuator mounted on the upper side and on a circular plate, respectively. A new force-measurement device



(a) Design of small capacity LCM



(b) New force measurement device with four 1-D load cells

Fig. 1. Small capacity LCM system for testing a pick cutter.