Technical Paper

# Development of Equipment Performance Visualization Techniques Based on Distinct Element Method (DEM)

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*With dump trucks for mining and other applications in civil engineering work projects, pre-shipment performance evaluation such as of loadability, dumpability and haulability has been made using prototypes following the release of relevant drawings. This also holds true with subsequent substantial redesigning for performance upgrade where a cycle of shape review following prototype trials, the release of revised drawings and further trials has to be repeated: pre-trial performance estimation is extremely difficult and tends to rely largely on individual experience. Accurate estimation of earth spills from dump trucks during loading or uphill haulage operation is important as it leads to operational efficiency and productivity at work sites and ultimately to customer satisfaction, one of the most important targets for those involved in product development. With the above in mind, the authors established the technique to visualize the earth behavior using the recently introduced analysis software PFC (Particle Flow Code), which utilizes the distinct element method. This technique can estimate the dump truck performance on the desk in the same way as FEA technique. The authors then performed the verification using this technique.*

*This report briefly explains the distinct element method and, as an example of its applications, techniques to verify the performance difference between variously shapes like dump truck bodies.*

***Key Words:*** *Equipment, Visualization, Estimation, Distinct Element Method (DEM), Earth*

## 1. Introduction

Dump trucks are a type of construction machinery used at mines and other large-scale work sites. They are designed to receive earth from excavators and wheel loaders and carry and dump the earth. The part of a dump truck that receives and holds earth is called “the body.” The body must be shaped in ways that ensure minimum spill of earth during loading and uphill haulage and smooth flow of earth down the body during dumping. It is practically not possible to design and produce many prototype bodies and run trials to compare and select the best performing option. It is, therefore, a substantial saving of labor can be realized by running simulations to select best performing options on computers. It is for those reasons that Komatsu recently became interested in DEM (Distinct Element Method)[1) as a technique to analyze earth and other powders and introduced PFC (Particle Flow Code), an application software for such analysis.

DEM is an analytical technique proposed by Cundall[2) in which the object being analyzed is deemed as a collection of small particles. The technique analyzes the behavior and reactive force of the collection as a whole by looking at the motion of individual particles. Unlike FEA (Finite Element Analysis), DEM does not require a mesh and allows easy rearrangement of particles. In addition, with DEM it is possible to simulate real soil grains as individual elements, enabling the best possible approximation of real shapes of soil grains.

However, the following issue still exists, preventing our study from establishing a real shape modeling technique.

With the smallest particle being spherical, a number of spherical particles need to be combined together (hereafter “combined particles”) to reproduce complex shapes of soil grains. Handling thousands or tens of thousands of combined particles is an enormous, time-consuming computation task.

In our study, to overcome that obstacle, soil grains are reproduced not by using combined particles, but by using individual spherical particles in a reduced size, or 250 mm in diameter, to minimize computation load.

**Fig. 1** shows the dynamic model of the distinct element method used.

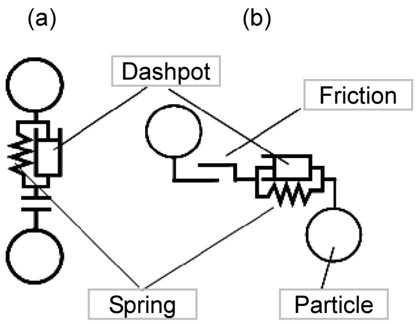



**Fig. 1** DEM Model Schematic
(a) Normal direction (b) Shear direction

In DEM, each element is represented by a spherical particle. Interaction between particles is expressed in spring stiffness, damping and friction.

While numerous studies have been conducted in this research field on powders in a consolidated environment[3),4)], no techniques have yet been established with regard to non-consolidated powders. For that reason, no specific parameters have yet been identified that ensure quantitative agreement to the reality of heaps and spills in earth loading and uphill haulage phases: in DEM, the following parameters are normally entered —— shape, size, spring constant, coefficient of friction, coefficient of restitution, specific gravity, damping in acceleration and damping in contact. Parameters can also be changed by the earth properties (shape, size, material, coefficient of friction, moisture content, degree of compaction, etc.) change. Some of these parameters change from one site to another, and change daily even at the same site.

Our study, while not aimed at specific types of earth, attempted to establish techniques to analyze spill mechanisms and earth behavior by finding and applying parameters that enable a comparative evaluation, not so much as the absolute evaluation.

## 2. Comparative Computation with DEM (Analysis of Earth Loading)

### 2-1. Prior considerations

There were several considerations that had to be addressed in the following specific order to ensure our subsequent analysis, the first of its kind, was successfully carried out.

In the first step, standard parameters of basic particles were considered.

(1) Shape: Due to their handiness, spherical particles are used. As described earlier in this paper, it is not practically possible to use combined particles that are equal in shape to those at actual work sites due to the constraint from the relationship between particle shape and computation load.

(2) Parameter: Parameters are selected based on the information from the software manufacturer's support and by referring to DEM analyses being carried out elsewhere.

(3) Particle size: Due to the constraint mentioned in (1), particles 250 mm in diameter are used.

In the second step, a heap of particles in the bucket of an excavator (hereafter "the HE bucket") was considered. An HE bucket model was created and set up in a field. Then, an appropriate number of particles were placed above the HE bucket and were dropped in a free fall into the HE bucket. **Fig. 2** shows a heap in the HE bucket and a sample of heaps photographed at actual work sites.

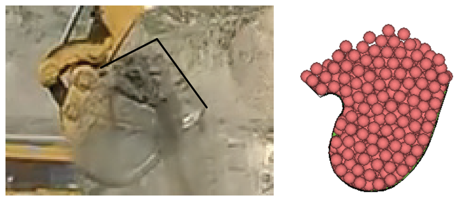


**Fig. 2** Heap in Actual Bucket and DEM Computed Heap

**Fig. 2** shows two heaps that agree with each other fairly well. This result was considered as a success and proceeded to the next step.

In the third step, earth loading from the HE bucket onto the dump body was considered. There are as many loading methods as the number of the excavator operators. The position of the first loading was determined by referring to videos of actual loading operations at work sites. The position of each of the second and subsequent loadings was automatically determined to make the optimal loading in accordance with the state of the particles from the previous loading(s) on the body. This logic eliminated the need to determine the position of the HE bucket for every loading, enabling automatic computation in loading analysis.

**Fig. 3** shows a typical heap on an actual dump body and a DEM computed heap based on this technique.

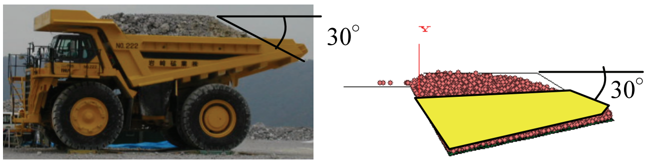



**Fig. 3** Actual Heap and DEM Computed Heap

**Fig. 3** shows a general approximation between an actual heap and a computed heap, with which it was decided that the techniques described above were reliable enough to justify subsequent comparative evaluation.

The bodies to be designed for analysis were to be left-right symmetrical as shown in **Fig. 4**, and to shorten the calculation time, the computation was performed on the right-half model of the body.

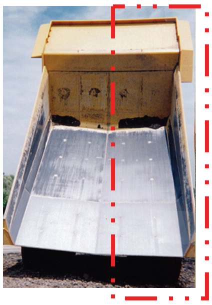
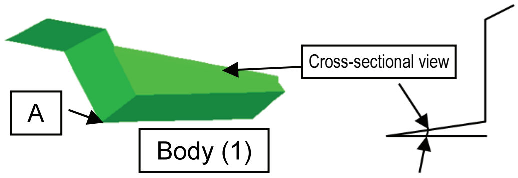


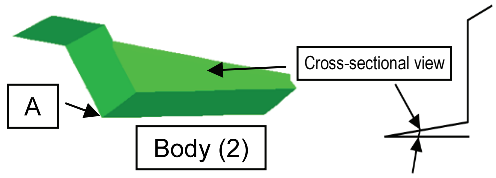
**Fig. 4** Body shape and the area on which analysis was performed

## 2-2. Bodies used for computation

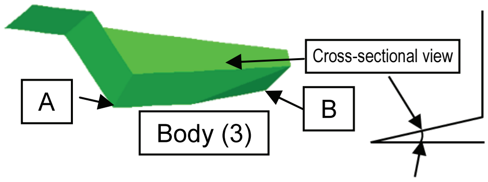
**Fig. 5** shows the four types of bodies ((1) to (4)) that were used in computation.



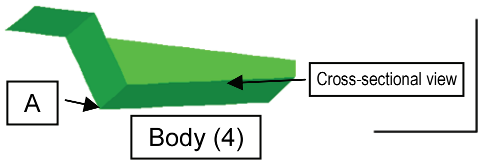

Body (1): Standard body shape model
Front, rear, left and right all sloped to Point A




Body (2): Longer, narrower model
Longer and narrower than Body (1)




Body (3): Bent rear end model
Same length and width as Body (1) but rear end B was bent




Body (4): Wider, flat model
Same length as Body (1), wider than Body (1) and with no lateral slope

These bodies are summarized in the following table.

| | Overall length | Overall width | Longitudinal slope | Lateral slope | Rear bend |
|---|---|---|---|---|---|
| Body (1) | - | - | Provided | Provided | Not provided |
| Body (2) | Longer | Narrower | ↑ | ↑ | ↑ |
| Body (3) | Same | Same | ↑ | ↑ | Provided |
| Body (4) | Same | Wider | ↑ | Not provided | Not provided |

NOTE: The descriptions in the “Overall length” and “Overall width” columns are in comparison with Body (1).

**Fig. 5** Body Shapes with Cross-sectional Profiles (at right angle to the fore-aft floor inclination)

## 2-3. Logic for loading analysis

### 2-3-1. Loading of particles into the HE bucket

After the HE bucket is set up in the field, an appropriate number of particles are created above the bucket. The particles are then dropped in a free fall. The condition that the particles are stable in the HE bucket is the condition for the first loading. (See 2-3-2 for how to determine the position of the HE bucket for the first loading.)

**Fig. 6** shows loading into a bucket and the filled bucket.

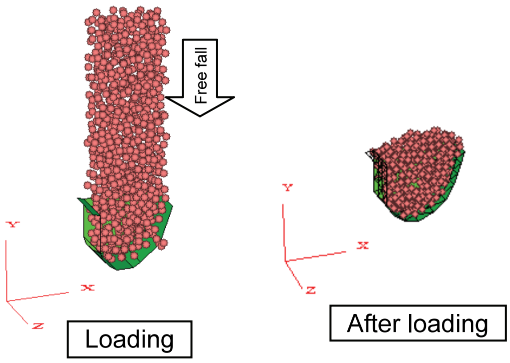



**Fig. 6** Loading and After Loading

Data on particles in a stable state after loading in HE bucket (coordinates, particle size, etc.) are saved for reuse (for purposes described later in this paper).

### 2-3-2. Setting the center of HE bucket rotation (1st loading)

The center of HE bucket rotation for the 1st loading was set at a point that was obtained by averaging the vertical and longitudinal positions shown on videos.

**Fig. 7** shows the position of the HE bucket relative to the position of the body. (Shown in the drawing are the dimensions from the reference point.)

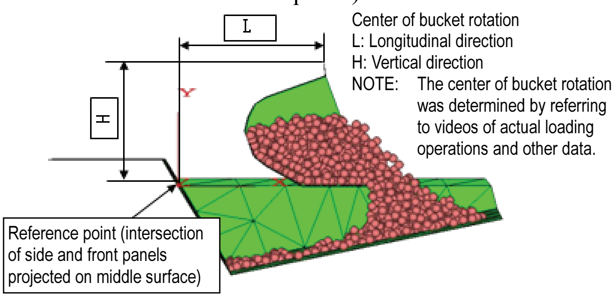



**Fig. 7** Position of HE Bucket Relative to Position of Body (1st loading)

### 2-3-3. Setting the center of HE bucket rotation (2nd and subsequent loadings)

The center of HE bucket rotation for each of the 2nd and subsequent loadings was determined, or fine-tuned, in accordance with the state of the particles on the body from the previous loading(s), just like it would be decided by the operator in actual loading operation.

Refer to the following drawing.

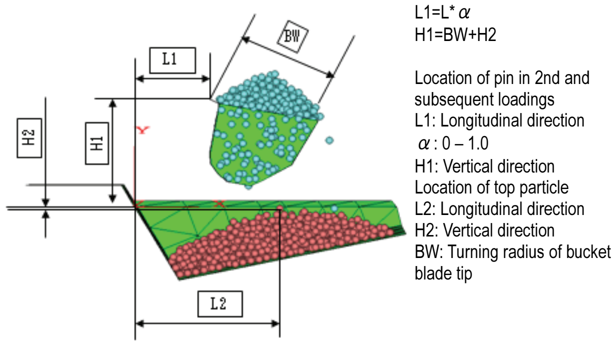



**Fig. 8** Position of HE Bucket Relative to Position of Body (2nd and subsequent loading)

As shown in **Fig. 8**, the center of HE bucket rotation for the 2nd loading was set at L2 multiplied by α in the longitudinal direction and H2 plus BW, the turning radius of the bucket blade tip, in the vertical direction (L2 and H2 converge on the position of top particle of the 1st fill). The subsequent loadings were computed following this logic. The computation was terminated at the end of the 5th loading.

Body shape performance was evaluated by counting the number of particles that spilled over the side and rear panels or using the ratio of the number of particles that spilled to the total number of particles that were loaded (called as “spillage rate”).

## 2-4. Analytical flow chart

**Fig. 9** shows the analytical flow chart representing the series of logic described in the earlier paragraphs.

In the loading analysis, the process is captured in a video format, enabling it to be viewed after the computation.

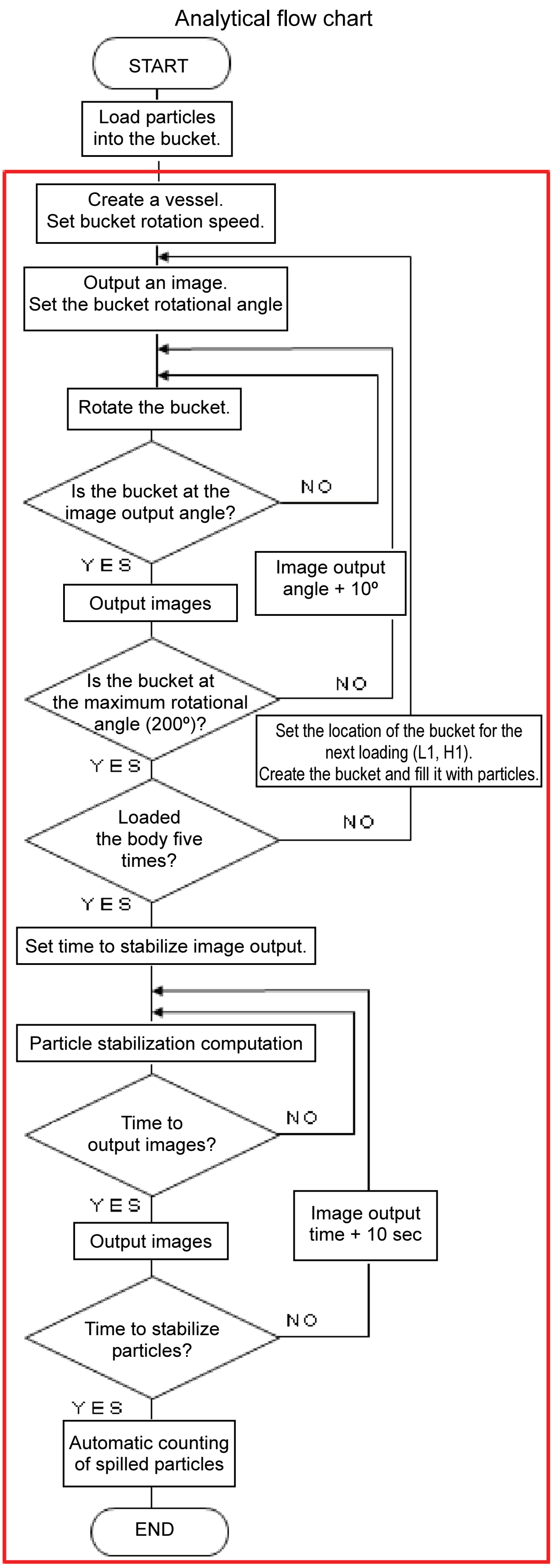



**Fig. 9** Analytic Flow Chart

To analyze plural types of bodies, it can be performed by the computation within the red frame.

## 3. Loading Analysis

Following the logic described in 2, particles were loaded onto the four body types using the HE bucket to find out any difference in spillage.

### 3-1. 1st loading

**Fig. 10** shows the results of the 1st loading.

On Body (3) with a bent rear end, the heap is located more to the front of the body than other body types.

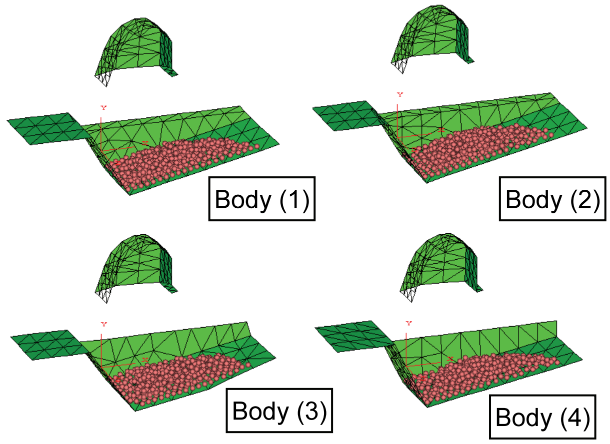



**Fig. 10** Heaps After 1st Loadings

### 3-2. 2nd loading

**Fig. 11** shows the results after the 2nd loading.

On Body (3) with a bent rear end, the heap is still located more to the front of the body.

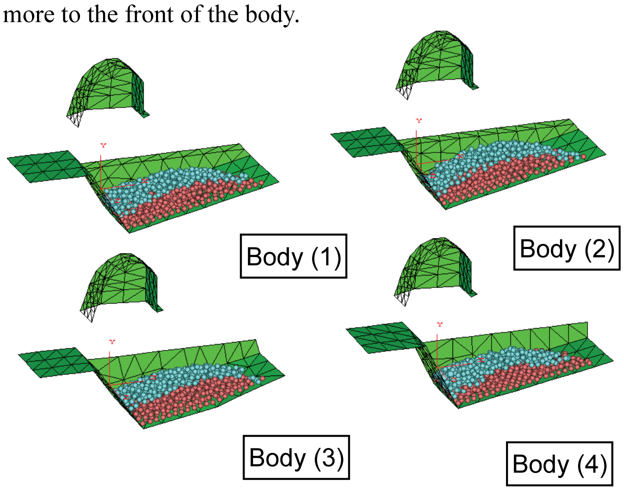



**Fig. 11** Heaps After 2nd Loadings

### 3-3. 3rd loading

**Fig. 12** shows the results after the 3rd loading.

On Body (1) with a short overall length, the heap is reaching the rear end of the body. Body (2) has the largest unladen space at the rear.

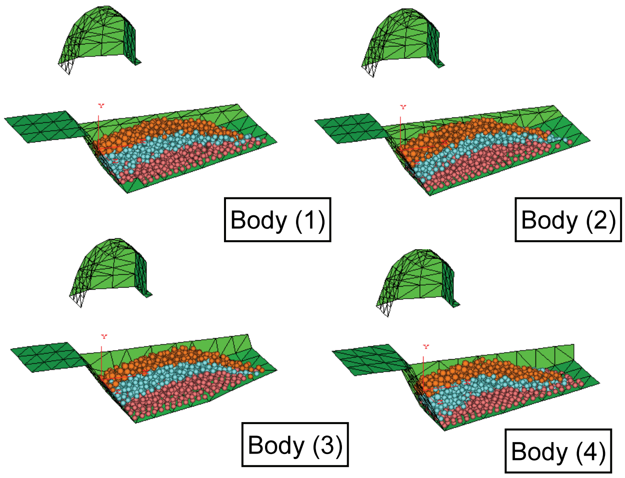



**Fig. 12** Heaps After 3rd Loadings

### 3-4. 4th loading

**Fig. 13** shows the results after the 4th loading.

No dump body has yet experienced any spillage. On Body (4), however, the area near the front panel is running out of unladen space with the heap heavily concentrated towards the front.

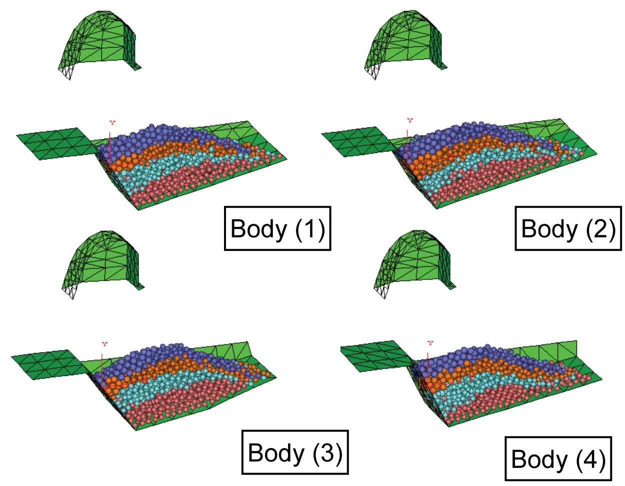



**Fig. 13** Heaps After 4th Loadings

### 3-5. 5th loading

**Fig. 14** shows the results after the 5th loading.

All bodies have experienced spillage over the side panel. There is a substantial difference in the shape of heap between the four bodies.

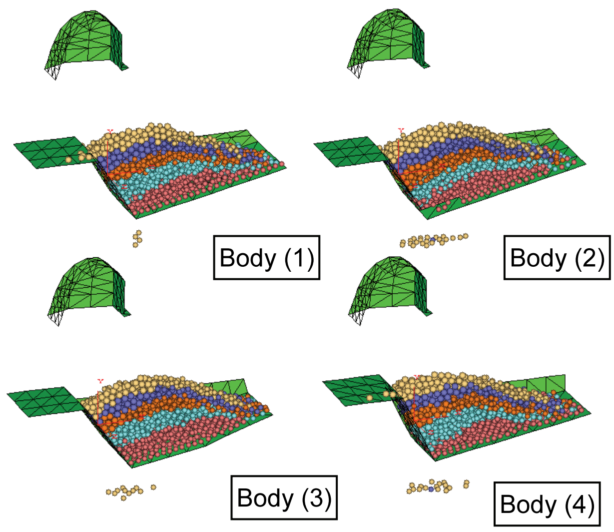



**Fig. 14** Heaps After 5th Loadings

### 3-6. After stabilization computation

**Fig. 15** shows the heap in each body in a stabilized state after the 5th loading.

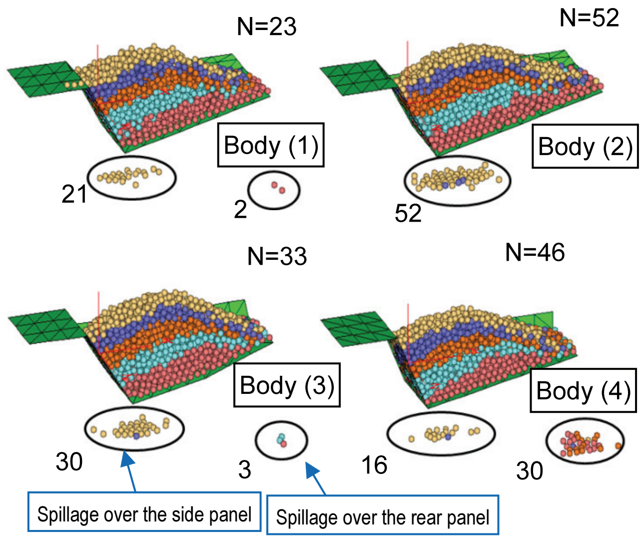



**Fig. 15** Different Results with Different Body Shapes

When compared with Body (1):

- Body (2) with a narrower width had a higher number of spilled particles over the side panel.
- Body (3) with a bent rear end had a higher stability of the heap in the longitudinal direction but a lower stability of the heap in the lateral direction, resulting in a slightly higher number of spilled particles over the side panel.

- Body (4) with no lateral slopes had a lower stability of the heap at the rear, resulting in a higher number of spilled particles over the rear panel.

Those were the differences found in the analysis between the four body types.

### 3-7. Summary of the loading analysis

Loading analysis of Body (1) (the standard body shape) and three other variants with different body shapes (Body (2), Body (3) and Body (4)) visualized the differences in spillage between those differently shaped bodies. This demonstrates the utility of this loading analysis method.

## 4. Comparative Computation Based on DEM (uphill haulage analysis)

### 4-1. Prior considerations

Uphill haulage is another typical operation of dump trucks and therefore is, like loading, one of the important design considerations. Using the same four body types and their characteristic heaps that were discussed in 3, spillage over the rear panel was simulated which, when combined with the loading analysis technique, should improve the accuracy of our simulation of actual dump truck operation. For this exercise, the direction of gravity that works on the bodies was altered to reflect the angle of the uphill used in the simulation, instead of tilting the bodies to match the uphill angle. It was thought that this simulation should provide enough data to judge any differences in ease of spillage in uphill haulage between the four body types with their specific heaps.

### 4-2. Bodies used in the computation

In the computation, the same bodies with their respective heaps after the stabilization computation for loading analysis were used for better reproduction of the actual condition.

### 4-3. Logic for uphill haulage analysis

In the loading analysis, the dump trucks were parked on a horizontal plane and the bodies were subjected to gravity working straight down. In the uphill haulage analysis, the direction of gravity was angled towards the rear of the body to match the angle of the uphill to simulate the dump truck stationary on an uphill, as shown in **Fig. 16**.

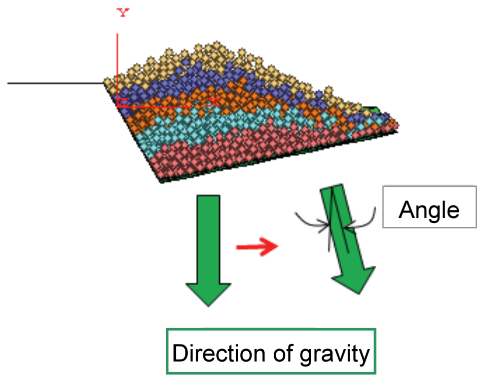



**Fig. 16** Altered Direction of Gravity

## 5. Uphill Haulage Analysis

### 5-1. Analysis

Using the uphill haulage logic, analysis was conducted on the loaded Bodies (1) - (4) for comparison.

The results are shown in **Fig. 17**.

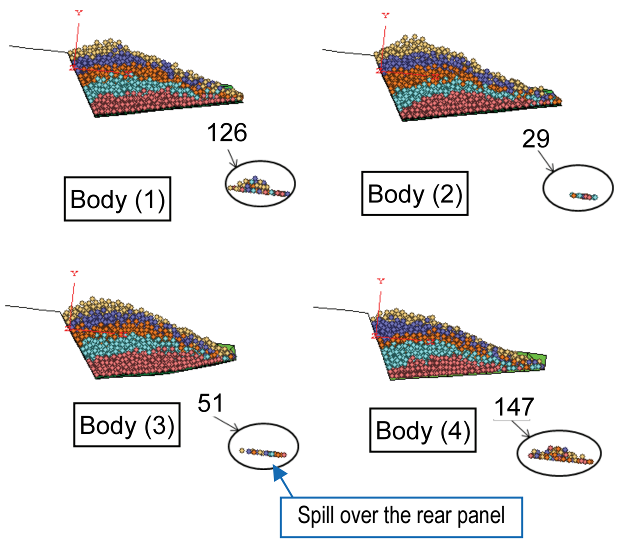



**Fig. 17** Different Results with Different Body Shapes

On all of the bodies analyzed, the center of gravity of the heap during uphill haulage was shifted towards the rear.

Body (1) with a short overall length had many spilled particles over the rear panel.

Body (2) with a longer overall length had the smallest number of spilled particles over the rear panel.

On Body (3) with a bent rear end, the particles were more able to resist the shift of the center of gravity, resulting in a relatively small number of spilled particles.

Body (4) with no lateral slopes had a lower stability of the heap than the other bodies, resulting in the highest number of spilled particles over the rear panel.

### 5-2. Summary of the uphill haulage analysis

The uphill haulage analysis, conducted after the loading analysis described in 3, visualized the differences in spillage over the rear panel between the differently shaped bodies, demonstrating the utility of this analysis method.

## 6. Consideration

The loading and uphill haulage analyses presented visualized difference between the differently shaped bodies. Body (1), which had the smallest number of spilled particles in the loading analysis, had a relatively high number of spilled particles over the rear panel in the uphill haulage analysis. This is presumably due to the body's relatively short overall length. In future body development efforts, the combination of these two analysis techniques should contribute to optimum body design.

## 7. Future Plans

The techniques presented in this paper will be applied to the bodies of other dump truck models.

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**Introduction of the writers**


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**[A few words from writers]**

Today, CAE application software technology is advancing by leaps and bounds, offering visualization even where it has been thought impossible. We must keep closely monitoring for any development and keep up with the times so that we will be continuously in a position to be able to contribute to even higher design quality and customer satisfaction.