

Dynamic Simulation of Soil Cultivation using Particle Method

Yosuke YAMAMOTO*

Takayuki SATO*

Genki ANRAKU*

ABSTRACT

It is desirable for the rotors used in tillers to be shaped appropriately for the specific characteristics of soils in different regions. A technology for the prediction of the dynamic behavior of soils that makes it possible to study soils with varying characteristics on a computer is therefore demanded for the efficient design of tiller rotors.

However, soil cultivation is a dynamic phenomenon involving the deformation, breakage, and agitation of the soil, and it is challenging for methods that use grids, such as the finite element methods and finite volume methods generally used in conventional CAE technologies, to treat phenomena of this type. The research discussed in this paper therefore attempted to develop a simulator for three-dimensional fluid-structure analysis using the particle method, a method suited to the analysis of large-scale deformation and breaking phenomena. In conducting this development, analytical accuracy was increased by reproducing the boundaries between soil and rigid bodies using polygons. In addition, to make it possible to faithfully reproduce the break-up behavior of soil, a model of soil break-up conditions that considered the effect of soil consolidation was formulated, and measurements of soil properties were conducted in order to provide input conditions for the simulation.

Comparison of the results of simulations of a single tiller tine and an entire rotor with test results demonstrated that results matched for the break-up behavior of the soil and the shape of the plough pan. The simulator developed in the research discussed here has made it possible to reproduce soil cultivation on the desktop, and it is believed that it will be effective in helping to enable the efficient development of tillers.

1. Introduction

The rotors used in tillers rotate in order to till soil. The fact that soil characteristics differ from region to region necessitates the development of rotors suited to specific soils. The efficient development of tiller rotors demands technologies for the prediction of the dynamic behavior of soil under a variety of soil conditions.

CAE technologies for the analysis of strength and stiffness are conventionally employed in tiller development. However, the study by computer of the condition of the soil following tilling represents a challenge. This is because it is necessary to reproduce the deformation and breakage of the soil by tilling, but the amount of deformation is high in conventional methods employing grids, and the computations fail when the distortions in the grid become too great.

Particle methods have recently attracted attention as methods able to resolve the issues described above. By contrast with conventional methods using grids, particle methods can discretize a continuous body using particles able to move freely through space. Because the particles

do not carry data concerning connections with contiguous points, unlike in the case of grids, calculations will not fail even when particles move a significant distance from their initial positions. This means that free surface problems and phenomena associated with large-scale deformation or breaking can be handled with comparative ease, leading to the application of the methods in dynamic analyses of fluids and structures⁽¹⁾. Calculation methods classified as particle methods include the discrete element method (DEM), the smoothed particle hydrodynamics (SPH) method, and the moving particle semi-implicit (MPS) method⁽²⁾.

In order to reproduce the tilling of soil on the desktop, the research discussed in this paper attempted to develop an original three-dimensional fluid-structure simulator for the Power Products R&D Center using an MPS method^{(2),(3)}. To increase the accuracy of the simulator, modifications were made to the treatment of rigid boundaries. In addition, because the effects of consolidation result in localized changes in the strength of the soil, a model of soil-breaking conditions able to faithfully reproduce the mode of break-up of the soil was formulated.

* Power Products R&D Center

2. Overview of Simulator

2.1. Overview of Moving Particle Semi-implicit Method (MPS Method)

The research discussed here employed the MPS calculation method, a type of particle method. The method was developed in 1995 to provide semi-implicit algorithms for use in incompressible fluid analyses, and is known for its ability to be applied in structural analyses and fluid-structure coupled analyses⁽²⁾⁻⁽⁴⁾. The MPS method discretizes equations formulated using Lagrange methods. In specific terms, using this method continuous bodies are expressed as particles, and partial differential equations are discretized using interparticle interaction models. The weighting function shown as Eq. (1) is used in the interparticle interaction model.

$$w_{ij}(r) = \begin{cases} \frac{r_e - r}{r_e} & r \leq r_e \\ 0 & r > r_e \end{cases} \quad (1)$$

r is the distance between particle i and particle j , and r_e is termed the effective radius, expressing the range of effect of interparticle interaction. Figure 1 shows a conceptual diagram of the effective radius. The interparticle interaction model is applicable only to particles existing within the effective radius for any specific particle. The larger the effective radius, the higher the number of neighboring particles; calculation accuracy increases as a result, but calculation time also increases. Because of this, it is necessary to set appropriate values based on a balance between calculation accuracy and calculation time.

The MPS method uses the interparticle interaction model to discretize gradient, Laplacian, divergence and other operators employed in the equations. Using the weighting function, gradient, Laplacian, and divergence models are defined for a variable ϕ or a vector $\vec{\phi}$ as follows:

$$\langle \nabla \phi \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \frac{\phi_j - \phi_i}{|\vec{r}_j - \vec{r}_i|} \frac{(\vec{r}_j - \vec{r}_i)}{|\vec{r}_j - \vec{r}_i|} w_{ij} \quad (2)$$

$$\langle \nabla^2 \phi \rangle_i = \frac{2d}{n^0 \Lambda} \sum_{j \neq i} (\phi_j - \phi_i) w_{ij} \quad (3)$$

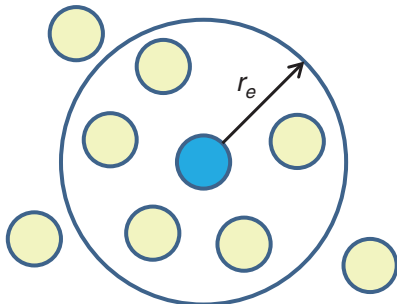


Fig. 1 Effective radius for MPS method

$$\langle \nabla \cdot \vec{\phi} \rangle = \frac{d}{n^0} \sum_{j \neq i} \frac{(\vec{\phi}_j - \vec{\phi}_i) \cdot (\vec{r}_j - \vec{r}_i)}{|\vec{r}_j - \vec{r}_i|^2} w_{ij} \quad (4)$$

Here, the position vector of the particles is termed $\vec{r}$, and the number of spatial dimensions is termed d . Λ is defined as follows:

$$\Lambda = \frac{\sum_{j \neq i} w_{ij} |\vec{r}_j - \vec{r}_i|}{\sum_{j \neq i} w_{ij}} \quad (5)$$

The particle number density at the position of particle i is defined as follows:

$$\langle n \rangle_i = \sum_{j \neq i} w_{ij} \quad (6)$$

This is the sum of the weighting functions for all the interparticle interactions in the vicinity of particle i . n^0 in Eqs. (2), (3), and (4) represents the initial state of $\langle n \rangle_i$, and the same value is employed for this parameter throughout the calculations.

When treating fluids using the MPS method, Navier-Stokes equations for incompressible flows shown as Eqs. (7) and (8) are used as the governing equations.

$$\frac{D\rho}{Dt} = 0 \quad (7)$$

$$\frac{D\vec{v}}{Dt} = -\frac{\nabla P}{\rho} + \nu \nabla^2 \vec{v} + \vec{f} \quad (8)$$

Here, t is time, $\vec{v}$ is velocity, P is pressure, ρ is density, ν is the kinematic viscosity coefficient, and $\vec{f}$ is external force. Equations (7) and (8) are discretized using the gradient model (Eq. (2)) and the Laplacian model (Eq. (3)) for the interparticle interaction model. Explicit calculations are conducted for the MPS method algorithms with the exception of the pressure term in Eq. (8), and a provisional velocity for the next step is determined. Following this, implicit calculations are conducted for pressure in order to equate the particle number density for each particle in Eq. (5) to n^0 , and the velocity is corrected.

When treating structures using the MPS method, the governing equation for elastic bodies shown as Eq. (9) is employed.

$$\rho \frac{\partial v_\alpha}{\partial t} = \frac{\partial}{\partial x_\beta} (\lambda \varepsilon_{\gamma\gamma} \delta_{\alpha\beta} + 2\mu \varepsilon_{\alpha\beta}) \quad (9)$$

Here, ρ is density, v is velocity, x is position, ε is a strain tensor, and δ is the Kronecker delta. λ and μ are Lamé's elasticity constants. These constants can be expressed as follows using Young's modulus, E , and the Poisson ratio, ν :

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)} \quad (10)$$

$$\mu = \frac{E}{2(1+\nu)} \quad (11)$$

The strain tensor in Eq. (9) is defined using the relative interparticle displacement shown in Fig. 2. The initial relative position vector between particle i and particle j in Step 1, $\vec{r}_{ij}^0$, becomes $\vec{r}_{ij}$ when particle j moves to its position in Step 2. The difference between the two position vectors is considered as the relative interparticle displacement vector, $\vec{u}_{ij}$. In relation to vector $\vec{r}_{ij}$, this vector is further divided into the vertical component $\vec{u}_{ij}^n$ and the non-vertical component $\vec{u}_{ij}^s$. The product obtained by dividing this relative interparticle displacement by the initial interparticle distance is defined as the strain tensor in the MPS method. Because divergence of the strain tensor is necessary for the calculation of the right side of Eq. (9), the divergence model, Eq. (4), for the interparticle interaction model is used for discretization and the velocity and position of the particles are explicitly calculated for the next step.

The MPS method also considers interparticle rotational motion. The force acting on a particle in the shear direction, $\vec{F}_{ij}$, and the moment produced by this force, $\vec{M}_{ij}$, are defined as follows:

$$\vec{F}_{ij} = \frac{2dm}{\rho n^0} \frac{\vec{\tau}_{ij}}{|\vec{r}_{ij}^0|} w_{ij} \quad (12)$$

$$\vec{M}_{ij} = \left| \vec{r}_{ij} \times \vec{F}_{ij} \right| \quad (13)$$

Here, m is the mass of a single particle, and $\vec{\tau}_{ij}$ is the shear stress acting between particles i and j . $\vec{\tau}_{ij}$ is calculated from the second term within the parentheses on the right-hand side of Eq. (9). To conserve angular momentum, a half-torque is applied to particles i and j in order to cancel the resultant moment.

$$I \frac{\partial \omega_i}{\partial t} = -\frac{1}{2} \sum_{j \neq i} \vec{M}_{ij} \quad (14)$$

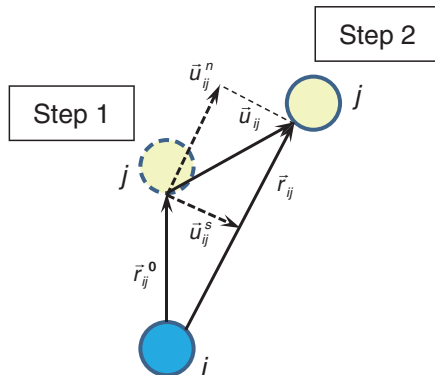


Fig. 2 Relative interparticle displacement

Here, I is the moment of inertia for a single particle, and ω is angular velocity. By imparting degrees of freedom to the rotation of each particle, the MPS method makes it possible to remove the rigid rotational components from the relative interparticle displacement vectors and calculate stress even in the case of large-scale deformation.

2.2. Modifications to Increase Accuracy

2.2.1. Treatment of boundaries with rigid bodies

Boundaries with rigid bodies are generally expressed using particles when applying the particle method. In the present study, “rigid body” refers to the tines of a tiller. When the boundary has a complex configuration, it is necessary to increase particle resolution in order to accurately express the configuration, which can increase calculation time. Altering the particle resolution locally or not employing particles at boundaries have been proposed as methods of resolving this issue⁽⁵⁾⁻⁽⁷⁾. The use of a method in which polygon models rather than particles are employed at boundaries reduces the number of particles necessary for the calculation, thus reducing the calculation load. However, it is necessary to take care with regard to the interaction between the polygons and the particles in order to accurately reproduce curvature.

In the present research, polygon models were used to express boundaries, and the polygons affecting any specific particle were determined using the velocity vector of that particle. Figure 3 shows the relationship between a particle and a polygon model. The boundary is composed of an infinitesimal triangular element (a polygon); the polygon acts as a boundary that imparts a repelling force when a particle approaches to within a given distance. Because a polygon that exists in the direction of the velocity vector of the particle and at the shortest distance from the particle is selected as the boundary, two or more polygons will not exert a repelling force on the particle even in areas of high curvature.

2.2.2. Model of breaking conditions for reproduction of soil behavior

On the microscopic level, soil is composed of the elements soil particles, water, and air (Fig. 4), and its properties change depending on the ratio and geometrical configuration of these elements^{(8),(9)}. When soil is deformed

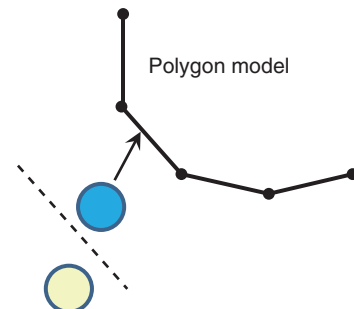


Fig. 3 Particle and polygon models

by the action of tensile and compressive forces, its porosity changes, and this results in changes in its hardness and strength. Because the numerical analysis assumes a homogeneous continuous body obeying the governing equation shown as Eq. (9), the faithful reproduction of properties with consideration of the elements composing the soil represents a challenge. The present research, therefore, attempted to modify the breaking conditions employed in order to reproduce the break-up of soil.

Normally, the breakage of structures in the MPS method is determined by the interparticle distance, and the equivalent stress is defined as follows, using the interparticle stress tensor⁽¹⁰⁾:

$$\bar{\sigma} = \sqrt{\frac{3}{2}(\sigma^n^2 + \sigma^s^2)} \quad (15)$$

σ^n is interparticle deviatoric stress in the vertical direction, and σ^s is deviatoric stress other than in the vertical direction. This is identical to Von Mises equivalent stress and is not affected by mean vertical stress. However, soil properties are thought to change with consolidation due to soil structure. The equivalent stress was, therefore, corrected as follows:

$$\bar{\sigma}' = \bar{\sigma} - \alpha\sigma_m \quad (16)$$

σ_m is mean vertical stress and α is the coefficient for the adjustment of the degree of influence of the mean vertical stress. Breakage is considered to occur when the corrected equivalent stress exceeds breaking strength. Positive values for σ_m express the action of tensile forces, while negative values express the action of compressive forces. Because the corrected equivalent stress declines when tensile forces are acting, strength declines. By contrast, the corrected equivalent stress increases when compressive forces are acting, and strength thus increases. The consolidation of the soil can be reproduced through the changes in soil strength due to tensile and compressive forces.

2.3. The Simulator

The present research employed Fortran90 as the development language for the simulator. Approximately

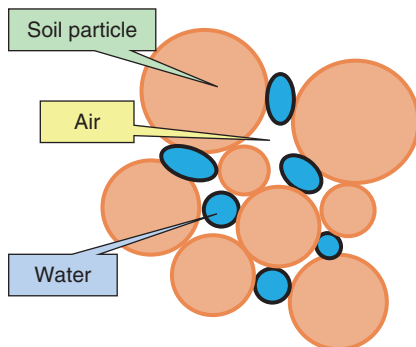


Fig. 4 Microscopic structure of soil

7000 lines were used in the program. OpenMP was used for parallelization in order to increase calculation speed.

As indicated in Section 2.1., it is possible to conduct dynamic fluid analyses, structural analyses, or fluid-structure coupled analyses. At present Newtonian fluids and elastic bodies can be treated, and customization is possible by means of the program.

With regard to the input of shapes, three-dimensional point sequence data is formulated for the fluids and structures to be treated as particles, and this data is input. For the polygon models, STL models formulated from 3D models can be employed without modification as input data. It is not necessary to formulate high-quality mesh data from 3D models produced using a grid or other method. It is possible to set parallel translation and rotational motion at fixed speeds for the polygon models, and more complex motion can also be realized by means of the program.

3. Analysis of Soil Cultivation

3.1. The Tiller

Figure 5 shows an external view of a self-propelled tiller. A rotor to enable tilling of the soil is attached to the bottom section of the tiller. Because the condition of the soil following cultivation is an important element in the raising of crops, it is essential to evaluate the performance of these rotors.

3.2. Measurement of Soil Properties

In order to conduct a simulation of soil cultivation, it is necessary to conduct measurements of the properties of the soil under study. The research discussed here used unconfined compression tests in order to conduct measurements of the modulus of deformation and breaking strength of the soil to be simulated, and these measurements were reflected in the simulation. Tests for particle size



Fig. 5 External appearance of tiller

distribution were also conducted in order to help enable the quantitative classification of the soil for simulation.

The tests were conducted following the methods specified in JIS A 1216⁽¹¹⁾. The relationship between strain and compressive stress shown in Fig. 6 was obtained when loads were applied using an Autograph to soil compressed into a cylinder. The maximum value of compressive stress is equivalent to breaking strength, and the modulus of deformation can be found from the gradient at the point at which 50% of maximum compressive stress occurs. A clay soil was used in the tests. This soil possessed a high level of hardness, and was resistant to breakage. Test specimens were formulated that reproduced the water content and density of the soil in an actual field, and unconfined compression tests were conducted. Variations were observed between the test specimens, but the soil under study was found to have a modulus of deformation of 0.7-1.5 MPa and a breaking strength of 0.06-0.10 MPa.

In addition, because the composition of the size of the particles making up the soil has a significant effect on its properties, tests for particle size distribution based on JGS 0131 were conducted⁽¹²⁾ in order to determine the size of the particles. For these tests, a dispersant is applied to soil samples in order to disperse the soil particles into water and create suspension liquids, which are then left untouched. As time elapses, the dispersed particles settle, and the density of the suspension liquids changes. Because the speed of settling is faster the larger the particles and slower the smaller the particles, the composition of the size of the particles can be determined from the ratio of the change in density to the elapsed time. Figure 7 shows a particle size distribution curve obtained by measuring density at specific points in time using a hydrometer and applying Stokes' theorem. Tests for particle size distribution were conducted on the clay soil forming the subject of the present study and a black soil possessing different properties. The smaller the size of the particles making up the black soil, the closer its properties were to those of clay soil. From Fig. 7, it is possible to quantitatively verify the fact that the clay soil under study is composed of finer particles than the black soil that was tested.

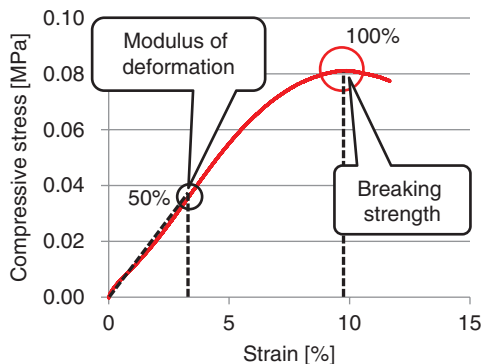


Fig. 6 Stress-strain diagram for soil

3.3. Unit Analysis of Tiller Tines

First, a simulation of soil break-up was conducted on a parallelepiped soil model composed of soil particles using a single tiller tine rotating at 10 rpm. Approximately 50000 particles with an interparticle distance of 5 mm, treated as elastic bodies, were subject to analysis. Comparisons were conducted between two cases with differing breaking conditions, as described in Section 2.2.2. For Case 1, α in Eq. (16) was set at 0 without consideration of the effect of consolidation, and for Case 2, α in Eq. (16) was set at 1 with consideration of the effect of consolidation. Other than the soil-breaking conditions, all conditions were identical for the two cases. Values for the physical properties of the soil were determined on the basis of the values for the clay soil measured in Section 3.2. In order to compare the simulation results with the break-up behavior of actual soil, a parallelepiped clay soil test specimen was subjected to tests involving the rotation of a single tine (Fig. 8), and the break-up behavior of the soil in the tests and in the analysis results was compared.

Figure 9 shows soil behavior during a test using actual soil. Break-up of the soil occurred in areas distant from the tine, and scraping that raised the soil across a wide area was observed. The results of the simulations of soil cultivation are shown in Fig. 10. In Case 1, because the

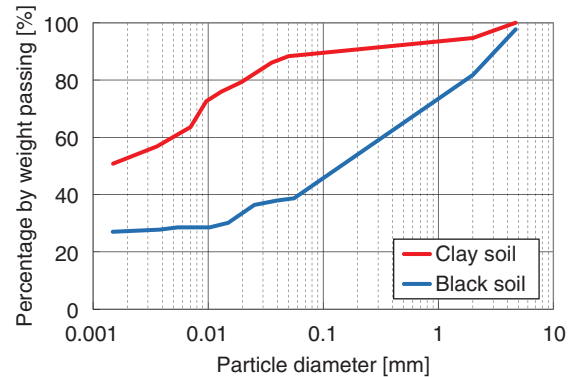


Fig. 7 Particle size distribution curve

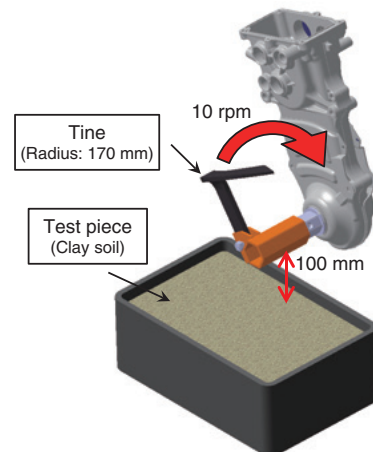


Fig. 8 Experimental apparatus for single-tine unit

break-up of the soil occurred close to the tine, the shape of the scraped-up clods of soil was similar to the width of the tine. By contrast, in Case 2, because the break-up of the soil occurred farther away from the tine, the scraped-up clods were larger than those in Case 1. These results indicate that the behavior displayed by the soil in Case 2, which considered the effect of consolidation, was most similar to the break-up behavior of actual soil. Quantification of the break-up behavior of the soil and evaluations in which loads are applied to the tines, to make it possible to conduct quantitative comparisons, will be issues for the future.

3.4. Analysis of Entire Tiller Rotor

Next, an analysis of an entire rotor was conducted, and the results were compared with the shape of the plough pan produced by tilling with an actual tiller. As Fig. 11 shows, multiple tines were attached to two rotors by means

of holders, and the rotors were attached to each side of the transmission case as a left-right pair. Figure 12 shows an example of the analysis of the entire rotor. Analyses were conducted using rotors of two different shapes, and the shapes of the resulting plough pans were compared. As Fig. 13 shows, in the case of Type A some soil remains in the center of the plough pan, while the plough pan for Type B is flat. For both Type A and B, the tine tips are the furthest points from the center of rotation, but in the case of Type A the tips of the tines are distant from the transmission case at the center of the tiller, while in the case of Type B there are tine tips that are positioned close to the transmission case. It is believed that it is because of this that soil remains in the center of the plough pan in the case of Type A, while the soil in the center of the plough pan is broken up in the case of Type B. Figure 14 shows the shapes of plough



Fig. 9 Soil behavior using actual machine

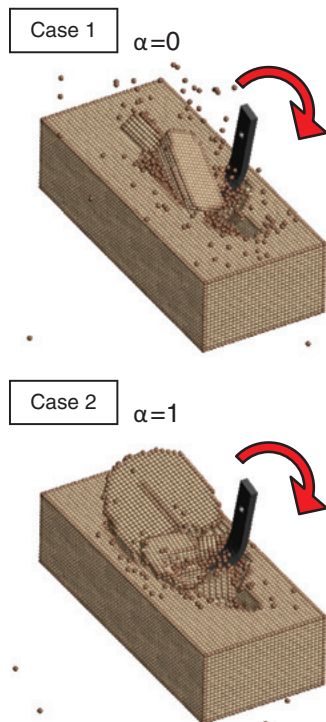


Fig. 10 Analytical results for single-tine unit

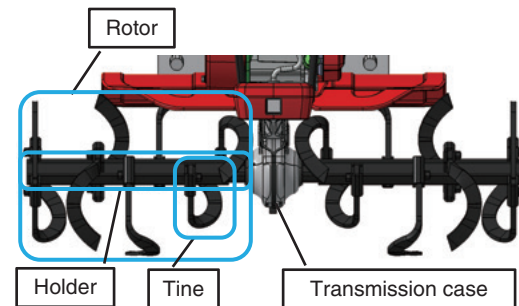


Fig. 11 External appearance of rotor



Fig. 12 Analysis of entire rotor

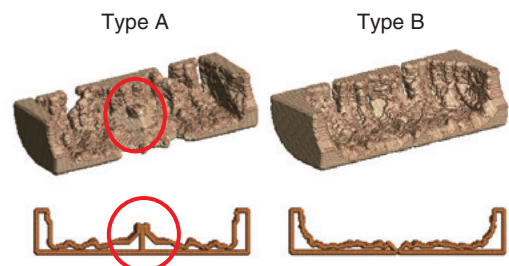


Fig. 13 Analytical results for soil cultivation

pans following cultivation by an actual tiller. As in the simulations, soil remains in the center of the plough pan in the case of Type A, while no soil remains in the case of Type B. For the entire rotor also, a qualitative match was achieved between test and simulation results.

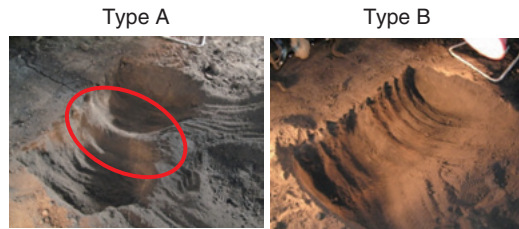


Fig. 14 Results for soil cultivation by actual machine

4. Conclusion

The development of a technology for the simulation of soil cultivation by a tiller using the particle method generated the following conclusions.

- (1) The reproduction of soil as particles using the MPS method and the expression of boundaries between soil and rigid bodies as polygons made it possible to calculate dynamic phenomena such as the break-up and agitation of soil by the tines of a tiller with comparative stability.
- (2) In order to faithfully reproduce the break-up of soil, a breakage model that considered consolidation was formulated and measurements of the properties of actual soils were conducted. The results indicated that a qualitative match was achieved between simulation and test results for the break-up behavior of soil under a single tine and the shape of the plough pan following cultivation.
- (3) The results of the research discussed in this paper have made it possible to reproduce the cultivation of soil on the desktop, and it is believed that the technology will be effective in helping to enable efficient development of tiller rotors.

References

- (1) Yamamoto, Y., Sato, T. Anraku G.: Dynamic Simulation of Water and Soil Using the Particle Method, SAE paper, 2011-32-0563 (2011)
- (2) Koshizuka, S.: Particle Methods (Computational dynamics lecture series), The Japan Society for Computational Engineering and Science, p. 1-139 (2005)
- (3) Koshizuka, S.: Numerical Analysis of Flow using Particle Method, Flow 21, p. 230-239 (2002)
- (4) Song, S. M., Koshizuka, S., Oka, Y.: Dynamic Analysis of Elastic Solids by MPS Method, Transactions of the Japan Society of Mechanical Engineers, Series A, Vol.

71, No. 701 (2005-1), p. 16-22 (2005)

- (5) Tanaka, M., Masunaga, T., Nakagawa, Y.: Multi-resolution MPS method, Transactions of JSCES, Paper No. 20090001 (2009)
- (6) Iida, K., Akimoto, H.: Water Slide Simulation using MPS Method, 17th Numerical Fluid Symposium D4-3 (2004)
- (7) Harada, T., Koshizuka, S.: Wall Boundary Calculation Model using MPS Method, Transactions of JSCES, Paper No. 20080006 (2008)
- (8) Murayama, S.: Dynamic Behavior of Soil, Gihodo Shuppan, p. 1-23, p. 119-221 (1990)
- (9) Yamaguchi, H.: Soil Mechanics (All revisions), Gihodo Shuppan, p. 1-32, p. 91-106, p. 141-194 (1969)
- (10) Tomita, Y.: Foundation and Application for Theory of Elasto-Plasticity, Morikita Publishing Co., Ltd., p. 25-64 (1995)
- (11) JIS 1216: Method for unconfined compression test of soils, p. 1-5 (2009)
- (12) JGS 0131: Test method for particle size distribution of soils, p. 23-33 (2008)

■ Author ■



Yosuke YAMAMOTO



Takayuki SATO



Genki ANRAKU