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Comparison of DEM and experimental results for evaluation of ground surface displacement due to fault movement below architectural structures

Ayaka Oya[1], Norihiko Hashimoto[1], Kaoru Kawaji[1], Guoqiang Cao[1], Akihiro Toyooka[2] & Tatsuya Doi[2]
[1] *ITOCHU Techno-Solutions Corporation, Tokyo, Japan*
[2] *Railway Technical Research Institute, Tokyo, Japan*

1 INTRODUCTION

The quantitative evaluation method of ground surface behavior in the case of fault movement below architectural structures is required in a variety of areas. In this study, the Distinct Element Method (DEM) using code *PFC* (Itasca 2018) is proposed, as it can simulate the discontinuity of displacement on a fault surface and a large deformation of the ground. It is possible to estimate the influences of soil characteristics and properties around the ground surface when the fault displacement occurs and then propagates to the ground surface. When an architectural structure on the ground surface is considered, it may cause a complicated stress distribution around the ground surface and the propagation of displacement in the ground.

There is a fundamental investigation into the problems mentioned above. Osida et al. (2019) focused on dip slip fault displacement that was affected by a railway structure foundation using a simple model test. This research considered the difference in the development of the shear zone between the experimental cases with and without structure. The results concluded that shear zones can grow up to the ground surface while avoiding the structure; they also mentioned that DEM analyses are suitable for simulating the fault displacement.

In this study, the *PFC* model is created based on an experiment that simulated fault movement which occurred below an architectural structure, based on the precedence study explained in the previous paragraph. Two cases of analyses are performed to examine the effects of a structure on the ground, based on the precedence study that replicates fault displacement by a simple model lab-experiment, as the first step of the research. By comparing the results between the cases of without and with the structure, the effects of the structure on the ground is discussed in the case of fault displacement. The analyses results are also compared to experimental results to validate the analyses model.

2 ANALYSIS CONDITIONS

2.1 *Input conditions*

The analysis model is shown in Figure 1. The model dimensions are based on the experimental model shown in the reference (Oshida et al. 2019). The ground is modeled by DEM balls. The structure is modeled using a convex rigid block, which is newly integrated in *PFC* version 6.0. The structure is based on the experimental model and set with a height of 0.1 m, width of 0.3 m, and weight of 200 kg; the contact model is a linear model. The input parameters are shown in Figure 1. As this study presents the first attempt using these analyses to demonstrate the applicability of the DEM to the analysis of fault movement, the input parameters are set to general values. A detailed investigation of the parameters is planned for future research. The parameters are determined as follows: the particle density is determined based on the soil particle density of silica sand (Public Works Research Institute 2014); stiffness is calculated from the shear elastic velocity (*Vs*), as mentioned in the book by Hakuno (2004); and *Vs* is set at 100 m/s. The friction coefficient is equal to the friction angle of the soil used in the model experiment mentioned in Oshida et al. (2019). The particle radius is set to homogeneous, as shown in Table 1. The same parameters are applied to Ball-Wall contact, except for the friction coefficient which is set to 0, as friction is assumed to be reduced to nearly 0 between the soil and the wall in the experiments.

Fault displacement at the bottom wall of the model is replicated by applying the velocity to the y-direction, as indicated in the blue color shown in Figure 1. The bottom wall vertical velocity is set to 1 to 2 mm/min in the preceding experiments to be quasi-static. In order to set the vertical velocity for the analyses, the effect of the vertical velocity on the analyses results was investigated, and it was found that there is almost no effect and the velocity of the bottom wall is adjusted to a possible value to run analyses. Then, the bottom wall vertical velocity is set to 0.005 m/s in both analysis cases. The velocity is applied until the bottom wall vertical displacement reaches 120 mm.

Two cases are analyzed to examine the effects of a structure on the ground, as the preceding research did. Case-1 is the analysis without a structure and Case-2 is the analysis with a structure.

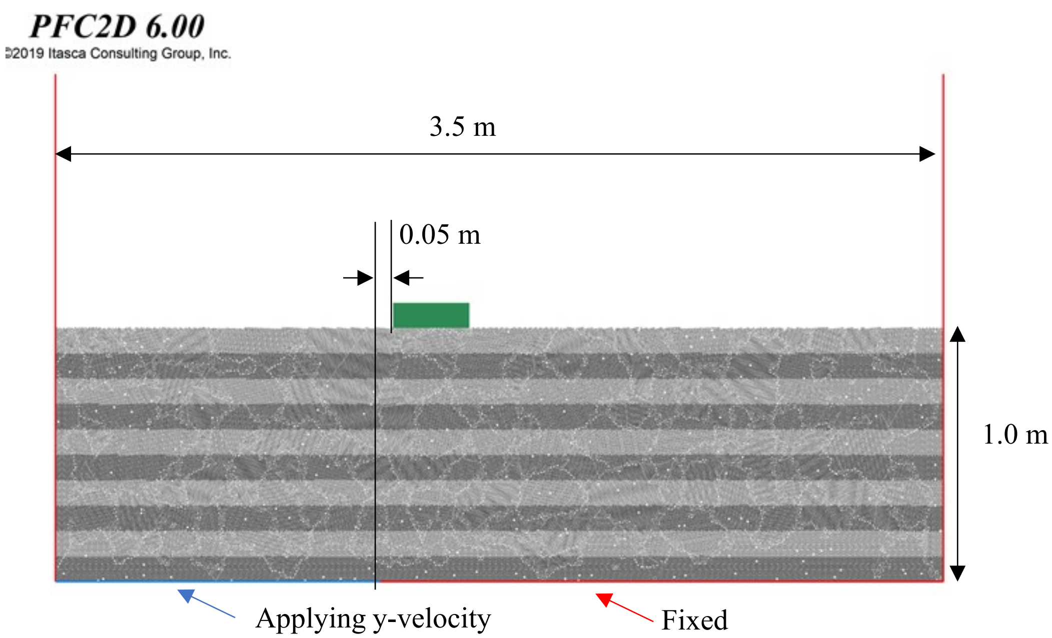


Figure 1. Analysis model.

Table 1. Input parameters.

Contact	Particle density	Normal stiffness	Shear stiffness	Friction coefficient	Particle radius
Ball-Ball	2560 (kg)	6.24×10^7 (N/m)	6.24×10^7 (N/m)	0.67 (-)	0.004 (m)
Ball-Wall	-	6.24×10^7 (N/m)	6.24×10^7 (N/m)	0.00 (-)	-

2.2 *Analysis procedures*

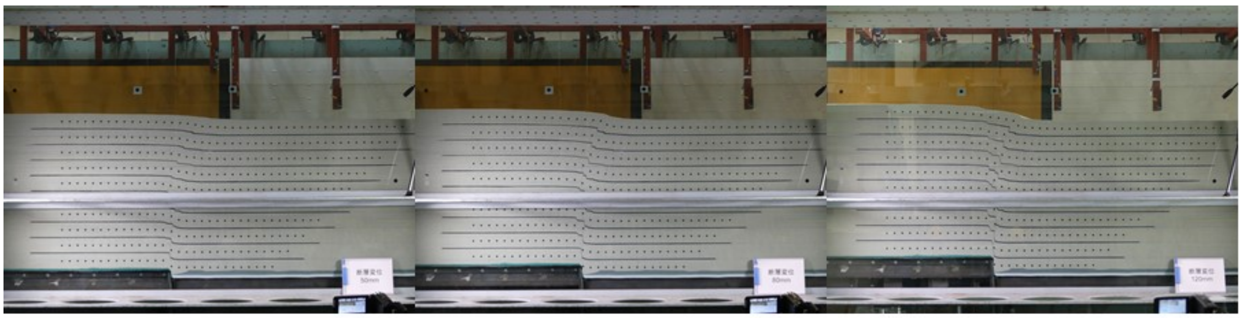
In this study, analyses are conducted as follows.

1. A two-dimensional box region is set as a computational region. The side and bottom boundary planes are constrained by walls.
2. The balls are generated within the computational region and the gravity is loaded. In this stage, to set the particles to homogeneous, only normal stiffness is set as shown in Table 1, and shear stiffness and the friction coefficient are set to zero.
3. After gravity loading, which is mentioned in step 2, the analysis model is cycled until the unbalanced force is sufficiently low. In the case with the structure, a convex rigid block is installed in

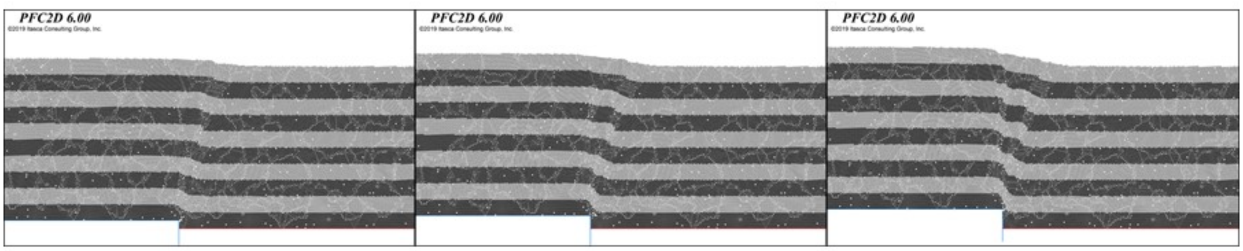
this step. The rigid block is placed on the ground and vertical velocity applied until it is in contact with enough balls. Then, the analysis model is cycled again in order to achieve mechanical stability.
4. The normal stiffness, the shear stiffness, and the friction coefficient are assigned as shown in Table 1. Then, the analysis model is cycled again to stabilize.
5. After the model becomes mechanically stable, the simulation of the fault movement is finally performed. Vertical velocity is applied to the left side bottom wall as shown in Figure 1.

3 RESULTS AND DISCUSSION

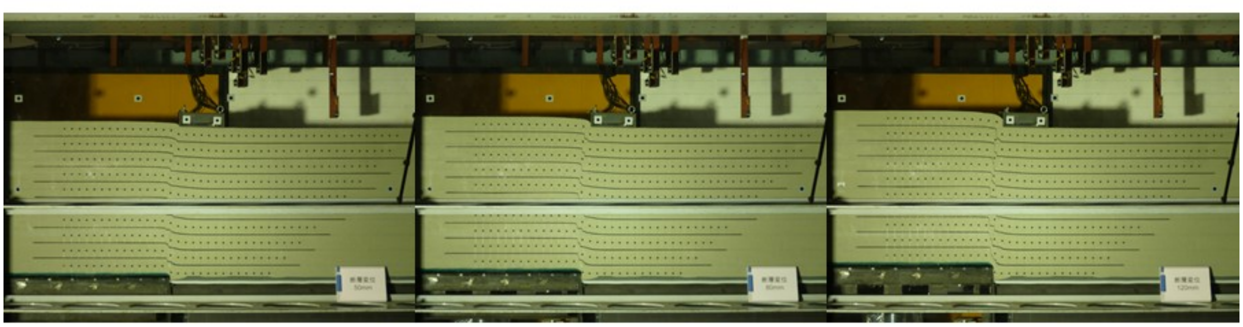
Figure 2 shows the results of the simulation comparing to the experimental results (Oshida et al., 2019). In both analysis cases, the ground is deformed and the ground surface is tilted as the bottom wall rises. Slip lines are observed from the boundary of the ascending bottom wall and the fixed bottom wall.



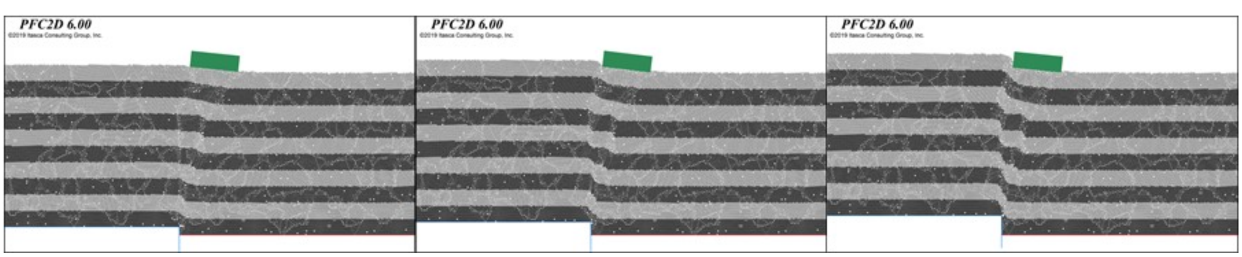
Case-1 Experiment 50 mm | Case-1 Experiment 80 mm | Case-1 Experiment 120 mm



Case-1 Analysis 50 mm | Case-1 Analysis 80 mm | Case-1 Analysis 120 mm



Case-2 Experiment 50 mm | Case-2 Experiment 80 mm | Case-2 Experiment 120 mm



Case-2 Analysis 50 mm | Case-2 Analysis 80 mm | Case-2 Analysis 120 mm

Figure 2. Comparison of the results of the experiments and the analyses.

In Case-1, the slip lines also develop nearly vertically from the bottom, and then branch off near the ground surface which draws arcs from side-to-side near the ground surface; as is similar to the experimental results. In Case-2, a drastic change in ground surface displacement is observed close to the left side of the structure; this is reproduced in the experiment as well.

Despite strong agreement with the experimental results, as mentioned above, the slope of the ground surface is consistently gentler than the experimental results in both analysis cases. Focusing on Case-2, the rotation of the structure is excessively estimated when compared to the experimental results. The shape of the slip line and slope degree of the ground surface highly depend upon the stress conditions of the ground. The contact state between the structure and ball can affect the rotation of the structure. Therefore, these problems may be solved by a more detailed fitting of the input parameters, such as the friction coefficient. Imitation of the DEM particle radius to the soil particle distribution is also assumed to overcome this problem.

4 CONCLUSIONS

This paper demonstrates the first attempt in simulating ground deformation using the DEM due to fault movement that occurred below the structure, based on the preceding experiment to examine the effect of the structure on the ground.

The results of the analyses are in strong agreement with the experimental results and prove the applicability of using DEM to analyze these types of problems. The analyses can also simulate the effect of the structure on the ground surface displacement. There are some differences between the analyses results and the experimental results, such as rotation of the structure and slope of the ground surface. Further inspection of the input parameters and particle radius may help overcome these problems, which is left to future research.

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