Study on Excavation Performance of a Multistage-Type Rock Excavation

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Abstract

Blasting method is a conventional method for hard rock mass excavation. Recently, the use of blasting method is getting difficult due to environmental problems, such as noise pollution and ground vibration. Mechanical excavation method is an alternative for the blasting method, however, the present excavation method has two problems, the low efficiency due to the wear of cutting bits and the high cost to exchange cutting bits. Thus, through this research, we are trying to innovate the edge excavation method in order to solve the two problems. The purpose of this study was to develop a rock excavator attached to backhoe by using multistage edge excavation method. We carried out the experiments by using model excavator to find out its efficiency and force acting on the rock excavator. In this study, we conducted a basic experiment by using a displacement controlling method to determine the load required to control a model excavator. The specimen used was high-strength mortar specimen. In the experiment, a model excavator was attached to the experimental device, and the speed was set to be constant by displacement control. Excavation was performed by rotating the specimen. The vertical force F_z, torque T, excavation depth z and, soil volume m, the excavation time t was measured. As a result, the load required for the model excavator was verified and the capability of the experiment to be performed through load controlling was confirmed.

Keywords –

Multistage type edge excavation, Edge excavation, Displacement control, Disk cutter bit

1 Introduction

Blasting method is a conventional method for hard rock mass excavation. Recently, the use of blasting method is getting difficult due to environmental problems, such as noise pollution and ground vibration. Mechanical excavation method is an alternative for the blasting method, however, the present excavation method has two problems, the low efficiency due to the wear of cutting bits and the high cost to exchange cutting bits. Thus, through this research, we are trying to innovate the edge excavation method in order to solve the two problems. Fig. 1 shows the outline of the plane excavation and the edge excavation. Based on other research so far, almost all excavation methods have adopted the plain excavation method, in which the excavation of the plain rock mass was carried out under the condition of one degree of freedom. The use of edge excavation method was considered to be more effective than the plain excavation method. The failure mechanisms of the conventional plane excavation method by using disc cutter bits in tunnel-boring machines are, as mentioned by Snowdon et al. (1982), both the compressive failure and the tensile failure in the rock when the penetration of an adjacent disc cutter bit is made. On the other hand, the edge excavation method experiences shear and tensile failure in stepped rock, which is shaped by the wedge action of a ripping-type disc cutter bit, in the condition of two degrees of freedom. A specific cutting energy is calculated as the ratio of an excavation power of a disc cutter bit to the amount of cutting debris per unit time (Snowdon et al. 1982). The specific cutting energy of the edge excavation method with a ripping-type disc cutter bit is much smaller than that of the conventional plane excavation method involving a tunnel-boring machine. Muro et al. (2001, 2001, 2002, 2002, and 2004) have reported that the measured specific cutting energies of the edge excavation method were one-tenth energies of the conventional plane excavation method for several kinds of rock. Instead of a point attack bit, disc cutter bits are often used during excavations because the disk cutter bits can spin around and avoid the strong impact of cutting loads, while the point attack bits receive the impact completely and directly.

The purpose of this study was to develop a rock excavator attached to backhoe by using multistage edge excavation method. Previously, experiments ware conducted with the model excavator to find out the efficiency and the force acting on the rock excavator (Shigematsu et al. 2008). Further experiments conducted with the “model excavator” showed that the accumulated sediment caused the decrease of the excavation efficiency (Shigematsu et al. 2013). Furthermore by changing the position of the model excavator from vertical to horizontal setting, the removal efficiency of excess sediment had remarkably improved. This improvement provides the following benefits: 1) increase of excavation speed, 2) decrease of torque, 3) increase of overall excavation efficiency.

In this study, we conducted a basic experiment by using a displacement controlling method to determine the load required to control a model excavator. The vertical force F_z, torque T, excavation depth z and, soil volume m, the excavation time t was measured. As a result, the load required for the model excavator was verified and the capability of the experiment to be performed through load controlling was confirmed.

2 Experiment method and model excavator

2.1 Model excavator

Photo 1 and figure 2 show the outline of model excavator. The model excavator attaches 4 disk bits under the Steel pedestal. 4 disk bits are arranged respectively about placement interval of cutter, cutter 1 is 45 mm outside the center of the specimen, cutter 2 is 24 mm outside the cutter 1, cutter 3 is 25 mm outside the cutter 2, cutter 4 is 25 mm outside the cutter 3. Disk cutter bits size are configured, cutter 1 is φ100 mm, cutter 2 is φ90 mm, cutter 3 and cutter 4 are φ100 mm. The model excavator has 3 stages. 1st stage is cutter 1 and cutter 2 contact at the same time and plain excavate. 1st stage form 2 free side. After that, 2st stage excavator by cutter 3, Finally, 3st stage excavator by cutter 4. Also, cutter 2 and cutter 4 deploy diagonally due to lower peripheral friction.

2.2 Model machine

Figure 3 shows the outline of model machine, photo 2 shows the specimen after the excavation. Model

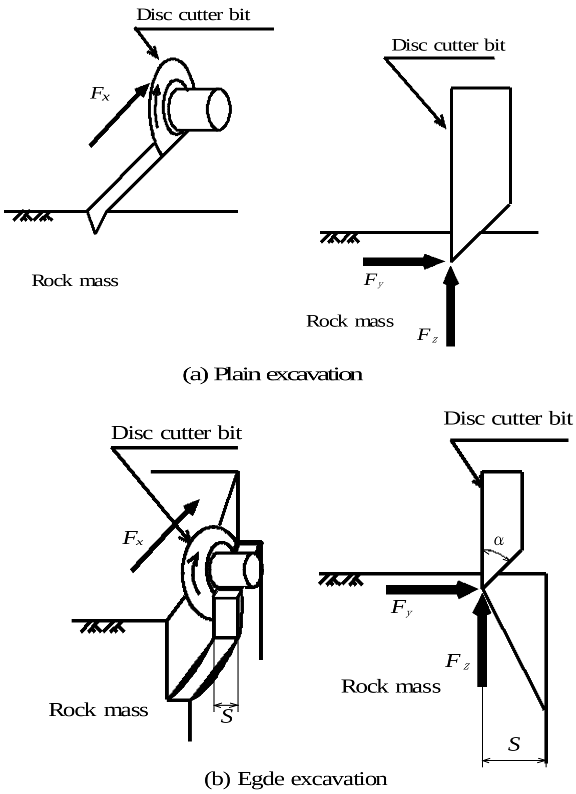

Fig.1 Outline of plate excavation method and edge excavation method

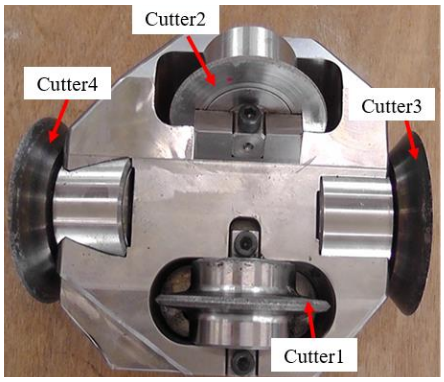

photo 1 Model excavator

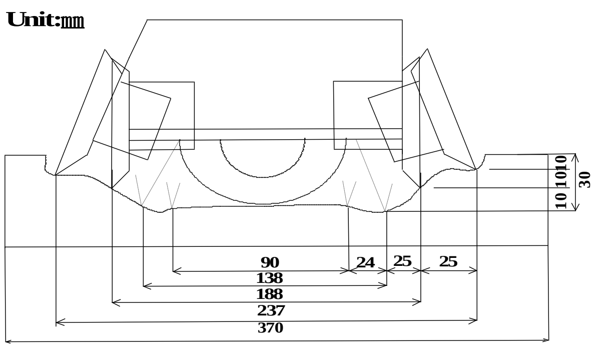

Fig.2 Model excavator arrangement

machine apparatus consisting of a worm jack, a turntable of 400 mm diameter, a model excavator, and an axial torque transducer. The apparatus has a height of 1,750 mm, a width of 700 mm, and a depth of 700 mm. The turntable was driven by a 1.5 kW motor via a reduction gear, the rotation speed was kept at 2.0 r.p.m by using a screw rod. Displacement is controlled with a worm jack. It is possible to move up and down the apparatus operating the worm jack. By changing position of the model excavator from vertical to horizontal settings, removal of the excess sediment was remarkably improved. The axial torque transducer placed on top of the excavator measured the thrust F_z, torque T. The displacement sensor was used to measure the penetration depth z. The model machine can be tilted using the hydraulic cylinder. It is possible to roll the device 90° due to discharge excavated soil efficiently by expanding and contracting the hydraulic cylinder beside the machine.

2.3 Specimen

Tables 1 and 2 show the one axis compressive strength of high-strength mortar specimen and combination table of high-strength mortar specimen. Specimen uses high-strength mortar specimen (axis compressive strength 153.5 N/mm²) with water binder ratio W/B＝17 %. The shape of each specimen use columnar form, the height was 172 mm, and the diameter was 365 mm.

2.4 Displacement control experiment

Displacement control which is to excavation with a constant excavation depth z uses a worm jack which can set a certain amount of penetration. Set speed was set to 5 patterns (0.0223 mm /sec, 0.0302 mm /sec, 0.038 mm /sec, 0.0459 mm /sec, 0.0537 mm /sec) and each set of speed was performed 3 times except for set speed v_{set}=0.0537 mm/sec was performed 2 times.

2.5 Method

The specimens were excavated up to excavation depth of z=35 mm while moving toward the model excavator at a constant speed. At the same time, the turntable revolution was set at 2 r.p.m. The specimens were first set to steel moulds and tighten with M8 hex bolt before fix to the turntable by using M10 hex bolt. The excavation time, t, vertical force F_z, excavation depth z, torque T, excavated soil volume m where measured through data collection machine every 0.02 second. The machine was connected to ground wire to prevent noise from occurring.

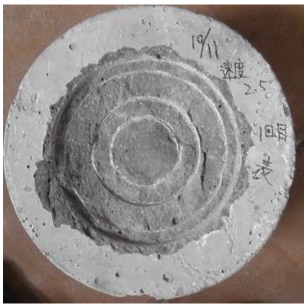

photo 2 Specimen after the excavation

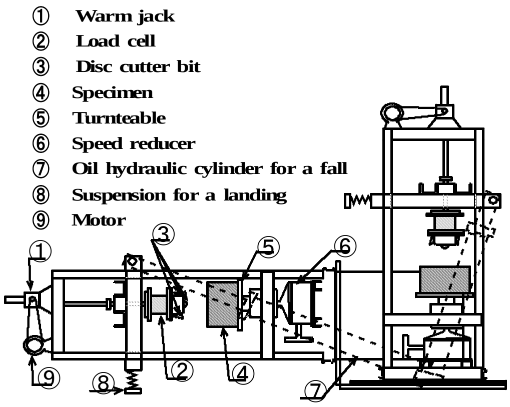

Fig.3 Outline of model machine

Table 1 One axis compressive strength of high-strength mortar specimen

Specimen numbers	one axis compressive strength of high-strength mortar specimen (N/mm²) (Strength after three month)	Average (N/mm²)
①	161.6	153.5
②	147.2	
③	151.7	

Table 2 Combination table of high-strength mortar specimen

Combination table of high-strength mortar specimen (W/B =17%)					
Materials	Water (kg/m^3)	Cement (kg/m^3)	Silica Fume (kg/m^3)	Fine Aggregate (kg/m^3)	Admixtrue Ingredient (kg/m^3)
Unit quantity	222	1187	118.7	872	19.586

3. Experimental results and discussion

3.1 Excavation time

In this chapter, the results of high strength mortar specimen and set speed v_{set} = 0.0223 mm/ sec and v_{set} = 0.0537 mm/ sec will be considered as an example.

(1) Vertical force F_z and excavation time t

Figure 4 and 5 show the relationship between vertical force F_z and excavation time *t*. The feature of plain face excavation is that the excavation stage can be roughly divided into two stages. After the initial end face excavation in which a large amount of separation is generated and excavation is performed, the steady end face excavation is performed in which a small amount of separation is generated and then excavated. As a result, the vertical force F_z increases from the start of the experiment to around 340 seconds. This can be considered as plain excavation. The reason was that immediately after the start of the experiment, the cutter cuts into the specimen, and the excavated plain tends to become unstable as the two free plains were formed. Then, in the vicinity of 540 seconds, the phenomenon that the vertical force F_z increased again due to the contact of the cutter 3 was observed. This is considered to correspond to the initial end plain excavation. There was a place where the fluctuation range of the value becomes small due to the stable excavation plain. This was due to the steady end face excavation. In addition, there was a tendency for the increase of F_z during flat excavation immediately after the start of the experiment to be larger than in the initial end face excavation. In addition, these tendencies were similar at other set speeds.

(2) Torque *T* and excavation time *t*

Figure 6 and 7 show the relationship between torque *T* and excavation time *t*. Right after the start of the experiment, the torque *T* increases rapidly as well as the vertical force F_z. It was considered that as the cutter cuts into the specimen, torque *T* increased rapidly due to the unstable excavation plain. In addition, the fluctuation range of the torque *T* value became shorter near 400 seconds. As a possible factor, the torque *T* was considered to be stable due to the fact that the cutter cuts sufficiently as the excavation progresses and the excavation plain stabilizes. In addition, regarding the tendency of the graph, the same tendency was observed at other set speed.

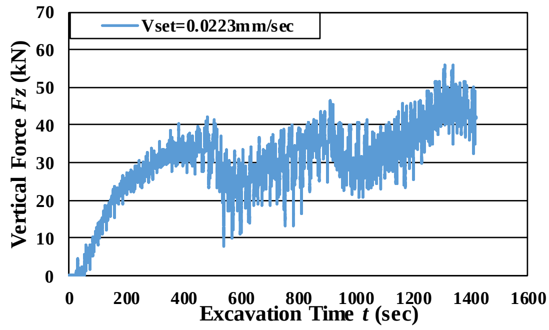

Fig.4 The relationship between the force F_z and the excavation time t.

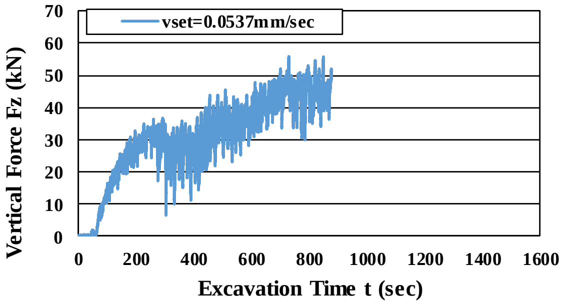

Fig.5 The relationship between the force *F_z and the excavation time t.*

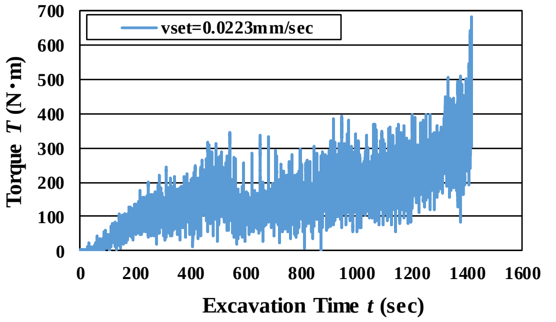

Fig.6 The relationship between the Torque T and the excavation time t.

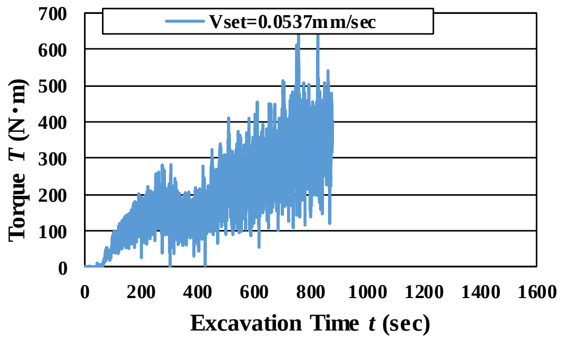

Fig.7 The relationship between the Torque T and the excavation time t.

(3) excavation depth *z* and excavation time *t*

Figure 8 and 9 shows the relationship between the excavation depth *z* and the excavation time *t*. Experiment, was conducted until the excavation depth *z* reached 35 mm as an experimental condition. Therefore, the excavation time *t* was measured at the moment the cutter hits the specimen to the time when excavation depth reached 35 mm. In addition, it was confirmed that the excavation had occur with the excavation speed *v* at a constant fluctuation because the experiment was performed by the displacement control performed by the displacement control. In addition, even with other set speeds v_{set}, there was a tendency for excavation to proceed around the set speed v_{set}. In addition, even with other set speeds v_{set}, there was a tendency for excavation to proceed around the set speed v_{set}.

3.2 Relationship with excavation speed

(1) Maximum vertical force F_{zmax}

Figure 10 shows the relationship between the maximum vertical force F_{zmax} and the excavation speed *v*. By obtaining the maximum vertical force F_{zmax}, it became an index for judging how much vertical force F_z should be applied when performing an experiment in load control in order to obtain a certain excavation speed *v*. To determine the maximum vertical force F_{zmax}, the maximum vertical force from the start of the experiment to the end of the experiment can be defined as the maximum vertical force F_{zmax}. As a result, the maximum vertical force F_{zmax} tended to increase as the excavation speed *v* increased. In addition, even when comparing the same measurement times for different set speeds v_{set}, it was confirmed that the higher the excavation speed *v*, the larger the vertical force F_z.

(2) Maximum torque T_{max}

Figure 11 shows the relationship between the maximum torque T_{max} and the excavation speed *v*. By obtaining the maximum torque T_{max}, the maximum torque T_{max} applied to the cutter during excavation can be known, and it can be used as an index to judge how much torque *T* was required for the excavation. The maximum torque T_{max} was determined from the maximum value from the start of the experiment to the end of the experiment. As a result, an increasing tendency ware seen as the excavation speed *v* increased. As a factor, the vertical force F_z and the torque *T* increase as the excavation speed *v* increases. In addition, even if the same excavation time *T* at different set speeds v_{set} was compared, the torque *T* was large when the excavation speed *v* is fast, confirmed.

(3) Excavation amount per revolution V_{round}

Figure 12 shows the relationship between the excavation volume per revolution V_{round} and the excavation speed *v*. It was possible to judge the

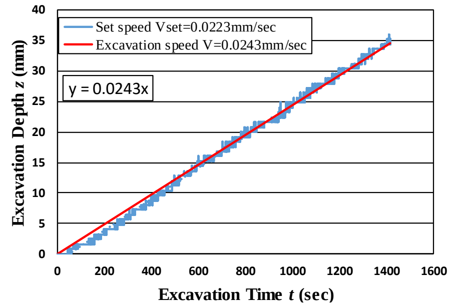

Fig.8 The relationship between the excavation depth z and the excavation time t.

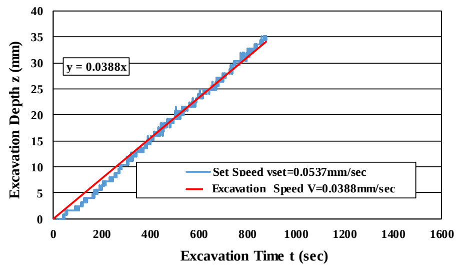

Fig.9 The relationship between the excavation depth z and the excavation time t.

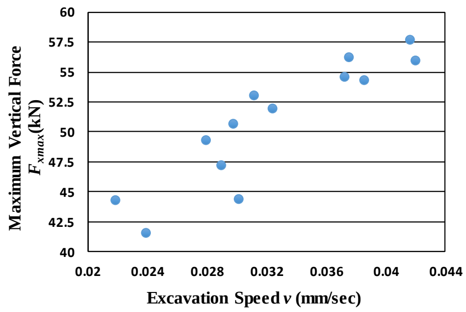

Fig.10 The relationship between the Maximum vertical force F_{zmax} and excavation speed v

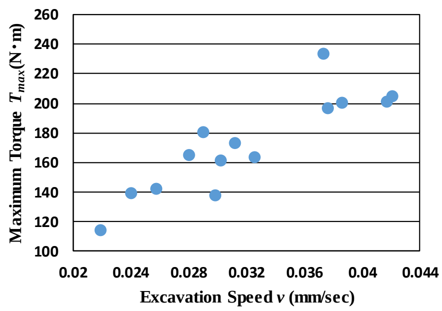

Fig.11 The relationship between the Maximum vertical torque T_{max} and excavation speed v

excavation efficiency by obtaining the excavation volume V_{round} per one rotation of the maximum vertical force F_z. The calculation method for the excavation volume V_{round} per revolution was calculated from the mass per unit of the specimen. The number of revolutions of the specimen during the experiment was obtained by dividing the excavation time T by the rotation speed of 2r.p.m. The excavated volume was divided by the number of revolutions of the specimen to obtain the excavation volume per revolution V_{round}. As a result, as the excavation speed v increased, the excavation volume per revolution V_{round} tended to increase. However, the amount of soil volume m was about the same value, and no changes in the amount of soil volume m was observed at the excavation speed v. This was because the experiment was performed with displacement control, and the faster the excavation speed v, the shorter the excavation time T and the smaller the divided value.

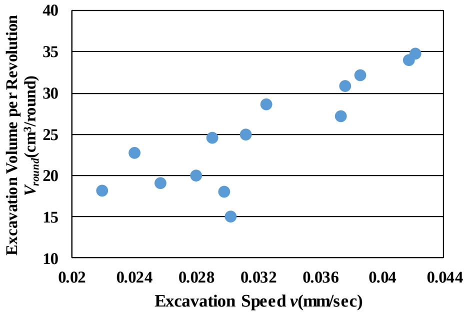

Fig.12 The relationship between the excavation volume per revolution V_{round} and excavation speed v

3 Conclusion

(1) The vertical force F_z rapidly increases until the initial plain excavation, and steady plain excavation occurs. After that, the vertical force F_z decreases, and the initial end face excavation can be repeated again. confirmed. A similar tendency was observed for the torque T. The torque T tended to decrease rapidly during centering.

(2) As the set speed v_{set} increased, the error in the excavation speed increased, so it is necessary to perform an experiment with a design with a lower water-binder ratio *W/B*.

(3) In the displacement control experiment, the same tendency was seen in vertical force, torque, and excavation depth for any set speed v_{set}, and it can be predicted. Therefore, since the force could be grasped by the displacement control by the new model excavator, it can be applied in the load control.

Acknowledgement

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