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A Linear cutting test to investigate fragmentation patterns of gravel and cobble and cutting behavior of a disc cutter

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ABSTRACT

Many recent tunneling projects have been constructed in crowded urban areas, while many more are under construction or are being planned. Most of urban tunnels are located in shallow depth and in soil compared to water or road projects that are mostly excavated in rock. Often times metro tunnels involve TBM tunneling where multitude of challenges and problems have to be dealt with in the area, most of them caused by the geological condition in shallow depth. Mixed ground condition and alluvium (gravel and cobble) formation are of primary concern, where it is very difficult to estimate the performance of a TBM mixed face condition in alluvium formations, especially due to lack of knowledge for cutting characteristic in the ground. This paper presents a series of small-scaled linear cutting tests carried out in specimens which simulate the grouted alluvium formations. The tests facilitated characterization of the cutting behavior and the performance of a TBM disc cutter in conditions where course grained soils including gravel, cobbles, and boulders are present. The tests showed that fragmentation patterns of gravel were strongly dependent on the cutting conditions and the strength of grout. The changes in the cutting forces acting on a disc cutter were analyzed relative to the cutting geometry and sample characteristics. The results of this study can be used to better understand the cutting behavior of TBM in similar ground conditions and to optimize the design of cutterhead and operation parameters of a TBM in underground tunnels that pass through course grain soils.

1. INTRODUCTION

Many tunneling projects are under construction or being planned in crowded urban

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area recently. Because the tunnels are located in shallow depth compared to early metro tunnels, tunnel boring machines (TBMs) often meet new challenges and problems, such as a decrease in the advanced rate, an increase in downtime, excessive damage to the cutting tool and cutterhead, jamming, face supporting problems, groundwater inflow, and the need for additional ground reinforcement work. A low overburden, mixed geological conditions, and alluvium (gravel and cobble) formation are among the greatest concerns. Cobble and gravel formations are considered to be among the most difficult ground conditions for TBM tunneling. Previous studies (Barzegari et al., 2014; Filbà et al., 2016; Gong et al., 2016; Li et al., 2017) have reported the difficulties of TBM tunneling in gravel and cobble areas. The major problems in cobble and gravel areas that are discussed in these studies include excessive wear of cutting tools and the impossibility of crushing gravel. These studies reported the difficulty in excavating cobble and gravel (including boulder in larger scale), which usually requires additional reinforcement work to provide sufficient strength for the ground.

It has been discussed that the strength of in-situ ground and the compressive (or shear) strength are of crucial importance for the cutting of gravel and cobble (Navin et al., 1995; Becker, 1995;, Dowden and Robinson, 2001;, Goss, 2002;, Hunt and Mazhar, 2004). When the ratio of strength of cobble or gravel to the in-situ ground is above a certain value, the grains can be fragmented or broken by a disc cutter, otherwise, it cannot be assured. Goss (2002) found the effective ratio as to be 600:1 (in terms of shear strength) through the finite element model (FEM) analysis and case history surveys. Barzegari et al. (2014) classified the behavior patterns of a boulder in TBM excavation into three categories (i.e., rotating, push aside, and breakage) based on the effect of ground compaction through the site observations.

This study attempted to identify the required grouting strength for successive cutting of gravel and cobble. The characteristics of the cutter forces and fragmentation patterns when a disc cutter cuts the particles were observed. The specimen was specially made with different strengths of grouting mixed with various sizes of gravel and cobble. The results confirmed that the fragmentation patterns were significantly dependent on the penetration depth of a disc cutter and the strength of the grouting. Also, it was found that a sufficient level of grouting strength should be provided to the gravel for successive cutting.

2. Experimental methodology

2.1. Small linear cutting machine (SLCM)

This study used a small-scaled linear cutting machine (SLCM) as shown in Fig. 1. The system`s 20-ton loading capacity can provide sufficient stiffness during the linear cutting tests. Previous studies (Jeong et al., 2018, Jeong and Jeon, 2018, Jeong et al., 2020, Jeong et al., 2021, Yudhidya et al., Jeong et al., 2022) have confirmed that such a small-scale testing system enables an economical evaluation of the cutting performance of different cutting tools. Because this study focused on micro-TBM tunneling, a small-scaled disc cutter was selected with 5 inch in diameter and CCS profile, and it was manufactured as a miniature referred to the large size of a disc cutter (17 inch). The mini disc cutter used in this study was applicable to the micro-TBMs, so the considered cutting conditions and strengths were applied in the real scale without any dimension analysis.

Cutter forces were measured in three directions (normal, rolling, and side force) in real time during the test by a load cell installed between the mainframe and the disc cutter. The rock specimen was placed in a steel box to provide efficient confinement during testing. The positions of the grouted rock specimen and the disc cutter were controlled with the control panel; the movement (cutting direction) of the rock specimen was servo-controlled to maintain a constant cutting speed. Cutting distance was also automatically controlled via the control panel to prevent the end effect of the specimen. Cut spacing was manually controlled, and the specimen position was displayed on the control panel.

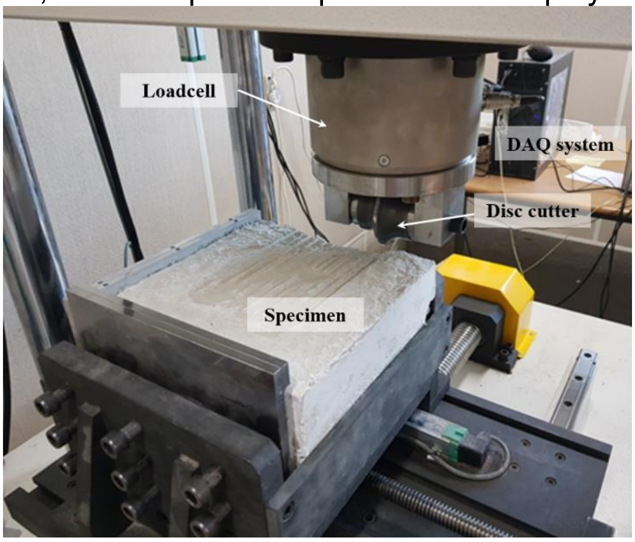


Fig. 1. Small scaled linear cutting machine used in this study

2.2. Specimen

Cobbles and gravels were generally classified according to their particle size. Various classification systems use different particle sizes and names to define the cobbles and gravels. In this study, various sizes of gravel were prepared based on the classification system proposed by Wentworth (1922). Considering the capacity of the SLCM system and the size of the cutting tool, four different sizes (VCC, CC, VCG, and CG) of gravels and cobbles were selected for the cutting tests, as presented in Table 1. The unconfined compressive strength of gravels and cobbles, as measured by the point load test, was estimated to be about 200 MPa for all sizes of gravels and cobbles. Hunt (2017) reported representative compressive strengths of 152 to 310 MPa in cobbles and boulders in North America, and the strengths of the gravels and cobbles used in this study fell into that range.

Table 1. Classification system for different size of gravel used in this study

Particle size range in classification system	Aggregate name (Wentworth class)	Selected particle size range	Aggregate name (This study)
>256 mm	Boulder	Not selected	

64-256 mm	Cobble	120-140 mm	 Very coarse cobble (VCC)
		70-100 mm	 Coarse cobble (CC)
16-32 mm	Coarse gravel	20-30 mm	 Coarse gravel (CG)
8-16 mm	Medium gravel	Not selected	
4-8 mm	Fine gravel	Not selected	

Cobbles and gravels were mixed with various grouting materials for the cutting tests. To determine the appropriate grouting materials, many previous studies proposed selection criteria of grouting material for the various sizes of particles based on field experiences and laboratory testing. This study selected the cement type grouting material referred to the criteria. Fig. 2 shows the process of specimen preparation for the LCM test. The specimen size was 300 × 300 × 200 mm in this study. The gravels were intentionally located at specific points of the molding frame to determine the location of the cutting line for the cutting tests. Before the cutting tests, the curing strength of grouting was confirmed to meet the target strength.

Fig. 2. Preparation of grouted gravel specimens in this study

2.3. Testing conditions

The testing conditions included six levels of penetration depths and four levels of gravel size in diameter and grouting strength each, while the cut spacing was fixed as the range of 10 to 20 mm, to provide the optimum cutting condition for the considered penetration depths and grouting materials. Because the gravels were located within certain area of the specimen, it was difficult to consider the effect of cut spacing on the test results. Total 96 cases were considered in this study, and they were summarized in Table 2. Fig. 3 shows the configuration of testing program used in this study.

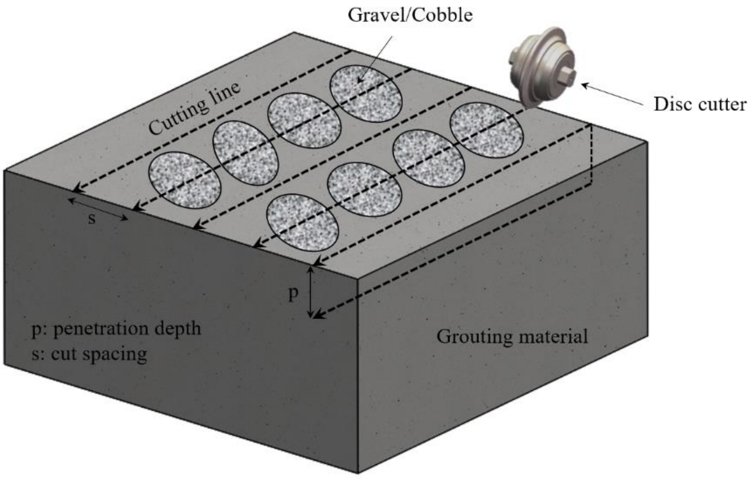


Fig. 3. Configuration of LCM specimen and testing in this study

Table 2. Testing conditions considered in this study

Variables	Testing conditions			
Strength of grouting (MPa)	1.5	3	7	11
Size of gravel (mm)	20-30	50-70	70–100	120–140
Penetration depth (mm)	0.5 – 3.0 mm			
Cut spacing (mm)	10 – 20 mm			

3. Results

3.1. Fragmentation patterns

In this study, 96 cases of SLCM tests were performed to investigate the effects of the variables on the cutting behavior and fragmentation patterns. Four representative fragmentation patterns, namely as pushing, scratching, splitting, and crushing, were found depending on the combination of grouting strength and penetration depth of the disc cutter. The fragmentation patterns are summarized in Fig. 4. When the strength of grouting material was weak, i.e., 1.5 MPa and penetration depth was low, gravel was pushed into the specimen without any cracking or fragments. In that case, the grouting material could not provide sufficient supporting strength for force-generation and transmission to cut the gravel. At greater penetration depths, gravel was fragmented with the grouting material somehow, however, the cutting did not make significant cracks to sufficiently break the gravel. This finding indicates that the strength of the grouting was not strong enough for the cutter forces to act effectively on the gravel.

However, in strong strength of grouting material, the gravels and cobbles could be effectively broken by linear cutting. The gravels were split at lower penetration depth, whereas they were crushed at greater penetration depths. Based on the results, the critical value of strength (i.e., the ratio of uniaxial compressive strength of grouting to the gravel) was found to be 1:130. The results indicate that it is important to provide sufficient strength for grouting material in the cutting behavior of gravels and cobbles.

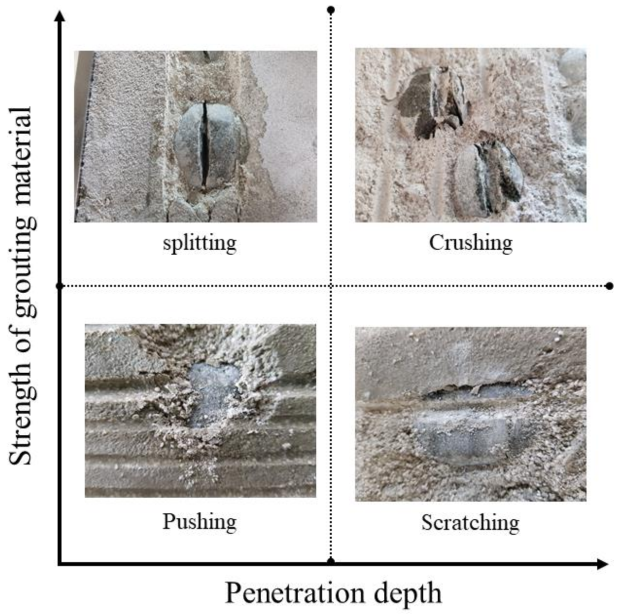


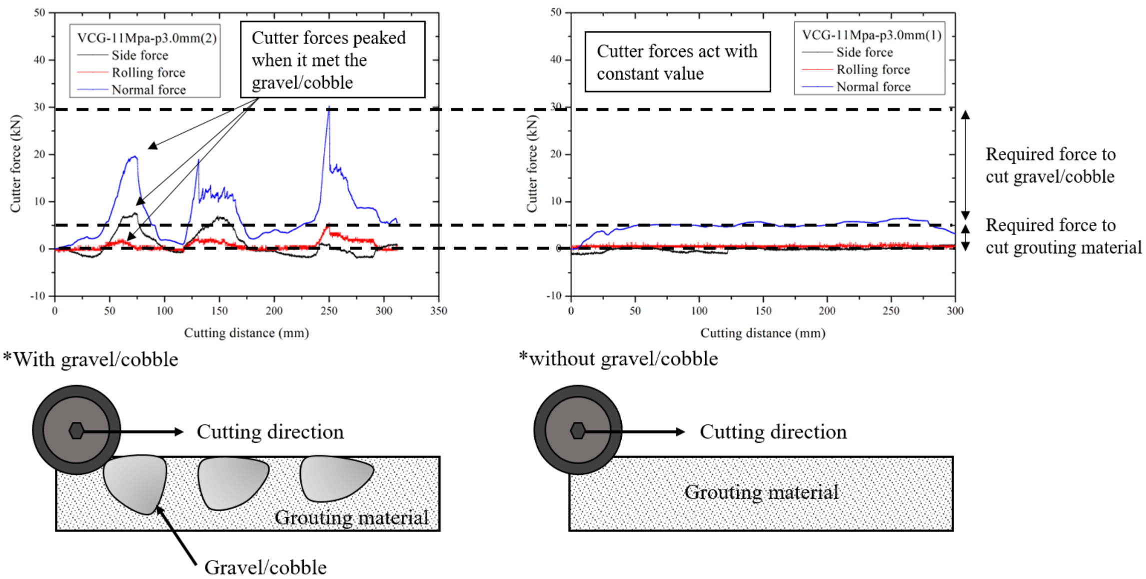
Fig. 4. Fragmentation patterns of gravel depending on grouting strengths and penetration depths

On the other hand, it is difficult to observe the effects of the size of the cobbles and gravel on the fragmentation patterns. It was judged that the range of particle sizes in this study was not sufficiently wide to make a significant difference in the fragmentation patterns relative to the size of the disc cutter.

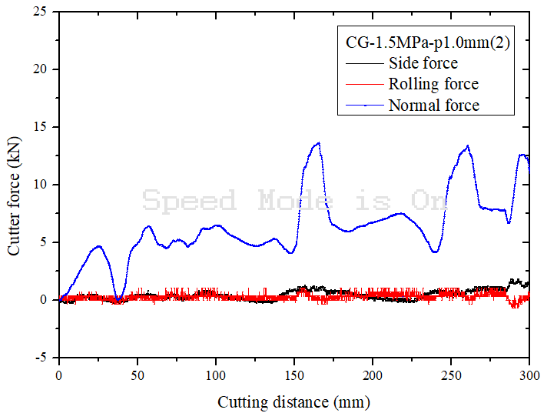
3.2. Cutter forces

When a disc cutter cuts a certain material, it is acted upon by three directional force components: normal force, cutting force, and side force. The cutter force in three directions, which depends on the strength of the rock and the cutting conditions, generally increases as the penetration depth increases, and the rolling and side forces occur within 20% and 5%, respectively, relative to the normal force.

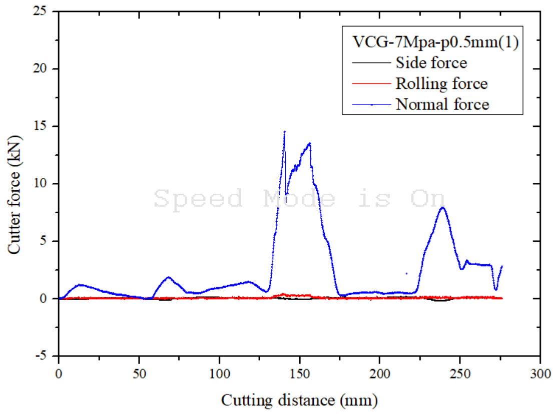
Fig. 5(a) shows the three representative cutter forces during the tests. The three directional cutter forces tend to increase when the disc cutter meets gravel or cobbles. In particular, the normal force significantly increases when the disc cutter makes the contact with gravel and cobble. In contrast, in most cases, the measured rolling force showed little change despite a drastic increase in the normal force (Fig. 5). The significant increase in rolling force only was observed when the large size of cobble (i.e., VCC) was highly broken, i.e., crushing pattern. This means that the rolling force acts when cutting gravel is not enough to exceed the preloaded torque on the bearing part of the disc cutter. The main breakage mechanism of gravel or cobble is an indentation process caused by a high level of compressive stress, rather than rock chipping that occurs in usual rock cutting. Also, the results indicate that the normal force plays an important role relative to the cutting force in the cutting of gravel. Fig. 5 shows the characteristics of the side force acts on a disc cutter. Significant features in the side force were observed while a disc cutter excavates gravel and cobbles. Usually, the side force is not considered as an important design variable for TBM, so that it is just recommended that the side forces retain about 5% of the normal force for maintenance of machine`s balancing. When a disc cutter contacts the gravel, the side force significantly increases, and this increase makes disc cutter structurally unstable. In this case, the normal and rolling forces, are not effectively applied to the rock. Thus, the side force should be considered an important issue in TBM tunneling for gravel and cobble formations.



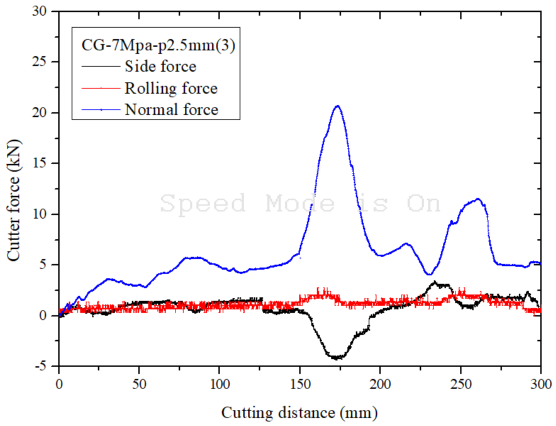
(a) Comparison of cutter forces with a cutting of gravel/cobble and grouting material



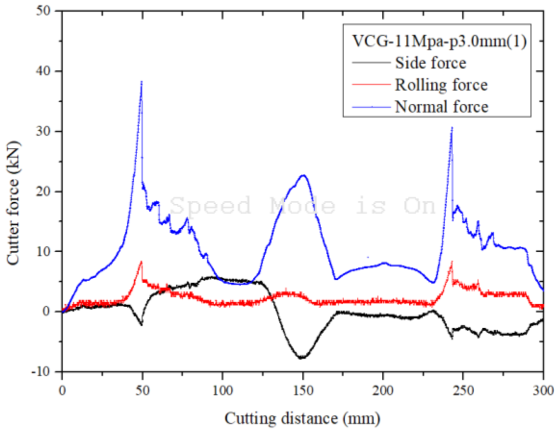
(b) Pushing



(c) Scratching



(d) Splitting



(e) Crushing

Fig. 5. Characteristics of cutter forces in the LCM tests

4. CONCLUSION

In this paper, a series of SLCM tests were performed on specimens with embedded gravel which was reinforced with grouting materials. A small disc cutter (5-inch) was used to excavate specimens using a linear cutting test. The specimens include various sizes of gravel embedded in grout materials of varying strength. The cutting test was carried out on cutting depth to assess the conditions by effectively crushing the gravel/cobbles.

The strength of the grouting and the penetration depth should both be properly selected to efficiently cut the gravels and cobbles. In particular, if the grout surrounding the larger rock pieces is weak, the cutting tool cannot cut effectively and induce fractures to break up the gravel and cobble pieces. The required strength of grouting material that could result effective breakage of gravel and cobbles was found to be 1:130 (i.e., the ratio of the uniaxial compressive strength of the grouting to the gravel). However, this value should be verified with different types of gravels and cobbles. This study identified the characteristics of the cutting forces when a disc cutter cuts gravel and cobbles. It confirmed that the normal force, rather than rolling or side forces, is mainly involved in the fragmentation process, and the main fragmentation mechanism of gravel and cobble is similar to the indentation process due to the concentrated stress in the vertical direction. The rolling force makes a lesser contribution to the breakage of gravel and cobble. A low level of rolling force was measured during SLCM testing. This abnormal behavior is related to a lack of sufficient friction between the particles and the cutting tool, or possibly to structural stability of disc cutter. Another possibility is skidding of the rock in the medium to the point that it could dig into the surface and avoid being cut. The measured side forces were larger than those seen when a disc cutter cuts a common rock specimen. In some cases, the side force was 5% above the normal force, which is typically very high in general rock cutting tests with disc cutters. Considering the magnitude of the force, the side force should be considered as an important design parameter, like with other cutter forces.

The results can be used as fundamental data for the selection of treatment methods, strength of ground reinforcement, and types of cutting tools in TBM tunneling through alluvium formation. It also provides useful information to better understand the mechanism by which gravel is excavated and to improve the excavation performance of micro-TBMs in gravel- and cobble-laden ground, large sizes of TBMs as well.

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