SIMULATION OF THE RESITIVE FORCES ACTING ON THE BUCKET OF WHEEL LOADER BY USE OF DEM

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ABSTRACT

In order to automate the scooping task, it is necessary to obtain the theoretical resistive forces acting on the bucket. The resistive forces strongly depend on the shape changing process of the rock pile due to the bucket movement. In other words, in order to derive the theoretical model on the resistive forces, the shape changing process of the rock pile due to the bucket movement has to be made clear.

In this paper, the behavior of particles in the rock pile due to the bucket movement was simulated by use of DEM (Distinct Element Method). Furthermore, the resistive forces acting on the bucket were calculated and compared with the experimental ones.

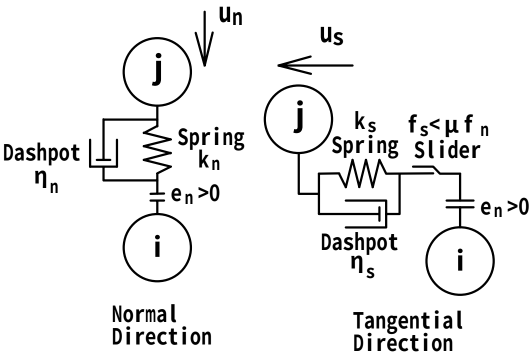
INTRODUCTION

Robotics has been receiving considerable attention in many fields, especially in mining and construction field because the working environment in these fields is very severe for workers. Many tasks in these fields have been mechanized and some of them are already carried out automatically [1-4]. However, the scooping task is much more difficult to automate compared to other tasks because the interaction between the bucket and crushed rocks is very complicated and many parameters are necessary to describe the scooping phenomena. In order to automate the scooping task, the resistive forces acting on the bucket of wheel loaders have to be obtained before the scooping task is performed [5]. And the resistive forces strongly depend on the shape changing process of the rock pile due to the bucket movement

In this study, the behavior of particles in the rock pile due to the bucket movement is simulated by use of DEM (Distinct Element Method)[6]. Furthermore, the resistive forces acting on the bucket are calculated and compared with the experimental ones obtained in the previous research.

PRINCIPLE OF DEM

DEM is often used to analyze the behavior of granular materials. In the calculation of DEM, an equation of motion is given in each element to analyze the behavior of elements. In order to derive the equation of motion, it is necessary to estimate the forces acting among elements. Usually, the model as shown in Figure 1 is used. The actual scooping process is three dimensional, but it is sometimes simplified and is analyzed two dimensionally. Therefore, two-dimensional model was assumed in this study. In this case, each element is assumed to be a circular disc, and the radius of the disc defines the size of element. When the two elements contact each other, a spring and a dashpot are introduced between two elements in the normal and tangential direction. The spring and dashpot indicate the effect of elasticity and viscous resistance, respectively. Furthermore, a slider is set in the tangential direction to consider the frictional effect.



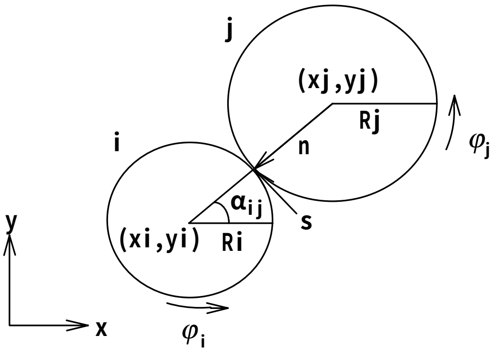


Fig. 1 Contact model in DEM   **Fig.2 Schematic Diagram of element contact**

The equation of motion of element is given by Eq.(1).

$$F_x = m\ddot{x}, \quad F_y = m\ddot{y}, \quad M = I\ddot{\varphi}$$

Here, *(x,y)* is the coordinate of central gravity of the element, φ is the rotation of the element, F_x and F_y are total contact forces and body forces acting on the element.

Figure 2 shows the schematic diagram of the contact between two elements. The contact between two elements can be judged by the following equations.

$$R_i + R_j \geq R_{ij}$$

$$R_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}$$

The normal direction coincides with the line connecting between the center of two elements. Now, let the angle between above mentioned line and x-axis be α_{ij}. Then, the next equation can be obtained.

$$\cos\alpha_{ij} = \frac{(x_j - x_i)}{R_{ij}}$$

$$\sin\alpha_{ij} = \frac{(y_j - y_i)}{R_{ij}}$$

The increment of relative displacement of the element in the time interval of calculation in the normal and tangential direction are expressed as follows:

$$\Delta u_n = -(\Delta x_j - \Delta x_i)\cos\alpha_{ij} - (\Delta y_j - \Delta y_i)\sin\alpha_{ij}$$

$$\Delta u_s = -(\Delta x_j - \Delta x_i)\sin\alpha_{ij} + (\Delta y_j - \Delta y_i)\cos\alpha_{ij} - R_i\Delta\varphi_i - R_j\Delta\varphi_j$$

Here, Δt is the time interval of calculation, Δx and Δy are the increment of displacement in *x* and *y* direction, $\Delta\varphi$ is the increment of rotation. The suffix, i and j indicate each element.

<u>Normal direction</u>

The increment of the force in the normal direction due to the spring, Δe_n and the force due to the viscous dashpot, d_n are expressed by the following equations.

$$\Delta e_n = k_n \Delta u_n$$

$$d_n = \eta_n \frac{\Delta u_n}{\Delta t}$$

Here, k_n is the spring constant in the normal direction, η_n is the viscous coefficient.

<u>Tangential direction</u>

The increment of the force in the tangential direction due to the spring, Δe_s and the force due to the viscous dashpot, d_s are expressed by the following equations.

$$\Delta e_s = k_s \Delta u_s$$

$$d_s = \eta_s \frac{\Delta u_s}{\Delta t}$$

Here, k_s is the spring constant in the tangential direction, and η_s is the viscous coefficient. e_n and e_s can be obtained by adding each increment to the values at t=t—dt.

When the two elements are separated, no force will act on two elements. Therefore, the following condition is necessary.

$$e_n < 0, \quad e_n = d_n = e_s = d_s = 0$$

From above equations, the forces acting on two elements in the normal and tangential direction are expressed, respectively as follows:

$$f_n = e_n + d_n, \quad f_s = e_s + d_s$$

The next condition should be introduced based on the assumption that the frictional force in the frictional direction follows the Coulomb's law.

$$\text{if } |f_s| > \mu \cdot f_n, \quad \text{then } f_s = \mu \frac{f_s}{|f_s|} f_n$$

Here, μ_S is the frictional coefficient between two elements.

The next step is to obtain the total forces from all elements, which are contacting with the element, i. Total forces acting on the element, i in x and y direction and total moment are expressed, respectively.

$$F_{xi} = \sum_j (-f_{nj} \cos\alpha_{ij} - f_{sj} \sin\alpha_{ij}) + B_{xi}$$

$$F_{yi} = \sum_j (-f_{nj} \sin\alpha_{ij} + f_{sj} \cos\alpha_{ij}) + B_{yi}$$

$$M_i = r_i (\sum_j f_{sj})$$

Here, B_x and B_y are body forces in x and y direction. The acceleration of the element is given by

$$\ddot{x} = F_{xi} / m_i, \quad \ddot{y} = F_{yi} / m_i, \quad \ddot{\varphi} = M_i / I_i$$

Here, m_i is the mass of the element and I_i is the inertial moment of the element. In the calculation, the above equations are integrated to obtain the displacement in Δt. Then, the same calculation is repeated by using the obtained displacement as an initial value for the next step of calculation.

<u>CALCULATION OF THE FORCES BETWEEN THE BUCKET AND PARTICLES</u>

When the bucket is penetrated into the rock pile, it is necessary to estimate the forces between the bucket wall and particles. In the case that the bucket wall contacts with the particles, the element with having zero-radius is assumed at the cross section of the bucket wall and the line from the center of element, which is perpendicular to the bucket wall. Physical properties, which are necessary for DEM simulation, are listed in Table 1.

Table 1 Physical properties used in the DEM simulation

Time Interval	0.00001sec.	Designed Value
Number of Particles	374	Designed Value
Particle Diameter	12mm	Designed Value
Slope of the Rock Pile	34 degrees	Designed Value
Density of Particles	2.5g/cm^3	Measured Value
Friction Coefficient between the Bucket and Particles	0.59	Measured Value
Friction Coefficient among Particles	0.93	Measured Value
Spring Constant	5.0×10^8 g/s^2	Assumed Value
Coefficient of Viscosity	8000g/s	Assumed Value
Air Resistance	100g/s	Assumed Value

SIMULATION RESULTS

Penetration of the bucket into the rock pile

Figures 3 and 4 show the particle behavior and trajectories when the bucket penetrates into the rock pile. The penetration speed of the bucket is 5cm/sec in this simulation. The simulation was carried out in the Sun work station and calculation time was about 50 hours. In our previous visualization experiment of the shape change of the rock pile [7], it has been already confirmed that the particle trajectories are divided into three regions, that is, 1)the region which moves horizontally with the bucket movement, 2)the region which moves upward with sliding on the failure plane and 3)the region which does not move. It was confirmed from Figures 3 and 4 that the simulation results show the same tendency as the experimental results.

Figure 5 shows the comparison between the simulated resistive forces acting on the bucket and measured resistive forces. The solid line indicates the simulated results and white circles indicate the measured resistive forces. The details about the experiments to measure the resistive forces are described in the reference [7]. Since the simulation is two dimensional, simulated results were multiplied by the bucket width that was used in the experiment, and were compared with the measured resistive forces. The horizontal axis shows the non-dimensional distance (X and L show the penetration distance and bucket bottom length, respectively). The DEM simulation does not consider the frictional force between the bucket side and particles. However, it was already confirmed that the effect of the frictional resistive force is very small. Therefore, simulated results well agree with the experimental results, although the fluctuation of the simulation results is very large.

Lifting of the bucket to scoop the rocks

Few studies have dealt with the internal change of the rock pile while scooping the rocks because the visualization of the internal shape change of the rock pile is very difficult. However, it is inevitable to know the internal shape change of the rock pile in the theoretical analysis on the resistive forces acting on the bucket of the loading machine. Therefore, the behavior of rocks by lifting the bucket was simulated.

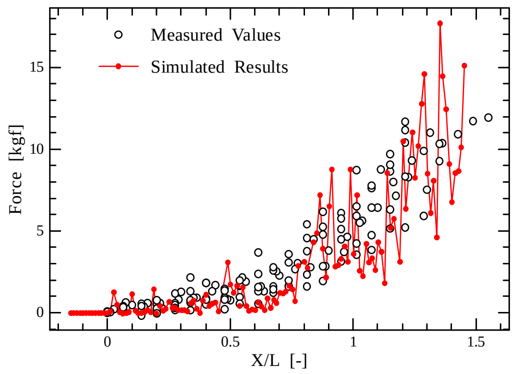


Fig.5 Comparison between Simulated Resistive Forces and Measured Ones

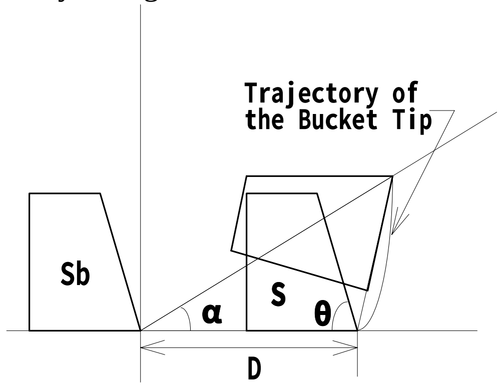


Fig.6 Schematic Diagram of the Bucket Movement in the Scooping Task

Some studies have already been conducted on the planning of the scooping, and it was reported that from the energy consumption of view, the smooth movement of the bucket from the skirts of the rock pile is the best. However, the most effective planning of scooping is not still made clear. Therefore, it was assumed that scooping strategy was as shown in Figure 6 with considering the task by an expert operator, that is, 1) the bucket is penetrated into the rock pile at distance, D, 2) then, the bucket is lifted to scoop the rocks. When the task is finished, it is assumed that the bucket tip is on the surface of the rock pile. Then, the scooped area by the bucket in Figure 6 is expressed by the next equation.

$$S = \frac{\sin\theta \sin\alpha}{2(\sin\theta - \sin\alpha)} D^2 \qquad (19)$$

The distance D is determined so that the scooped area is equal to the bucket area.

Figures 7 and 8 show the particle behavior and trajectories when the bucket is lifted to scoop the rocks. The lifting speed of the bucket is 5cm/sec in this simulation. It was confirmed that the particle trajectories are divided into three regions, that is, 1) the region which moves with the bucket movement, 2) the region which slides down to the bucket bottom and 3) the region which does not move.

CONCLUSIONS

The behavior of particles in the rock pile due to the bucket movement was simulated by use of DEM. Since the scooping task is usually carried out by two steps, that is, the penetration and lifting of the bucket, the trajectory of the bucket movement was assumed as shown in Figure 6. The shape changing process of the rock pile was made clear from the simulated results. These results will give useful information for the theoretical consideration on the resistive forces acting on the bucket in the scooping task.

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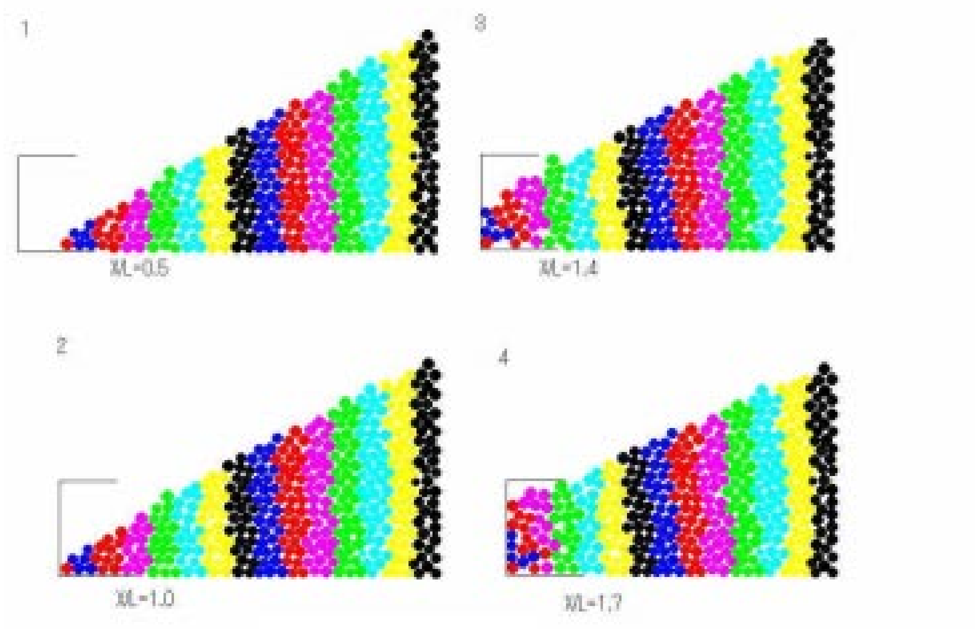

Fig.3 Behavior of particles (Penetration process)

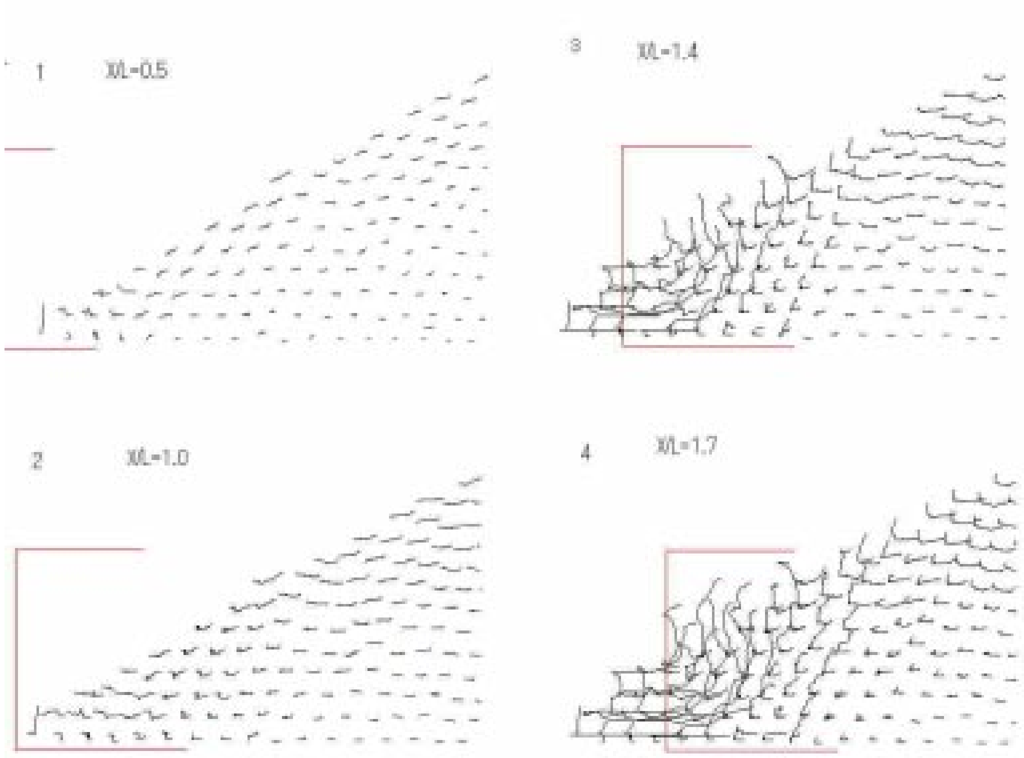

Fig.4 Trajectory of particles (Penetration process)

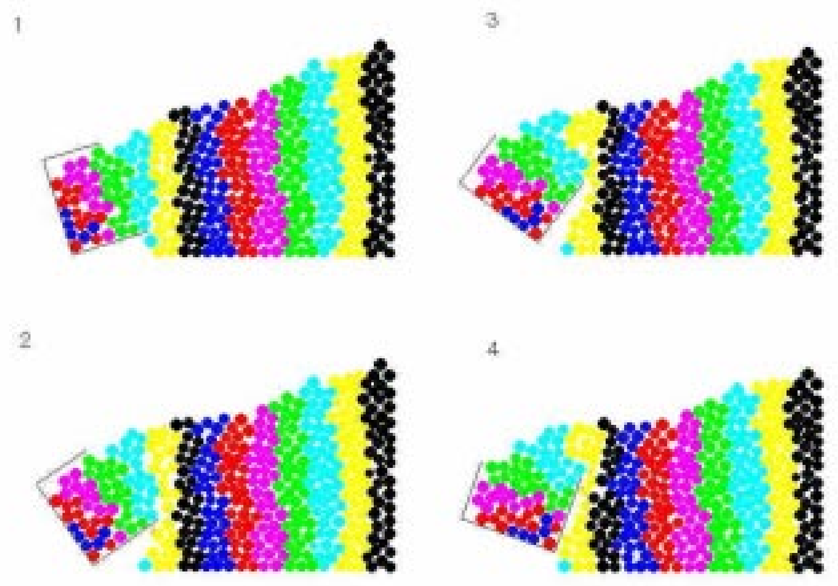

Fig.7 Behavior of particles (Lifting process)

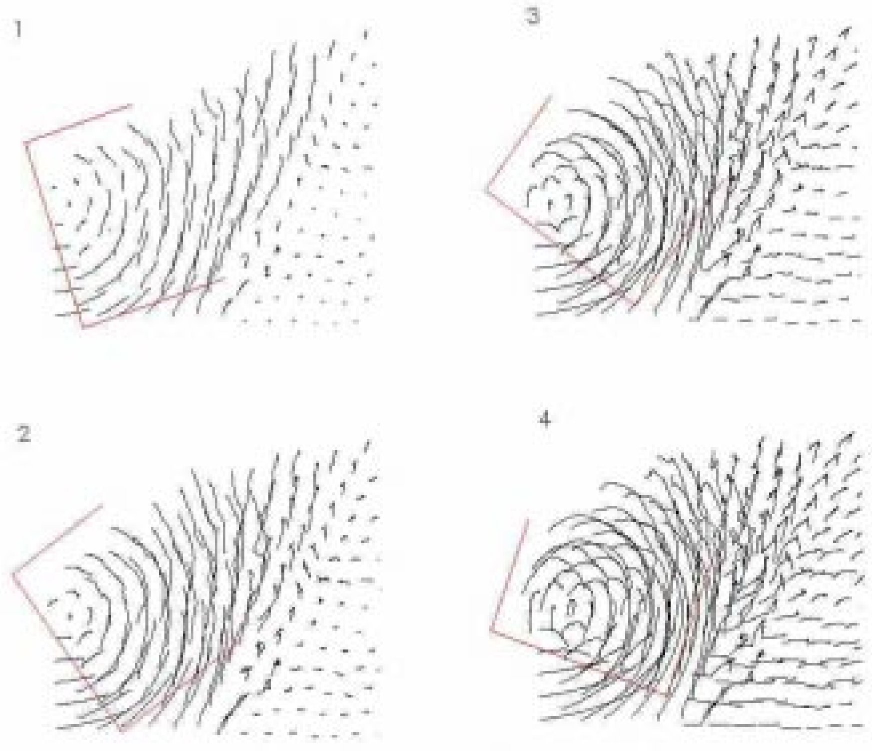

Fig.8 Trajectory of particles (Lifting process)