Analysis of Energy Efficiency of a Backhoe during Digging Operation

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Abstract –

The energy consumption of a backhoe during digging operation is the sum of the energy due to earth pressure and backhoe motion. The authors' previous studies have revealed the earth pressure model on the arc trajectory, but not on the horizontal trajectory, which is often used in normal digging operation. Moreover, in order to optimize energy efficiency, a comparative experiment of energy consumption was carried out for the multiple excavation trajectories involving horizontal direction. However, since the theoretical model of earth pressure has not been completed, the experimental data obtained from the testbed is used as a reaction force. If it can be confirmed that the reaction force of the horizontal trajectory can be calculated with a theoretical value, the energy efficiency can be calculated from the excavation trajectory without experiment. In this study, the earth pressure model for the horizontal trajectory was confirmed, and the method for the evaluation of energy efficiency was verified using the theoretical values.

Keywords –

Backhoe; Digging force; Coulomb's earth pressure

1 Introduction

In recent years, autonomous construction machines have been developed due to the decrease in the working population and the deterioration of infrastructure. The automatic construction system for construction machinery is complicated by three-dimensional measurement, operation planning, electronic hydraulic control, etc. [1]. In the case of a construction machine that excavates sediment like a backhoe, automatic control is difficult because the reaction force affects the operation and the energy consumption of the machine. We have formulated the reaction force during digging operation based on Coulomb's earth pressure theory by observing the behavior of sediment in the bucket when the backhoe scoops sediment on the arc trajectories [2]. The energy consumption of a backhoe during digging operation is the sum of the energy due to earth pressure and backhoe motion, and the excavation efficiency was evaluated [3]. However, although the earth pressure model for the arc trajectory has been clarified, but not on the horizontal trajectory which is often used in normal digging operation. The earth pressure model for horizontal trajectories depends on the amount of sediment deposited on the upper side of the bucket. Therefore, it is necessary to consider the amount of sediment. In addition, in order to optimize energy efficiency, a comparative experiment of energy consumption was carried out for the multiple excavation trajectories involving horizontal direction [3]. However, since the theoretical model of earth pressure has not been completed, the experimental data obtained from the testbed is used as a reaction force. If it can be confirmed that the reaction force of the horizontal trajectory can be calculated with a theoretical value, the energy efficiency can be calculated from the excavation trajectory without experiment. In this study, we verified the earth pressure model for the horizontal trajectory and applied it to the calculation of the excavation energy. Using the sum of the energy due to earth pressure and backhoe motion, we evaluated the energy efficiency without any experiment.

2 Overview of experiment system

Figure 1 shows an excavation testbed used in this study. The mechanism consists of three axes: an X axis that moves horizontally, a Y axis that moves vertically, and an R axis that rotates the bucket. The backhoe excavation motion can be simulated by giving displacement and velocity to each axis. The sediment container installed at the bottom of the equipment is the same size as the drive range, and the wall on one side of the container is made of polycarbonate. This makes it possible to observe sediment behavior during digging. The bucket made of stainless steel is designed on the 1/14 scale of the actual machine, and a removable side plate is attached. Only the side plates are made of polycarbonate, and the behavior of the sediment in the bucket can be observed in the same way. Table 1 shows the parameters of the sediment used in this experiment.

The dynamic friction angle between the sand and the bucket and the angle of repose were determined to be 23 degree and 32 degree from the results of the basic experiment.

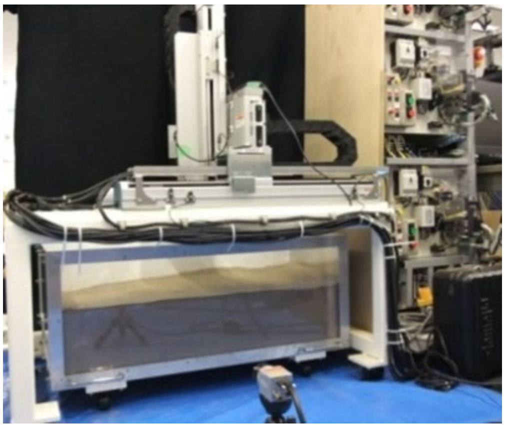

Figure 1. Overview of excavation testbed

Table 1. Parameters of sand

	Max.	Middle	Min.
density of sand [g/cm^3]	1.731	-	1.433
internal frictional angle [deg]	38.3	36.0	33.6

3 Modeling Reaction Force

3.1 Behavior during digging

Figure 2 shows the excavation trajectory using an excavation testbed. The trajectory is arc penetrating and horizontally sweep. At the end, scoop with the arc trajectory.

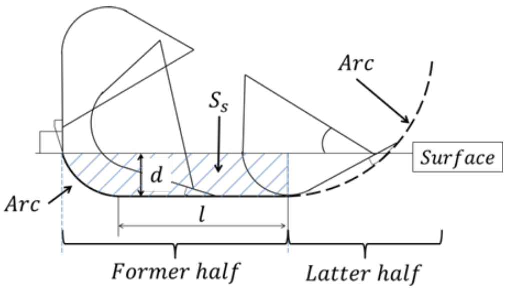

Figure 2 Digging trajectory for modeling

The behavior of the sediment in the bucket was observed from the video that reproduced a series of excavation motions of the backhoe. From the result, it was found that it is necessary to divide the process as follows for formulation (Figure 3).

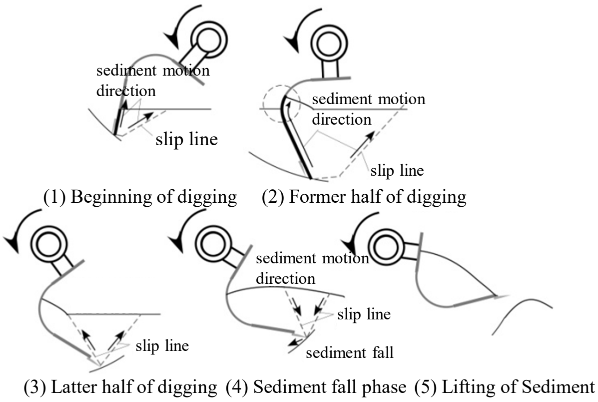

Figure 3. Divided digging phases based on sediment behaviour

1. Beginning of digging
2. Former half of digging
3. Latter half of digging
4. Soil fall phase
5. Lifting of sediment

The reaction force was formulated in each phase, and its validity was verified by comparison with the experiment result.

3.2 Reaction Force Model

It is known that the reaction force can be calculated with high accuracy by using a model of multiple triangles based on the Coulomb's passive earth pressure [4]. Based on this, the theoretical value of the reaction force was calculated using Coulomb's passive earth pressure.

First, assuming the slip on the bucket surface, the passive earth pressure is calculated. Next, the passive earth pressure assuming slippage in the sediment is calculated until the trajectory of the bucket teeth reaches the angle of repose. The phenomenon that actually occurs in this section is the one where the value of the passive earth pressure is small. In addition, the amount of sediment deposited on the upper side of the bucket is required to determine the passive earth pressure. The calculation of passive earth pressure is greatly affected by the accumulated sediment. From the observation results and the reaction force measurement results, it was assumed that sediment did not accumulate during the intrusion and 0.7 times the swept volume by the bucket accumulated after reaching the horizontal trajectory. Furthermore, the shape of the deposited sediment was calculated from the slip line shape in the sediment. This assumption makes it possible to calculate the increase in the reaction force when sweeping horizontally. When the trajectory of the tooth tip exceeds the angle of repose, sand collapses in the space below the tooth, and the sediment above the tooth begins to flow downward. At this time, active earth pressure is generated. And the reaction force becomes even smaller than the active earth pressure. When the tip of the tooth comes to the ground, the horizontal component of the reaction force disappears and the vertical component becomes the weight of sand in the bucket. However, since the amount of sediment in the bucket is unknown, it is set to zero in this model.

4 Excavation reaction force measurement experiment and simulation

4.1 Reaction force measurement

In order to evaluate the validity of the reaction force model during digging, the measurements were carried out using an excavation testbed. The reaction force of the trajectory shown in Figure 2 was measured and a video was recorded. An analysis was performed based on the behavior of the sediment at this time. A 6-axis force sensor attached to the bucket root was used to measure the excavation reaction force. At this time, the weight of the bucket etc. is corrected. Figure 4 shows the horizontal and vertical components F_h and F_v in absolute coordinates of the measured reaction force, and the coordinate system of F_{hr} and F_{vr} based on the bucket bottom. These transformations are calculated using the rotation matrix.

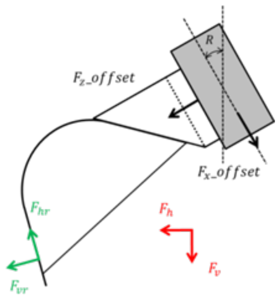

Figure 4. Coordinate system of reaction force

4.2 Comparison of excavation reaction force

For verification of the reaction force model, the difference between the theoretical value and the measurement result was compared. Figure 5 shows the horizontal component of the measurement result and theoretical value of the excavation reaction force, and Figure 6 shows the vertical component.

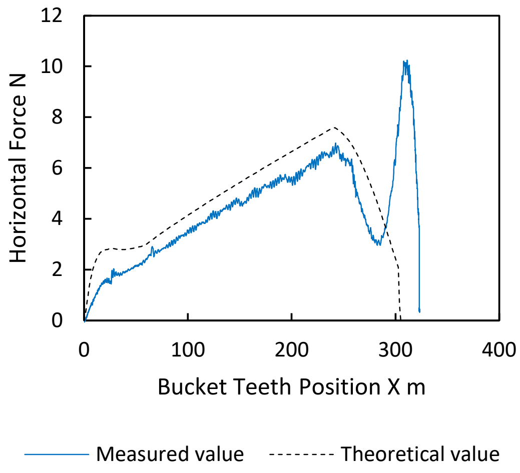

Figure 5 Reaction force comparison of horizontal direction

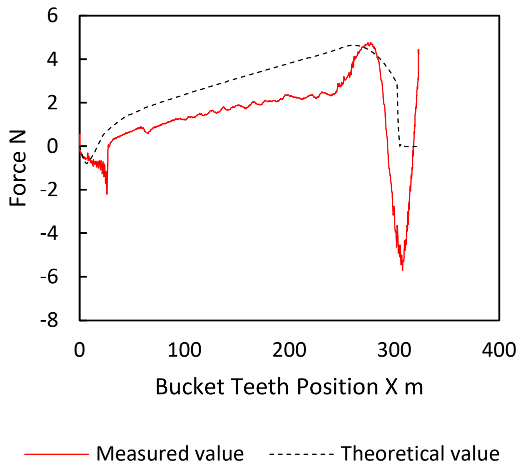

Figure 6 Reaction force comparison of vertical direction

From this result, it can be seen that the passive earth pressures until the tip of the tooth reaches 240 mm are approximately the same. The reaction force increase after 200 mm occurs in the phase of lifting the sediment. This is caused by contact between the sediment and the outside of the bucket. Since the trajectory does not contact the earth and sediment with the outside of the bucket, it is considered that the sediment that fell from the surroundings come into contact with the bucket. Ideally, there is no sediment on the trajectory, so the model does not consider this effect. Active earth pressure occurs at the tip of the tooth between 280 mm and 290 mm. The value of active earth pressure is very small and is mostly controlled by the weight of sediment in the bucket. Approximately 300 mm, the tip pf the tooth reach the ground. The vertical component of the reaction force is adjusted by the weight of the passive earth pressure inside the slip line. However, it can be seen that the theoretical value is larger than the measurement result because the weight inside the slip line is large.

5 Backhoe energy consumption

5.1 Backhoe modeling

The backhoe attachment consists of three axes: boom, arm, and bucket, and is driven by a hydraulic system. Since each joint rotates as the hydraulic cylinder expands and contracts, it can be treated as a 3-link manipulator. Figure 7 shows the model when the boom drive is used as the origin. However, L_3 is the distance from the bucket joint to the point of action of the reaction force. In this research, the trajectory is generated so that the bucket attitude is uniquely determined for the excavation trajectory. By determining the angle of the third joint of the bucket, the remaining joint angles are derived by inverse kinematics.

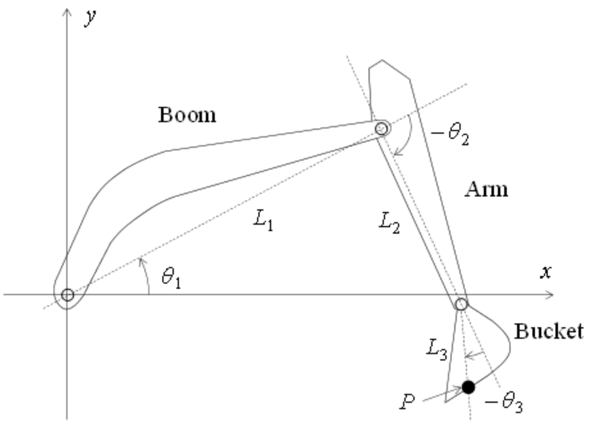

Figure 7. Kinematic model of backhoe

5.2 Energy consumption calculation

The work performed by each joint is represented by the product of joint displacement and torque. Energy is output when the rotation direction of the joint and the direction of receiving torque are different, but in the same direction, energy is received from the outside. However, in reality, torque is generated to keep the joint at the target angle. For this reason, the joint outputs the torque to oppose even if it receives a torque so as to receive energy. It is output as energy and consumes the energy that it should have received. This is called negative energy [5]. Therefore, in order to obtain the work, it is necessary to integrate the absolute value of the product of joint displacement and torque.

Since, the work required for the link to operate is represented by the sum of earth pressure and backhoe motion, the work required in the link model is expressed by Equation (1).

$$|\Delta\theta^T \tau_{ext}| = \sum_{k=1}^{3} |\Delta\theta_k||\tau_{ext\,k}| + |\Delta\theta_k||\tau_{mech\,k}| \quad (1)$$

Negative energy is generated depending on the posture of the link, the direction of travel, and the direction of external force. Therefore, the excavation starting point where negative energy is not generated as much as possible can maximize energy efficiency.

5.3 Excavation simulation

The factors that affect the reaction force are the attitude of the bucket and the excavation depth. Therefore, in order to reduce the reaction force during excavation and increase energy efficiency, it is known that the excavation depth should be as small as possible and the bucket during digging should be tilted. In the past research [3], excavation trajectories with these characteristics were generated, but since the theoretical model of reaction force was not completed, the experimental data obtained from the testbed was used as reaction force. In this research, the excavation efficiency was evaluated from the simulation results using the earth pressure model with horizontal trajectory described in Chapter 4.2.

The excavation trajectory applied for the simulation is shown in Figure 2, and the trajectory conditions are shown in Table 2. In order to excavate a certain amount of sediment, the volume to be excavated before lifting must be greater than the bucket volume. For this reason, the ratio of the excavation volume S_s and the bucket volume S_b was used as the trajectory parameter. Two patterns of excavation trajectories were created by combining excavation depth and excavation volume.

This is the same trajectory as when the experimental data was used as a reaction force in the past research [3]. Therefore, the experimental results are shown in Table 3 for comparison with the simulation. This is the result of a partial revision of past research. According to the experimental result, the energy consumption of Test case 1 and Test case 2 is almost the same. This result is the energy consumption generated by the testbed when the excavation trajectory is applied, and is not the result converted to the actual scale shown in Chapter 5.2.

Simulations were performed for each trajectory to confirm the effectiveness of the method that consumes less energy. The simulation was carried out with the value converted to the actual backhoe scale. The simulation results are shown in Table 4. Test case 1 is a "long and shallow" orbit, and test case 2 is a "deep and short" excavation trajectory.

Table 2. Trajectory conditions

Test case	S_s / S_b	l mm	d mm	Scooping velocity mm/s
1	2	208	23.5	20
2	1	47.5	33.5	20

Table 3. Experimental results of scooping [3]

Test case	Scooped soil [g]	Works [J]	Energy efficiency [g/J]
1	486	2.97	164
2	450	2.99	151

Table 4. Simulation results

Test case	Work ratio	Works ratio by earth pressure	Work ratio with gravity
1	1	1	1
2	0.486	1.099	0.408

From the simulation results, it is found that the backhoe consumes less energy under the condition 2 where the excavation depth is deep and the horizontal distance is short. The energy consumption at the tooth tip position during excavation is shown in Figure 8. The integral of this value becomes the energy consumption during excavation. It can be seen that Test1 consumes less energy at the same position than Test2, but the total energy is larger. This is because the excavated distance is long. It is considered that the influence of negative energy became large due to the long excavation distance. The energy consumption due to earth pressure has almost the same result. The experimental results in Table 3 show the energy consumption only by earth pressure, but both trajectories have the same energy consumption, and the simulation results and the experimental results show the same tendency. From this result, it can be said that it is possible to compare the energy efficiency with theoretical values.

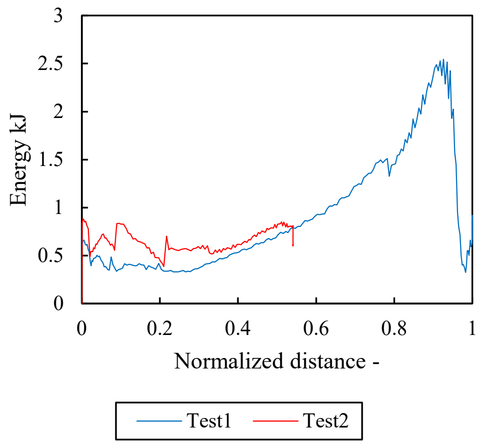

Figure 8. Energy consumption simulation result

The energy consumption due to the earth pressure is shown in Figure 9. As for the energy consumption due to the earth pressure, the maximum value of Test case 2, which is deep in the excavation trajectory, is large. It was also confirmed that the negative energy generation condition changes depending on the excavation start position, and the energy consumption changes. However, the energy consumption is about the same. The energy consumption due to the mechanism of the backhoe is shown in Figure 10. The energy due to the backhoe mechanism is more than twice as large in Test case 1 as in Test case 2. Under the condition that the distance to sweep horizontally is long, it is found that the energy consumption increases due to the negative energy.

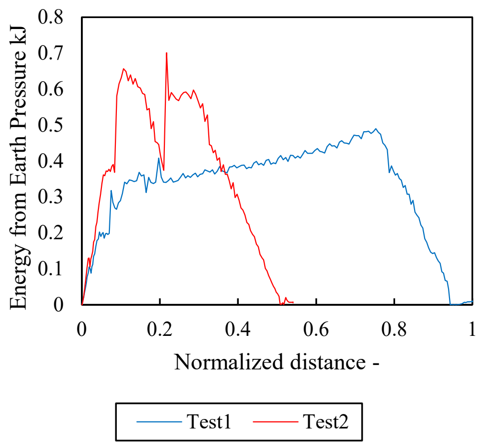

Figure 9. Energy consumption from earth pressure

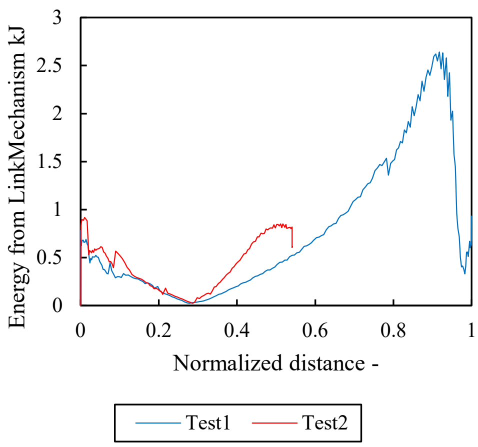

Figure 10. Energy consumption from link mechanism

6 Conclusion

From the analysis results of the reaction force using the testbed, the excavation reaction force in the horizontal trajectory, which is often used in digging operation, was formulated. It was confirmed that the theoretical values of the formulated model and the experimental results were almost the same. The energy efficiency in two patterns of excavation trajectories was evaluated using the newly derived earth pressure model. Regarding the energy consumption due to earth pressure, the results of simulation and experiment showed the same tendency. From this result, it was shown that the energy efficiency of the excavation trajectory can be evaluated by using the theoretical value. In the evaluation results of the excavation efficiency based on the theoretical value, the energy efficiency of the short excavation trajectory was good because of the energy consumption by the mechanism.

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