An analysis of the interaction between crawler and soil by the particle element method

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Abstract

This paper describes a new approach that analyzes the interaction between crawler and soil by using the Particle Element Method (PEM). The traction characteristics of the crawler shoe are discussed in detail using an analytical model constructed by the PEM. An analytical model is built by the PEM to analyze the behavior of soil particles. The model consists of a shoe, load weights and soil. In laboratory experiments, motion of the shoe is measured to verify the validity of the analytical model, and slip displacement and traction force are measured to examine dependency of traction characteristics. As a result, the analytical results are very similar to the experimental results. By analyzing soil particle flows and the traction force on each face of the shoe, the influence of ground pressure on the relationship between slip displacement and traction force is considered carefully. It is understood that the larger the ground pressure, the more hardened is the soil and the slower it flows, and in such conditions, contact forces from the contact particles to the underside of spacing and the inner side of the rear grouser are stronger so that the shoe does not move easily. As mentioned above, it is found that the PEM is quite effective in the analysis of the interaction between crawler and soil.
Keywords: tracked vehicle, crawler shoe, particle element method, slip displacement, traction force.

1 Introduction

Since tracked vehicles are often used on soil because ground pressure is lower and mobility on soil is higher than wheeled vehicles, it is important to investigate accurately the interaction between crawler and soil to forecast the mobility of

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tracked vehicles on soil. So the various relationships such as subsidence-slip displacement of tracked vehicles on soil are measured or analysed [1].

On the other hand, while tracked vehicles are driving on soil, the interaction between crawler and soil is complex because the grousers of the shoe crutch and shear on soil, and destructive phenomena such as subsidence and shearing deformation are generated. To simulate these phenomena, a soil model constructed from the level of a particle is required. One effective method is the PEM, which has contributed to the granular dynamics analysis [2,3].

The following sections present traction experiments of the shoe in the laboratory and an analysis of the behavior of soil particles by the PEM. The experiments are carried out by changing ground pressure and grouser ratio. The analysis is carried out on an analytical model that considered the contact force between each face of the shoe and soil. The validity of the analytical model is also verified by comparing the analytical and experimental results. Finally, soil particle flows and traction force on each face of the shoe are analyzed.

2 Analysis

An analytical model is carried out by the PEM to expect the soil particle flows and the interaction between shoe and soil particles.

2.1 Synopsis of the PEM

The PEM is a method that simulates the behavior of a particle element group by setting up motion equations for all particle elements. In a soil model constructed by using the PEM, it is possible to accurately analyze such microscopic physical quantities as displacement, contact angle, and contact force among elements.

In this method, contact force between elements is calculated by using the voigt model as shown in Fig.1. In this model, an elastic spring and a viscous damper are linked in parallel, and the contact force is divided into normal and tangential directions. In the tangential direction, a friction slider is modeled to consider friction force between elements.

Relative displacement u and rotational angle ϕ between the elements are expressed as eqns.(1),(2).

$$m\ddot{u} + \eta\dot{u} + Ku = 0 \tag{1}$$

$$I\ddot{\phi} + \eta r^2\dot{\phi} + Kr^2\phi = 0\,, \tag{2}$$

where m is the mass, I is the inertial moment, r is the radius, η is the coefficient of damper, and K is the coefficient of spring. Considering that the element has contact points with other elements, eqns.(1),(2) are transformed into eqns.(3),(4) using difference method advocated by Cundall [4].

$$m[\ddot{u}]_t = -\eta[\dot{u}]_{t-\Delta t} - K[u]_{t-\Delta t} \tag{3}$$

$$I[\ddot{\phi}]_t = -\eta r^2[\dot{\phi}]_{t-\Delta t} - Kr^2[\phi]_{t-\Delta t}\,. \tag{4}$$

Acceleration $\ddot{u}$ at t is calculated by velocity $\dot{u}$ and displacement u at $t-\Delta t$, and after the calculation, $\dot{u}$ and u at t is obtained by the integral calculus of $\ddot{u}$ at t.

2.2 Analytical model

A two-dimensional analytical model is built for expecting the interaction between shoe and soil particles. The model consisted of a shoe, load weights, and soil. There are contact definitions between the shoe and the soil and between the load weights and the soil, as shown in Fig.2. On the sides and bottoms of the grousers, the underside of the spacing, and the sides of the load weights, contact force is calculated based upon the depth of soil particle penetration to the contact line. On the inner and outer circles, set on the edge of each line, contact force is calculated based upon the relative displacement between the circle and the soil particle. Soil particles are arranged so as not to overlap mutually, are fallen freely, and are stabilised. Fig.3 shows initial condition of soil model. The properties of the soil model are summarized in Table 1. Physical properties of the soil model are adapted to that of silica soil. Considering settling and stability of solution, Δt is set at 1.0×10^{-7} s.

Analysis is carried out by falling the shoe model vertically and pulling it horizontally on the soil model with 0.16m/s traction speed, using a PC with 2.4Hz clock frequency.

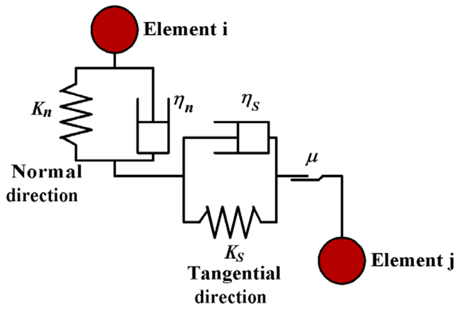


Figure 1: Voigt model.

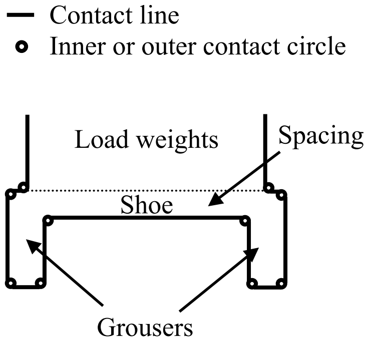


Figure 2: Definition of contact.

3 Experiments

The laboratory experiments are carried out to verify the validity of the analytical model and examine dependency of traction characteristics on ground pressure.

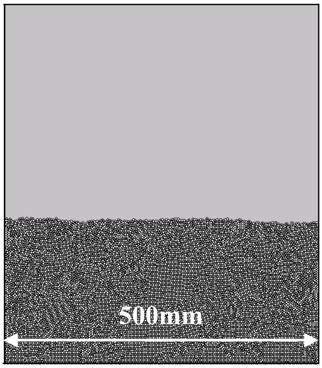


Figure 3: Initial condition of soil model.

Table 1: Properties of soil model.

Number of particles	11794
Diameter	3(mm)
Density	2480(kg/m^3)
Coefficient of friction Particle-Particle Particle-Wall	 0.25(-) 0.17(-)

3.1 Experimental apparatus

The experimental apparatus is composed of a soil bin, measurement materials, motor, test pieces, and load weights, as shown in Fig.4.

Fig.5 shows the soil bin. The height, width, and depth of the soil bin are 500, 1,000, and 500 mm respectively, and the soil is silica. An acrylic plate is set up on the side of the soil bin to make the inside of the soil bin visible. A basketed device that moves according to the guide rail is set on upside of the soil bin so that it becomes possible to horizontally and stably pull the test piece, and bring it closer to actual situations. In addition, lubricant is spread on the device to decrease friction resistance.

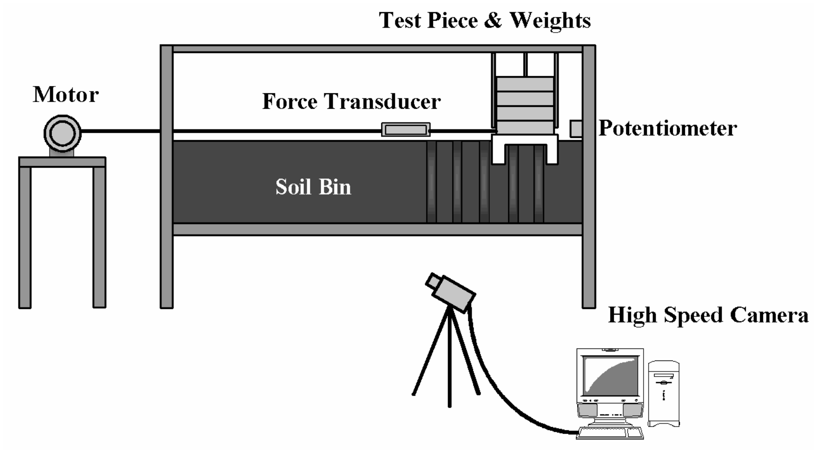
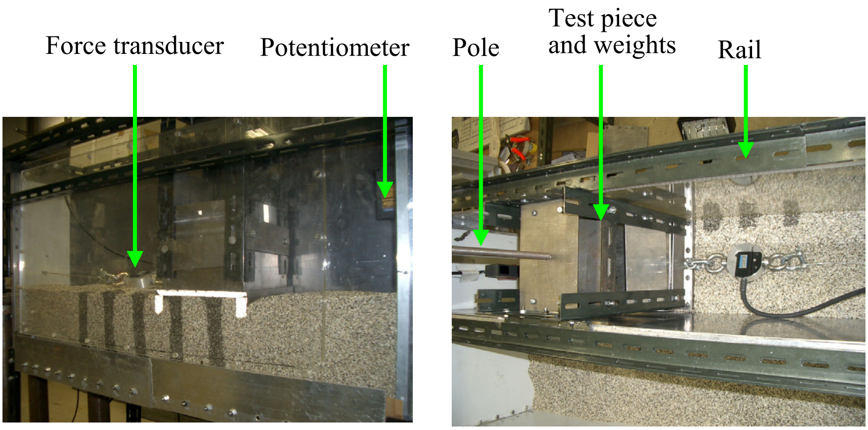


Figure 4: Schematic diagram of experimental apparatus.



(a) Overview from side (b) Overview from top

Figure 5: Soil bin.

Traction force is measured with a force transducer (Strain-gage load cell, Rated capacity: 2kN) on the wire between the test piece and the motor (AC speed control motor, Output power: 200W, Rated torque: 1.27Nm). The slip displacement of the test piece is measured with a non-contact potentiometer (Laser sensor, Resolution: 50 μm) on the soil bin. The behavior of soil in the soil bin and the motion of test piece are photographed with a high-speed camera (CCD sensor, Resolution: 480×420pixel/flame). The soil is dyed black at constant interval by lines 30mm wide to closely observe its behavior.

The length and width of the test pieces are both 200mm, as shown in Fig.6. Adding or removing the load weights to the test piece can change their mass. The load weights are combined with the shoe by a pole. The pole is not tied to the basketed device so that the test piece can move in the direction of the subsidence. The test piece is restrained from both sides by partitioning the soil bin, and on the side of the test piece, a reflection tape is pasted to photograph the motion clearly.

3.2 Measurement conditions

Laboratory experiments are carried out using load weights and test pieces. The parameters of the load weights are 40kg (ground pressure: 10.5kPa) and 60kg (ground pressure: 15.4kPa), and the parameters of the grouser height are 40mm (α=1/5), 50mm (α=1/4), and 67mm (α=1/3). The traction speed is the same as that in the analysis.

4 Results and discussions

In this section, by comparing the analytical results with the experimental results, the validity of the analytical model is verified, and using analytical results, the influences of ground pressure on traction characteristics on are discussed.

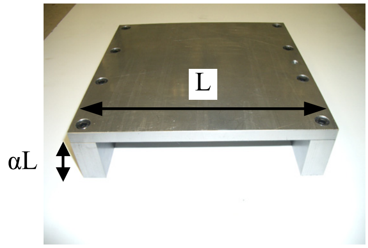
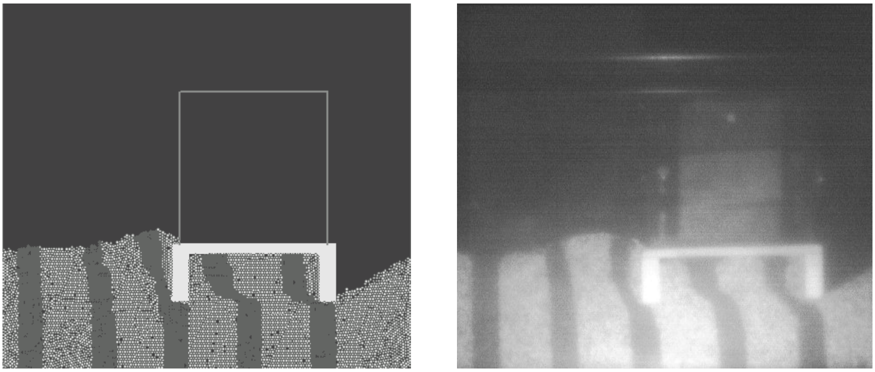


Figure 6: Test piece.

4.1 Comparisons of analytical and experimental results

Fig.7 shows an illustration of the analytical result and a still picture of the experimental result at a 40mm slip displacement from the initial position. Observing the deformation of black lines on the soil, it is found that in both case, a slip line is generated between the bottoms of grousers. In addition, the upsurges of soil at the front of the shoe are also almost same. Fig.8 shows the trajectory of the shoe. In both cases, the subsidence of the shoe increases gradually with an increase in horizontal displacement and steadies at approximately a 70mm slip displacement. As mentioned above, it can be considered that the appropriateness of the analytical model is validated.



(a) analytical result (b) experimental result

Figure 7: Visualization of analysis and experiment.

4.2 Dependancy of traction characteristics

Fig.9 shows the relationship between slip displacement and traction force above grouser ratios of 1/5, 1/4, and 1/3. In all cases, traction force increases steeply to the yield point with a slight increase in slip displacement; after attaining peak point, it falls gradually. As pointed out qualitatively by Bekker [5], the dependency is common on hardened soil, and it is supposed that in the slipping area to the yield point, the soil is not disturbed too much, but after yield point, the soil begins to be disturbed remarkably.

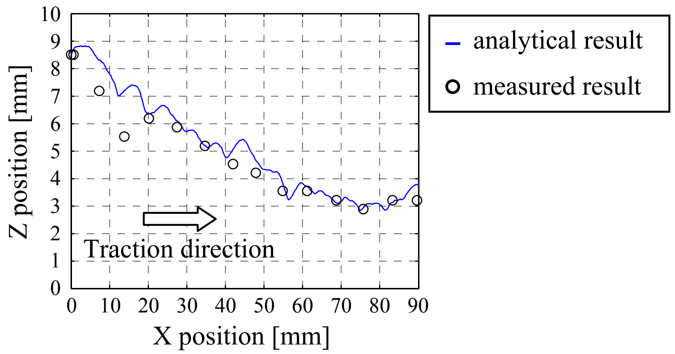


Figure 8: Trajectory of shoe.

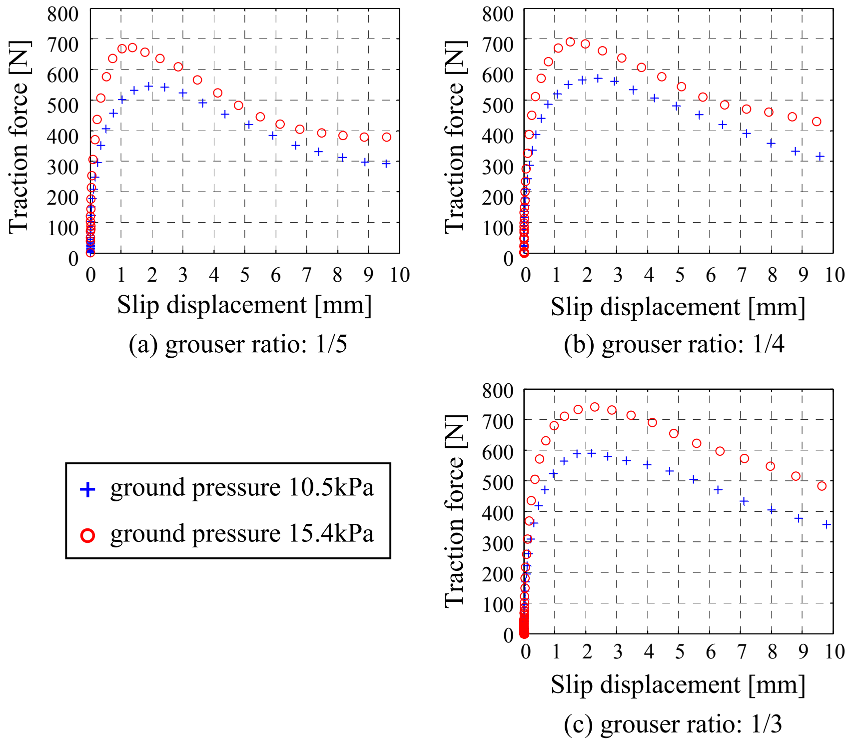


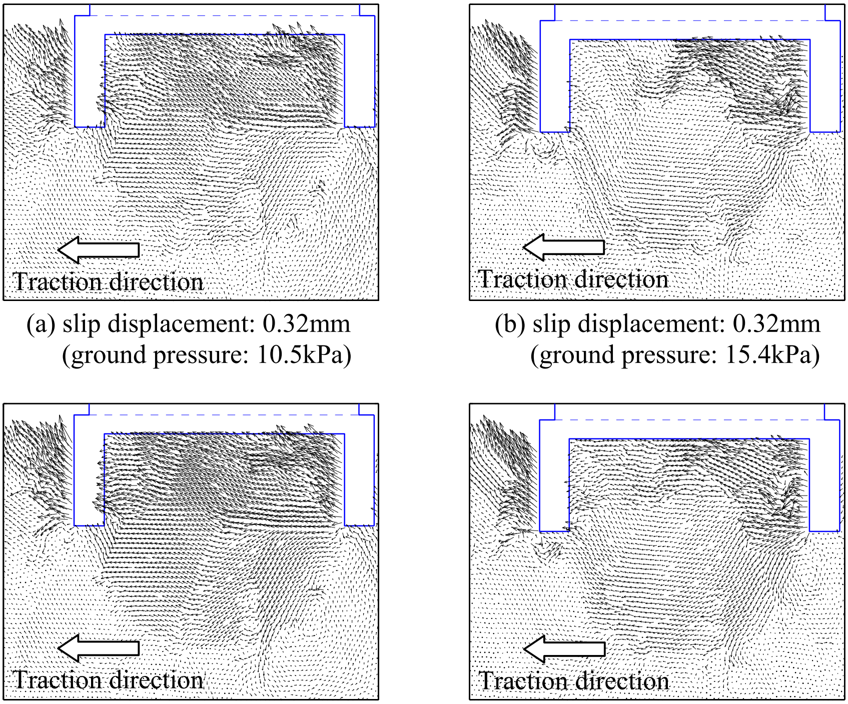
Figure 9: Experimental results of slip displacement and traction force.

At a grouser ratio of 1/4, traction force at 0.64mm slip displacement is about 450N at ground pressure of 10.5kPa and about 580N at ground pressure of 15.4kPa. These results show that ground pressure affects the increasing traction force rate to slip displacement.

4.3 Analysis for behavior of soil particles

By analyzing soil particle flows and traction force on each face of the shoe, the influence of ground pressure on the traction characteristics to the yield point is discussed.

The soil particle flows at 0.32mm and 0.64mm slip displacements are shown in Fig.10.



(a) slip displacement: 0.32mm (ground pressure: 10.5kPa)

(b) slip displacement: 0.32mm (ground pressure: 15.4kPa)

(c) slip displacement: 0.64mm (ground pressure: 10.5kPa)

(d) slip displacement: 0.64mm (ground pressure: 15.4kPa)

Figure 10: Soil particle flows on analytical model.

Fig.10(a),(c) and (b),(d) show the velocity vector of soil particles on ground pressures of 10.5kPa and 15.4kPa at a grouser ratio of 1/4, respectively. At ground pressure of 10.5kPa, soil particle flow has already been generally developed over the region restrained by the grousers. On the other hand, at ground pressure of 15.4kPa, the flow has not yet been developed in the forward region. It is understood that the larger is ground pressure, the more hardened is the soil and the slower it flows. Fig.11 shows the increment of traction force on the two faces, the underside of the spacing, and the inner side of the rear grouser, to a 0.64mm horizontal displacement at a grouser ratio of 1/4. The value is normalized based on the value at ground pressure of 15.4kPa. At ground pressure of 15.4kPa, the value is 0.8-0.85, which is close to the difference of increment of the traction force in Fig.9(b). It is also understood that shear force by the underside of spacing and pressed force by the inner side of rear grouser increase with a increase in ground pressure, and in such condition, stronger traction force is required to pull the shoe.

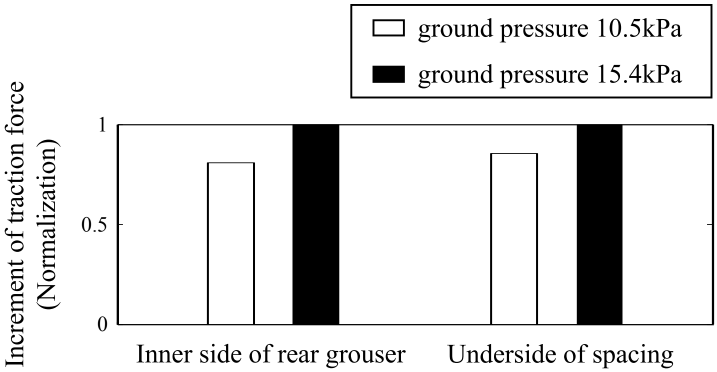


Figure 11: Normalization of traction force on inner side of rear grouser and underside of spacing.

5 Conclusions

This paper describes an approach to the detailed understanding of the interaction between crawler and soil by using the PEM, and the following results are obtained:

- An analytical model is built by the PEM to expect the behavior between a shoe and soil particles. The model consists of a shoe, load weights and soil. There are contact definitions between the shoe and the soil and between the load weights and the soil. Analysis is carried out by falling the shoe model vertically and pulling it horizontally on the soil model with 0.16m/s traction speed.
- Laboratory experiments are carried out using some test pieces with various ground pressure and grouser ratio to verify the validity of the analytical model and examine dependency of traction characteristics. In the experiments, the relationships between slip displacement and traction force in various ground pressure and grouser ratio are measured.
- The validity of the analytical model is carried out using an illustration of the analytical result, a still picture of the experimental result and the trajectory of

shoe. Comparing slip lines and upsurges of soil, it can be considered that the appropriateness of the analytical model is validated.

- From the experimental results, it is shown that the increasing traction force ratio to slip displacement depends on ground pressure. By analyzing soil particle flows and traction forces to each face of the shoe, it is understood that the larger is ground pressure, the more hardened is the soil and the slower it flows, and in such condition, shear force by the underside of spacing and pressed force by the inner side of rear grouser are stronger so that the shoe does not move easily. As mentioned above, it is found that the PEM is quite effective in the analysis of the interaction between crawler and soil.

In the future, the influence of the behavior of soil particles by grouser ratio will be analyzed.

Acknowledgements

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