# Terra-Mechanical Simulation Using Distinct Element Method

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*To our company that designs and manufactures equipment for handling soil and rock, analyzing the interaction or contact between equipment and soil/rock is one of important subjects of research from the viewpoint of carrying out rational design of such basic equipment performances as work efficiency, fuel efficiency, and durability. However, since this problem requires treating both equipment/parts ("continuous object") and soil/rock ("discontinuous object") at the same time, it can hardly be solved by the conventional finite element method (FEM) alone. Because of this, the problem has so far been analyzed by using mainly an experimental technique and models based on empirical knowledge accumulated in the past. With the aim of addressing the problem more effectively, we are developing a terra-mechanical simulation tool which combines the FEM method for treating continuous elements and the distinct element method for treating discontinuous elements.*

*In this paper, we shall describe our terra-mechanical simulation method taking excavation with the blade of a bulldozer as an example.*

**Key Words:** *Terra-Mechanical Simulation, DEM (Distinct Element Method), Excavation Analysis, Analysis of Excavation with Blade, Analysis of Discontinuous Object, Simulation, CAE, Analysis of Soil Behavior.*

## 1. Introduction

To our company that designs and manufactures equipment for handling soil and rock, analyzing the interaction or contact between equipment and soil/rock is one of important subjects of research.

Namely, by analyzing how the equipment acts upon the soil/rock, what behavior the soil/rock shows and how it gives its reaction to the equipment, it is possible to obtain valuable information for carrying out rational design of such basic equipment performances as work efficiency, fuel efficiency, and durability.

Problems like the ones shown above have been analyzed by using mainly experimental techniques and models based on empirical knowledge accumulated in the past. If computer simulations can be used to solve them, it should be possible to derive optimum solutions more efficiently. However, since those problems require treating both equipment/parts ("continuous object") and soil/rock ("discontinuous object") at the same time, they can hardly be solved by commercial analytical tools alone.

With the aim of addressing the problems more effectively, we are developing a "terra-mechanical simulation tool" which combines the finite element method for handling continuous elements and the distinct element method for handling discontinuous elements.

In this paper, we shall describe our simulation tool taking excavation of soil/rock with the blade of a bulldozer as an example.

## 2. Technique to analyze excavation of soil/rock

In order to analyze the excavation of soil/rock with a bulldozer, it is necessary to represent the movement of the soil/rock to be excavated by a suitable mechanical model. However, the movement of soil/rock which has many of the characteristics of a discontinuous object can hardly be analyzed by any of mechanics of elasticity, plasticity, and materials, which are used for stress analysis of solids, structural mechanics, which is used for stress analysis of structures, hydromechanics, which deals with fluids, and soil mechanics, which deals with soil, since all these mechanics assume the object of analysis as a continuous one. We, therefore, decided to make an attempt to analyze the excavation of soil/rock by employing the distinct element method that permits analyzing the movement of a discontinuous object by using mathematical models.

### 2-1 Distinct element method

The distinct element method is a theory proposed by Peter A. Cundall in 1971. In this method, any particle that exists is regarded as a rigid element and the behavior of this element is expressed by an equation of motion of mass point. A spring is provided between rigid elements which make contact with each other so as to express the interaction of force between them. Then, the equation of motion of each rigid element is solved and the solution is subjected to numerical integration on a time axis, whereby the behavior of the element is analyzed. The algorithm used in the distinct element method (DEM) is shown in **Fig. 1**, and the concept of the mechanical model of contact between rigid elements (particles) is shown in **Fig. 2**.
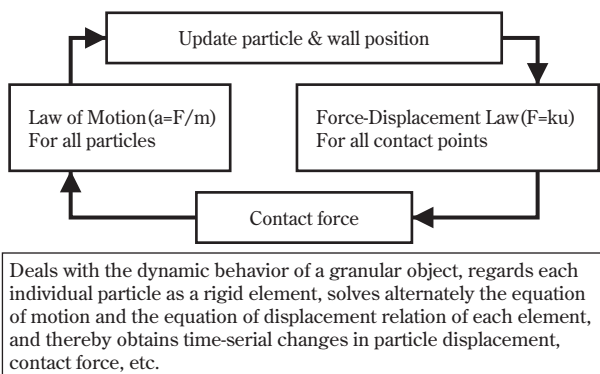


Deals with the dynamic behavior of a granular object, regards each individual particle as a rigid element, solves alternately the equation of motion and the equation of displacement relation of each element, and thereby obtains time-serial changes in particle displacement, contact force, etc.

**Fig. 1** Algorithm of the distinct element method



Calculates the force that acts between particles with springs representing the elasticity and a dash pot representing the damping of viscosity provided between elements.
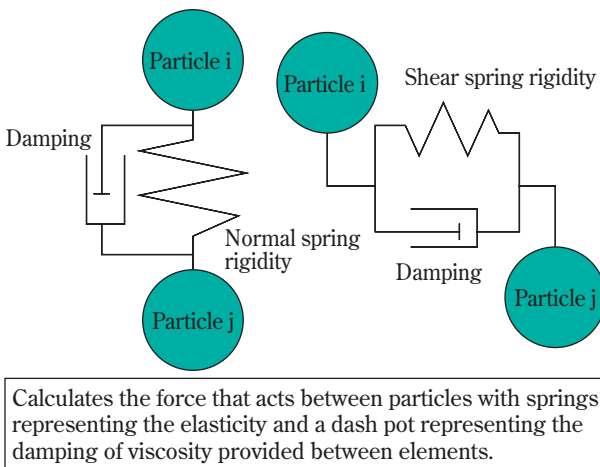
**Fig. 2** Mechanical model dealing with contact between elements

(1) Equation of motion of rigid element

The equation of motion of rigid element $i$ whose mass is $m_i$ and whose moment of inertia is $I_i$ can be expressed as follows.

$$F_i = m_i \cdot \ddot{u}_i \quad \text{.............................} \quad (1)$$
$$M_i = I_i \cdot \ddot{\phi}_i \quad \text{.............................} \quad (2)$$

where,

$F_i$, denotes resultant force acting upon the element;
$M_i$, resultant moment acting upon the element;
$u_i$, displacement vector of the element; and
$\phi_i$, centrifugal displacement.

Displacement vector, $u_i$, and centrifugal displacement, $\phi_i$, can be obtained by subjecting the solutions of Equations (1) and (2) to numerical integration on a time axis.

(2) Vertical force applied by normal spring

The mechanical model of the point of contact between elements in the normal direction shown in Fig. 2 is as follows.

$$\Delta \vec{e}_n = k_n \cdot \vec{u}_n \quad \text{.............................} \quad (3)$$
$$\Delta \vec{d}_n = \eta_n \cdot (\vec{u}_n / \Delta t) \quad \text{.............................} \quad (4)$$
$$[\vec{e}_n]_t = \Delta \vec{e}_n + [\vec{e}_n]_{t-\Delta t} \quad \text{.............................} \quad (5)$$
$$[\vec{d}_n]_t = \Delta \vec{d}_n \quad \text{.............................} \quad (6)$$

where,

$\Delta \vec{e}_n$ : Increasement of spring force acting vertically for $\Delta t$
$\Delta \vec{d}_n$ : Increasement of viscous resistance acting vertically for $\Delta t$
$[\vec{e}_n]_t$ : Force applied vertically by normal spring at time t
$[\vec{d}_n]_t$ : Force applied vertically by viscous resistance at time t
$\vec{u}_n$ : Increase of displacement
Kn : Spring constant
$\eta$ : Coefficient of viscosity

It is assumed that the normal spring is completely free from tension.

(3) Force applied in shear direction by shear spring

The mechanical model of the point of contact between elements in the shear direction shown in Fig. 2 is as follows.

$$\Delta \vec{e}_s = k_s \cdot \vec{u}_s \quad \text{.............................} \quad (7)$$
$$\Delta \vec{d}_s = \eta_s \cdot (\vec{u}_s / \Delta t) \quad \text{.............................} \quad (8)$$
$$[\vec{e}_s]_t = \Delta \vec{e}_s + [\vec{e}_s]_{t-\Delta t} \quad \text{.............................} \quad (9)$$
$$[\vec{d}_s]_t = \Delta \vec{d}_s \quad \text{.............................} \quad (10)$$

where,

$\Delta \vec{e}_s$ : Increasement of spring force acting in shear direction for $\Delta t$
$\Delta \vec{d}_s$ : Increasement of viscous resistance acting in shear direction for $\Delta t$
$[\vec{e}_s]_t$ : Force applied in shear direction by shear spring at time t
$[\vec{d}_s]_t$ : Force applied in shear direction by viscous resistance at time t
$\vec{u}_s$ : Increase of displacement
Kn : Spring constant
$\eta$ : Coefficient of viscosity

It is assumed that the shear spring is completely free from tension.

$$[F_i]_t = [\vec{e}_n]_t + [\vec{d}_n]_t + [\vec{e}_s]_t + [\vec{d}_s]_t \quad \text{.............} \quad (11)$$

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# 3. Selection of physical property values of soil

In a DEM analysis of the excavation of soil/rock by the blade of a bulldozer, it is necessary to express the characteristic movement of soil/rock by using only the parameters for DEM analysis shown in **Table 1**. When the excavation of soil/rock by a blade is to be analyzed, the items that must be analyzable in the first step are the 'reaction acting upon the blade during excavation' and the 'qualitative movement of the soil/rock excavated.' Here, we shall describe the method of calculating the physical property values for DEM analysis against the shear strength of soil that are considered absolutely necessary for obtaining the soil reaction during excavation. The content of the calculations we performed is also shown.

**Table 1** Parameters for DEM analysis

| Parameter setting point | Parameter name | Unit |
|---|---|---|
| Between rigid particles | Rigid element (particle) diameter | m |
| | Normal spring rigidity | N/m |
| | Shear spring rigidity | N/m |
| | Friction coefficient | – |
| | Particle density | kg/m$^3$ |
| Between rigid particle and blade | Normal spring rigidity | N/m |
| | Shear spring rigidity | N/m |
| | Friction coefficient | kg/m$^3$ |

## 3-1 Soil shear strength

When an external force acts upon soil, a slip can occur along a plane of the soil. It occurs when the shear force produced in the soil by the external force exceeds the shear resistance of the soil. The maximum value of shear resistance of soil is called soil shear strength. The soil shear strength varies according to particle size, water content in percent of dry weight, degree of compaction, drain condition, state of sedimentation, etc.

In a soil shear test shown in **Fig. 3**, assume that a soil sample is put in a container which permits the soil to be divided into an upper part and a lower part and that with vertical load Pn kept applied to the sample soil, horizontal shear force S is applied to the soil sample to shear it along the plane of division. (This plane is called the shear plane.)
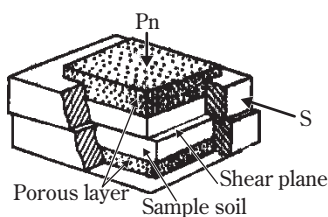


**Fig. 3** Soil shear test

In this case, the relationship between soil vertical stress σ and soil shear strength s, under a variable vertical load, can be expressed by Equations 11, 12, and 13, and σ and s are in a linear relationship as shown in **Fig. 4**.

$$\sigma = P_N/A \text{ (kgf/cm}^2) \text{ ............... (11)}$$
$$s = S/A \text{ (kgf/cm}^2) \text{ .................. (12)}$$
$$s = C + \sigma \tan \phi \text{ (kgf/cm}^2) \text{ ....... (13)}$$

where,
  A denotes shear area;
  C, soil cohesion;
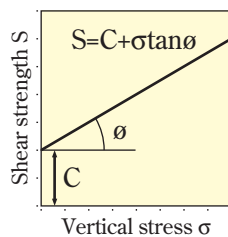  φ, soil shear resistance angle;
  and σ, vertical stress.



**Fig. 4** Relationship between soil shear strength and vertical load

## 3-2 Method of measuring soil shear strength

The shear strength of the soil sample for the excavation test was measured. Since the value of soil shear strength we needed was that in the actual excavation test environment, we decided to measure soil shear strength by using a Caspol – a simple soil bearing – capacity measuring instrument which is capable of measuring soil shear strength in the field, rather than by subjecting the soil sample to a laboratory shear test. (The appearance of the instrument, made by Marui, Ltd., is shown in **Fig. 5**.) The measuring principle of the Caspol is this. First, impact acceleration Ia when the rammer is let free-fall onto the ground is measured. Then, by using the value of Ia, approximate values of soil cohesion C and shear resistance angle Φ in Equation (13) are obtained. **Fig. 6** shows calculated values of soil shear strength S based on the results of measurement by the Caspol of soil of the excavation test site. As the water content in percent of total weight of soil in the actual excavation test, we used 10% which gave the maximum soil density in a soil compaction test (carried out in accordance with JIS A 1210).



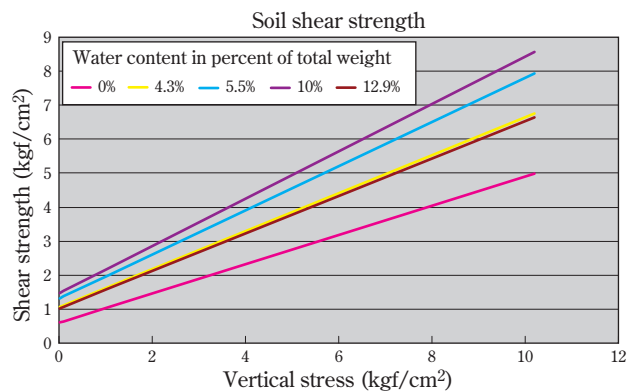**Fig. 5** Appearance of Caspol – simple soil bearing – force measuring instrument



**Fig. 6** Results of soil shear strength measurement by Caspol

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### 3-3 DEM analysis of soil shear strength

In order to analyze the excavation of soil by a bulldozer blade, it is necessary to determine the value of each of the parameters shown in Table 1. Concerning the rigidity of each of the normal and shear springs acting between particles and between a particle and the blade, a considerable volume of measurement data is available. Eventually, we decided to adopt the rigidity values that were recommended by a developer of the code which is widely used for DEM analysis and to study the values of two parameters – the coefficient of friction between particles which is considered to have strong correlation with soil cohesion C (this depends on water content in percent of total weight) and the particle diameter (number of particles) which is considered to have strong correlation with shear resistance angle Φ.

Concerning the values of these parameters, we decided to prepare a computer program for executing a soil shear test by DEM, obtain soil shear strength S under the same conditions as shown in 3-2, compare calculated results with the experimental results in 3-2, and adopt the values that can best reproduce the content of the experiment.

(1) Particle diameter

In order to measure the effect of particle diameter on shear strength, we carried out a soil shear test and analysis using constant vertical load Pn and three different particle diameters (0.1 m, 0.2 m, 0.4 m). The particles were arranged in such a manner that each of particles tangent to each other came at an apex of a regular hexahedron so as to eliminate the possibility of anisotropic particle movement. The conditions of shear analysis using different particle diameters are shown in **Fig. 7** (a), (b), and (c), and the shear strength – shear distance relationships obtained with different particle diameters are shown in **Fig. 8**. It can be seen from Fig. 8 that the number of times a particle run-over occurs (i.e., the number of times a peak value appears in the graph) over the shear distance depends upon the particle size but that the peak values of shear strength are nearly the same. This fact suggests that the particle diameter does not have marked effect on the soil shear strength. In the subsequent analysis of soil excavation by a bulldozer blade, we adopted a particle diameter of 0.1 m which is equivalent to the depth of soil the blade cuts into.

(2) Coefficient of friction between particles

In order to measure the effect of coefficient of friction between particles on soil shear strength, we carried out a soil shear test and analysis by DEM. The analysis results are shown in **Fig. 9**. From the vertical stress-shear strength curves shown in Fig. 9, it can be seen that there is strong correlation between friction coefficient and soil shear strength. In addition, a comparison of Fig. 9 with Fig. 6 reveals that there seems correlation between friction coefficient and water content in percent of total weight. We considered, therefore, that by properly adjusting the coefficient of friction, it should be possible to simulate the cohesion of sample soil using the water content in percent of total weight.
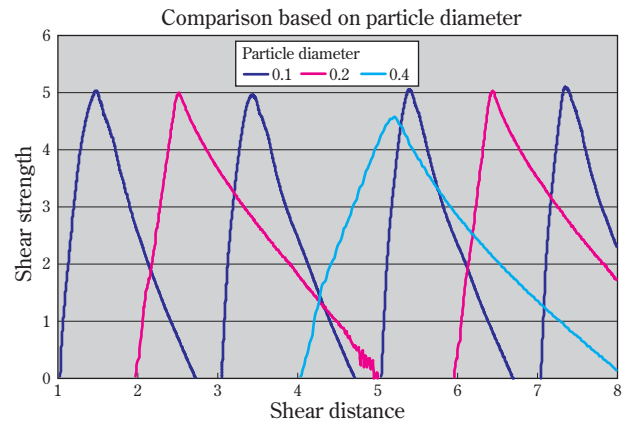


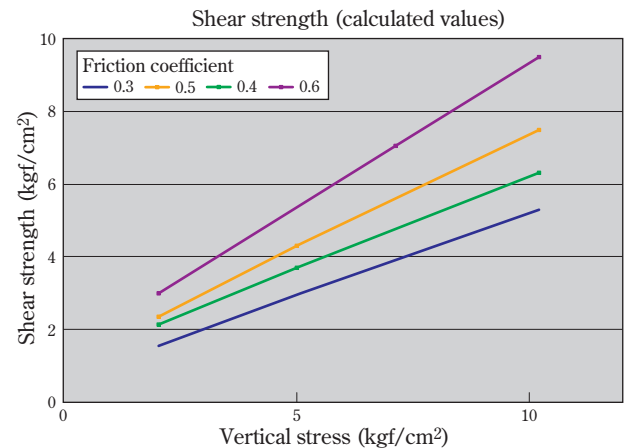**Fig. 8** Shear stress that occurs during particle run-over



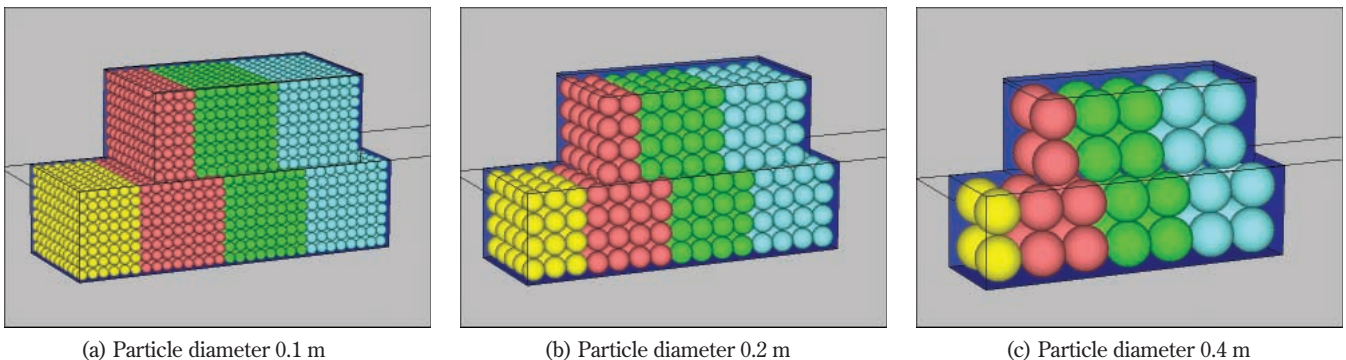**Fig. 9** Difference in shear strength due to difference in friction coefficient



| (a) Particle diameter 0.1 m | (b) Particle diameter 0.2 m | (c) Particle diameter 0.4 m |

**Fig. 7** Soil shear test by DEM

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Here, we decided to adopt a friction coefficient of 0.55 which gave analysis results the most similar to those of the shear strength test using the 10% water content that was determined from the sample soil compaction test (see **Fig. 10**).
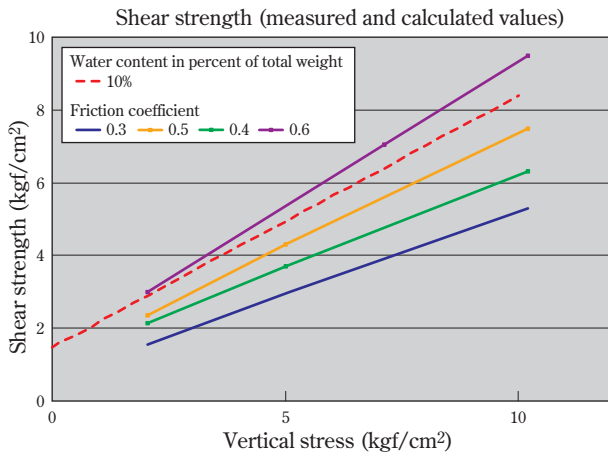
Shear strength (measured and calculated values)



**Fig. 10** Comparison between calculated and measured values of shear strength

## 4. Construction of terra-mechanical simulation system

We made an attempt to compare the excavation test results obtained with a bulldozer with the DEM excavation analysis results by using the particle physical property values obtained for sample soil in Section 3. In order to study the soil reaction acting upon the blade and the behavior of excavated soil by a DEM excavation analysis, it is necessary that the shape of the bulldozer blade for excavating soil particles should be accurately represented by a model. However, the DEM software available on the market is not equipped with the function that creates complicated wall-like elements for applying an external force to soil particles. Besides, since DEM treats wall elements as rigid ones, it cannot be used to study what stress occurs in the blade when the reaction of soil is applied to it. We, therefore, decided to develop a terra-mechanical simulation tool which links DEM to structural analysis so as to solve the above problems.

### 4-1 Method of creating analytical model

Creating rigid wall elements (hereinafter called wall elements) for DEM requires the coordinate values of three or four points of contact (apexes) which constitute each wall element and the counterclockwise sequence of apexes with the plane in which to apply an external force to particles as the normal direction. Thus, in order to create a model of the desired blade shape, it is necessary to make up a polyhedron by manually inputting wall elements of varying size one after another. On the other hand, the above procedure for creating wall elements closely resembles the content of data for a mesh model used for structural analysis. In view of this, we made it possible to create a wall of any shape by preparing an interface which permits extracting information needed to create wall elements for DEM analysis from mesh model data prepared for structural analysis. The interface also permits unifying the DEM analysis model and the structural analysis model. Namely, the particle reaction to each wall element apex that is obtained by DEM analysis can be used as apex load data for structural analysis. This has made it possible to build a terra-mechanical simulation system which allows for a structural analysis based directly on DEM analysis results. The concepts of modeling and sharing of data in the present system are shown in **Fig. 11**.
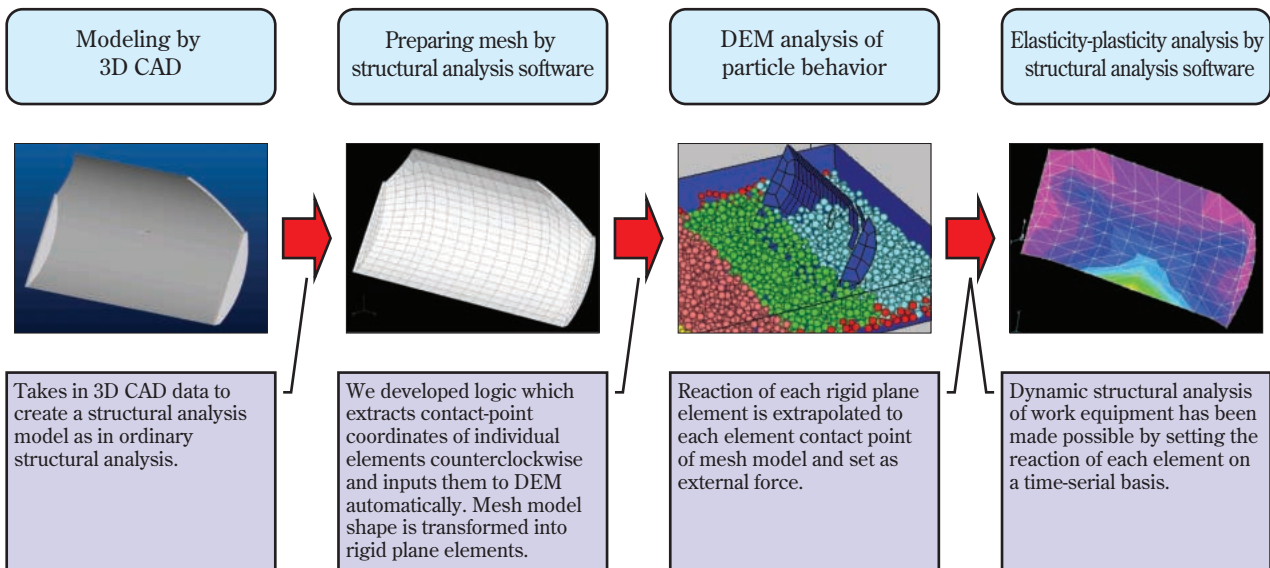


| Modeling by 3D CAD | Preparing mesh by structural analysis software | DEM analysis of particle behavior | Elasticity-plasticity analysis by structural analysis software |

| Takes in 3D CAD data to create a structural analysis model as in ordinary structural analysis. | We developed logic which extracts contact-point coordinates of individual elements counterclockwise and inputs them to DEM automatically. Mesh model shape is transformed into rigid plane elements. | Reaction of each rigid plane element is extrapolated to each element contact point of mesh model and set as external force. | Dynamic structural analysis of work equipment has been made possible by setting the reaction of each element on a time-serial basis. |

**Fig. 11** Outline of terra-mechanical simulation system

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**4-2 Analysis results**

The 3D bulldozer model used in the analysis is shown in **Fig. 12**, the mesh model used is shown in **Fig. 13**, and the wall element model for DEM analysis created from the mesh model is shown in **Fig. 14**. Thanks to the interface prepared for the system, when a model for structural analysis is created from the 3D CAD model, an analytical model that can be used for DEM analysis is automatically created.

**Fig. 15** compares the condition of soil particle excavation obtained by DEM analysis with the condition of soil/rock excavation by an actual bulldozer blade.

It can be seen from Fig. 15 that the way the wall elements wind up soil particles from the beginning of excavation and the way the wound-up particles are carried forward agree well with the way the soil is excavated and carried forward by the actual bulldozer blade.
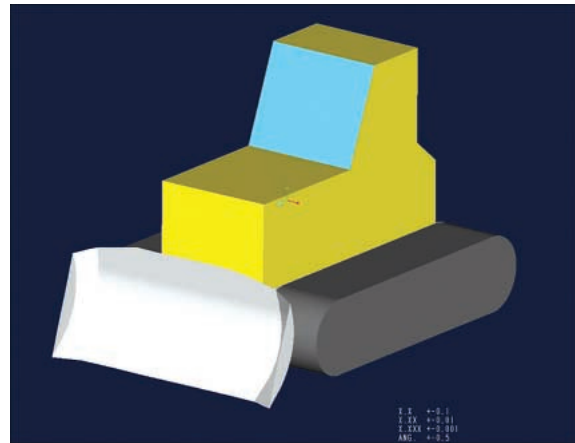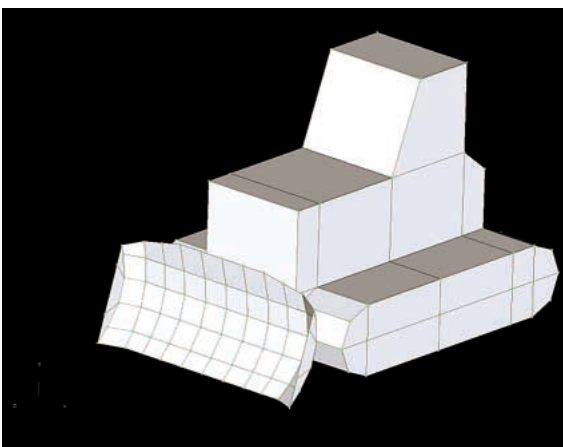


**Fig. 12** 3D CAD model of bulldozer
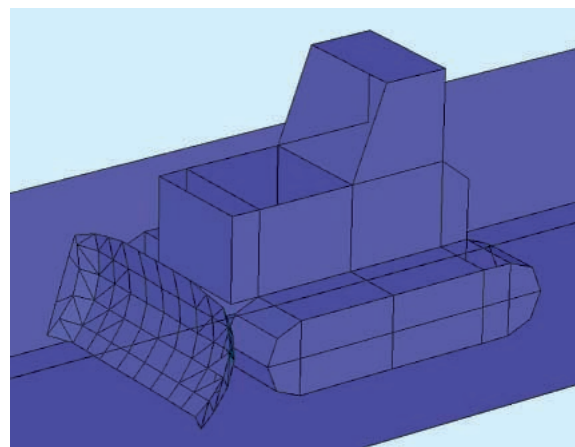


**Fig. 13** Mesh model of bulldozer



**Fig. 14** Rigid model of bulldozer for DEM analysis
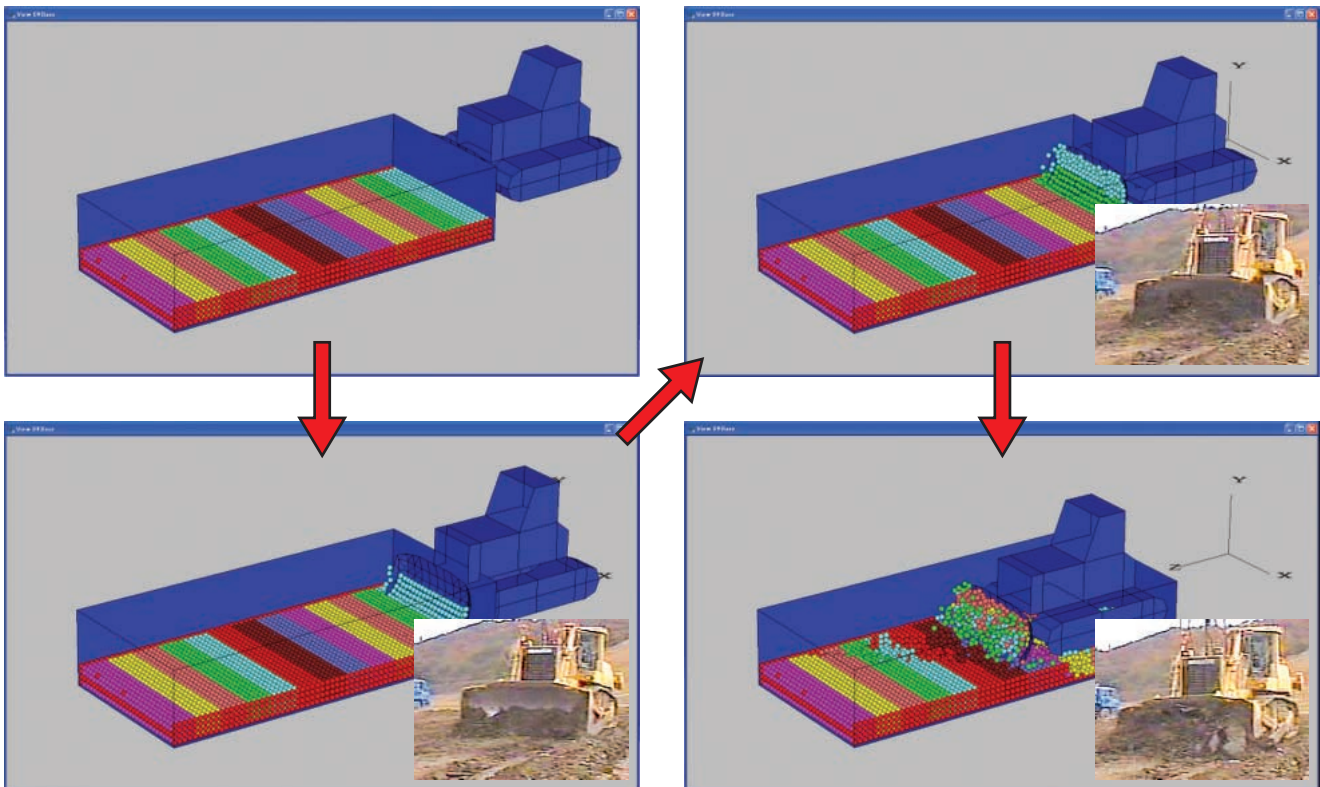


**Fig. 15** Comparison between analyzed particle excavation and actual soil excavation

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The results of a DEM analysis of the change in reaction acting upon the blade with the increase in excavation distance are shown in **Fig. 16**. Although the tendency that the reaction increases with the increase in distance of movement from the excavation start position nearly coincides with the actual phenomenon, the values of reaction differ from the measurement results by approximately 10%.
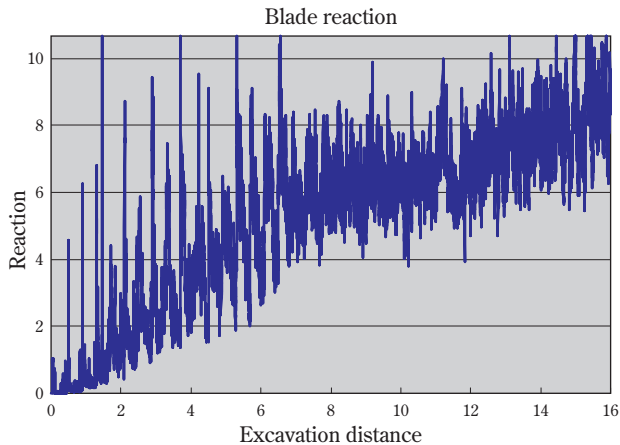


**Fig. 16** Blade reaction analysis results

**Fig. 17** shows the results of a dynamic stress analysis using the reactions obtained by a DEM analysis as input loads and taking the lapse of time into account. As shown, it is possible to dynamically grasp the change in stress distribution in the blade from the time excavation is started till the time excavated soil is transported, although absolute stress values have yet to be reviewed. We consider that this information is useful in structural evaluation in the design of a bulldozer blade and in examination of the wear resistance of materials to aim at optimum design of a bulldozer blade.
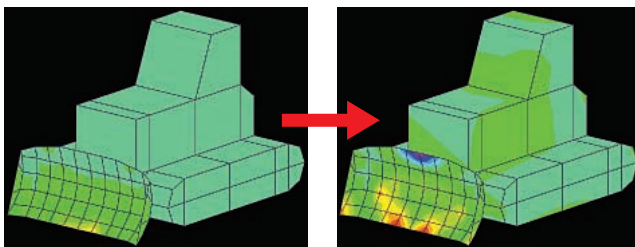


At start of excavation          Halfway during excavation
**Fig. 17** Dynamic blade stress analysis using DEM-analyzed reaction

## 5. Conclusion

By linking the finite element method that is capable of treating continuous objects and the distinct element method that is capable of treating discontinuous objects, we built a terra-mechanical simulation system for analyzing the dynamic excavation phenomenon of a bulldozer. Although we still have to improve the accuracy of analysis by selecting appropriate physical property values and setting optimum parameters, we consider that our system should contribute much to the implementation of more realistic structural evaluation and R&D on wear-resisting materials from the design stage, since it permits studying the interaction between construction equipment and soil/rock on the drawing board.

**Introduction of the writers**

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**[A few words from the writers]**

Analyzing soil is a tough job. Soil is a structure and a fluid in one aspect. It is neither a structure nor a fluid in another. Whenever soil is involved, it is extremely difficult to carry out numerical analysis. Recently, we met the challenge by employing the distinct element method. We think that our terra-mechanical simulation system has marked a new analytical approach, though there is still room for improvement.