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Discrete Element Analysis of Slope Collapse Behavior Triggered by Earthquake Generation around Nuclear Power Plants and Its Applicability

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ABSTRACT

Risk evaluation of slope failure against nuclear power plants, which is induced by unexpected large earthquakes, is required. For risk evaluation of slope failure, understanding of information such as traveling distances, collision velocities, and collision energies are very important. Discrete Element Method (DEM) is effective on predicting the detailed behavior of slope failure physics. In this study, instead of accurately predicting the complicated behavior of sliding and falling for each rock, we introduce DEM modeling to evaluate the average traveling distance of collapsed rocks and its statistical variability. We conduct the validation test of the proposed DEM model on the basis of reconstruction of experiment results. Finally, validity of the proposed method is evaluated and its applicability and technical assignments are also discussed

Introduction

In the process of risk evaluation of nuclear power stations and related facilities, it is important to evaluate the effects of slope collapse and rock fall from unexpectedly large earthquakes. For those evaluations, the discrete element method (hereafter called as DEM, Cundall1979) would be one of effective numerical approaches. This study investigates a hypothetical case where earthquake generation starts to disturb subsurface structure and quantities how far rocks go after slope collapse.

In analyzing rock collision, the slight difference in collision angle tends to significantly affect the rock kinematics after collision. Despite accurately modeling the rock geometry, it is difficult to deterministically evaluate the propagation natures (path, velocity, and traveling distance) of the collision process. In addition, because a realistic slope and nature of subsurface structure are very complex and variable, deterministic evaluation is even more difficult. Therefore, traveling distance of a rock mass falling down along the slope is usually estimated on the basis of probability distribution.

Basically, for kinematics of a single rock mass falling down the slope, the total variation of traveling path of falling rocks are evaluated on the basis of summing up uncertainty of rock mass collisions. The probability distribution of a single collision behavior is controlled by many physical factors such as, the variation of contact angle between rock mass and slope, and the variation of contact moment being originated from geometry of rock mass. If we can assume

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that the differences of those physical factors do not significantly affect the results, we can suggest that very accurate description of those physical factors is not necessary. For example, despite of simplifying geometry of rock mass, if accurate modeling of roughness of slope can enable us to synthesize the probabilistic behavior of a single collision, the analysis is good enough for probabilistic evaluation of rock falling.

Based on this assumption, in this study we evaluate the validity of simplifying geometry of rock mass in which rock mass is expressed by a single ball. Slope shape is expressed by spacing balls of same radius and parameters to express slope roughness are discussed. We compare the result of analysis with the rock fall experiments and validity is evaluated.

DEM modeling procedure

Modeling Concept

Without modeling the shape of the rock mass, the rock mass is modeled by one ball. The roughness of the rock shape is expressed by spacing balls of same radius on the slope or the floor in the equal interval as shown in Figure 1 and in Figure 2. Here, roughness 2r means that the ball interval is two times as large as the radius of the ball.

Namely, when the rock mass drops to the floor as shown in Figure 3, the irregular bounce is expressed by the impaction in spherical surfaces and bounce irregularly. For the convenience, this model is named simple model.

Restitution Coefficient

The restitution coefficient is the most important factor in rock fall simulations of this study. It is defined as the ratio of relative velocities after and before an impact. Figure 4 shows comparisons of results of the real rock mass and the simple model. Here, maximum restitution coefficient

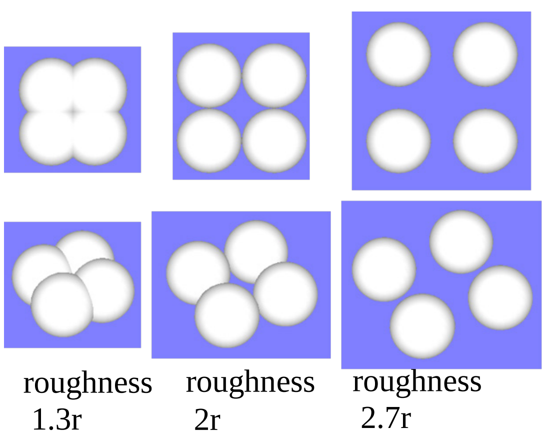

Figure 1. Real rock mass roughness expressed interval of ball placing

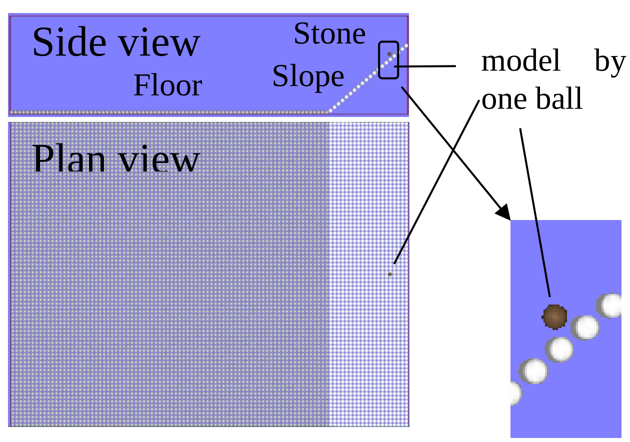

Figure 2. Proposed model

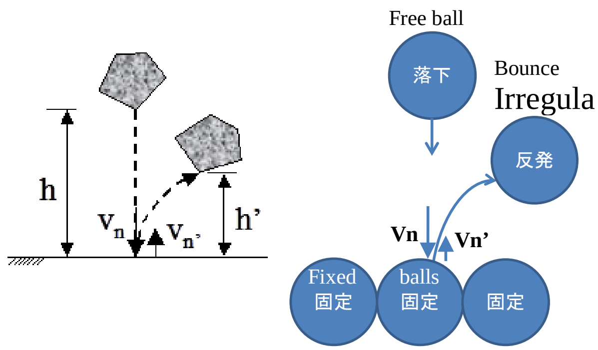

Figure 3. Irregular bounces of a real rock mass and expression by the impaction in spherical surface and bounce irregularly

means the result obtained from experiment and the simple model with a ball falling to the top of fixed ball. Apparent restitution coefficient means an average value in a set of measurements (Vn'/Vn, the ratio of vertical velocities of Figure 3(left)) in experiments. In the simple model it is an average value in a set of calculated values (Vn'/Vn, the ratio of vertical velocities of Figure 3(right)) by falling the ball from different horizontal positions. The results of the range of variation with $\pm\sigma$ by DEM simple model is shown by the long dashes lines, respectively. The experimental results are shown by the extending lines. Here, the floor is modeled by spacing the balls at the equal interval in the simple model, corresponding to roughness 2r in Figure 1 (left).

It seems that DEM result is close to the experiment results. However, in comparison with the experimental results, variation increases when both maximum and apparent restitution coefficient increase. This difference with the experimental results can be decreased by changing

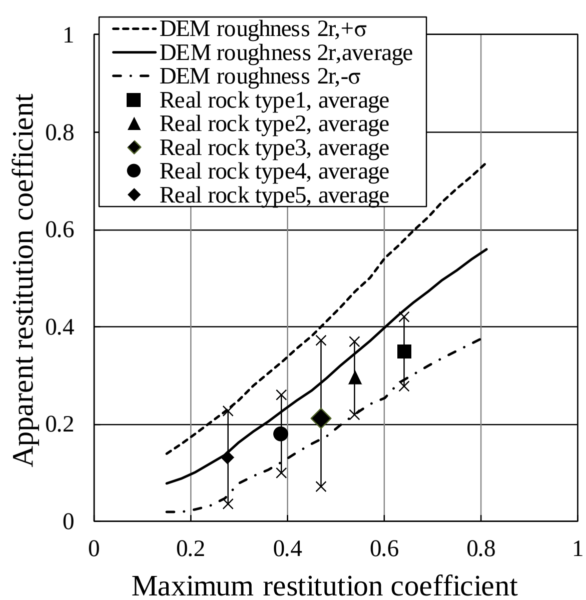

Figure 4. The relationship between maximum restitution coefficient and apparent restitution coefficient

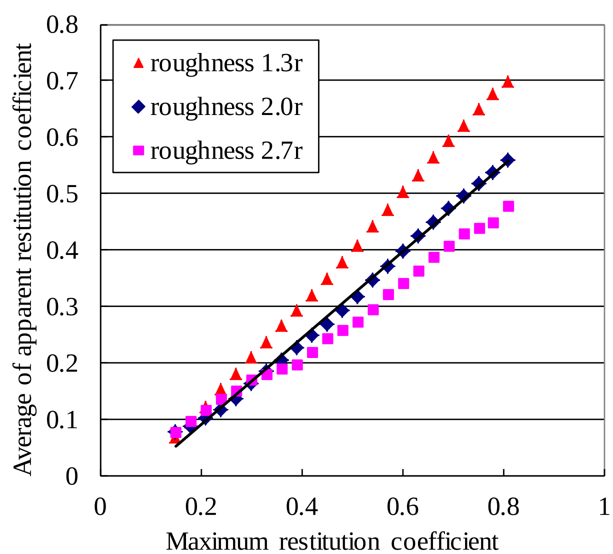

Figure 5. Difference of relationship between average of apparent restitution coefficient and maximum restitution coefficient due to roughness of basement

the ball interval for modeling the floor in the simple model. Figure 5 shows the results obtained from the simple model. Apparent restitution coefficient decreases when the ball interval increases.

Numerical representation of rock drop test

Single rock drop test

Tochigi (2010) conducted experiments by dropping more stones (limestone) with the diameters of 40-80mm. In single rock drop test shown in Figure.6, 300 stones were dropped under gravity one by one, and all arrival distances of stones were measured. In the experiment, each stone placed on the top of the slope along the long length was slowly put out by a finger to be fallen down and removed out after it stopped on the floor. All stones almost did not slip straight to the floor and begun to rotate after slipped centimeters along the slope.

Table 1. Micro parameters of DEM analysis.

radius(m)	0.03
density (kg/ m^3)	2,600
contact stiffness (N/m)	2.0×10^6
viscous damping (N・s/m)	3.92×10^2
friction	0.577
time interval(s)	3.80×10^{-2}

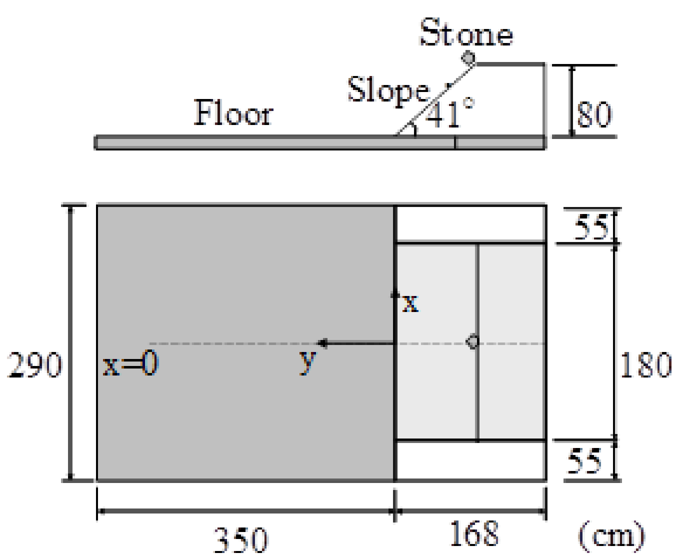

Figure 6. Experiment apparatus

The parameters and the analysis conditions of DEM are shown in Table 1. The density is assigned same as experimental stone. The contact stiffness and friction are assigned as in Tochigi(2010). The viscous damping coefficient between the stone and the concrete plate is assigned property corresponding to an estimated maximum restitution coefficient 0.48 studied in the separated part. The normal and shear stiffness and viscous damping coefficient are assumed to be equal. The initial positions of 300 stones are randomly placed within a square with the side equal to the diameter of stone model to vary the reached positions. The distance of ball interval on the slope and bottom are same as the diameter (roughness 2r shown in Figure.5).

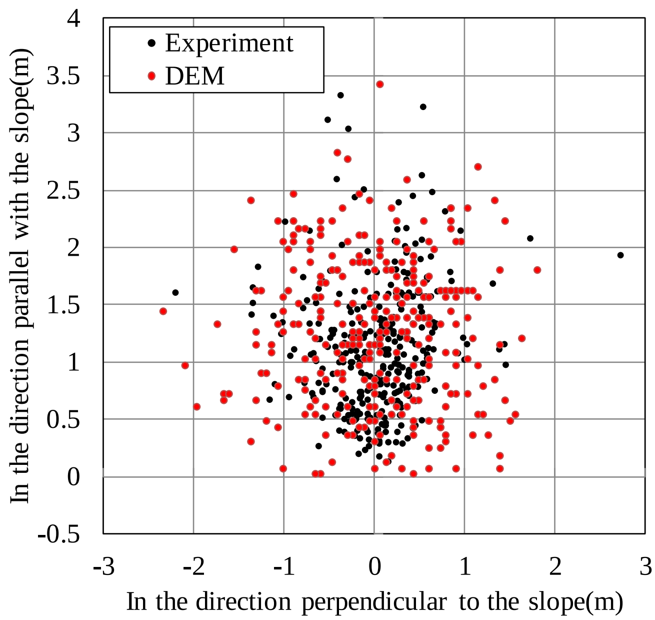

Figure 7. Comparison of distributions of stopped rock positions by experiment and simulation

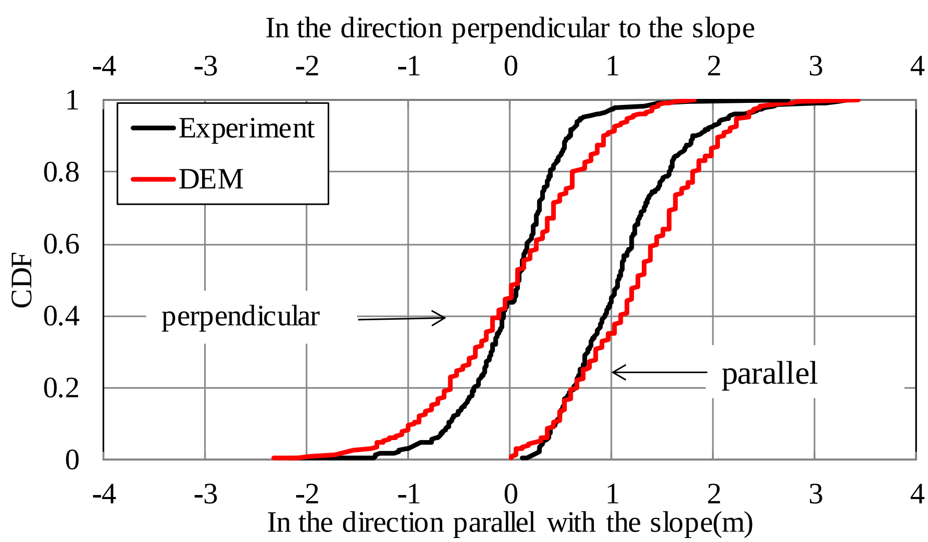

Figure 8. Comparison of cumulative distributions of stopped rock positions

Figure.7 compares the distribution of stopped positions of stones in the experiment and the simple model. The results of the simple model approximately correspond to the experiment.

Figure.8 compares the results of cumulative distribution probability in the direction perpendicular to the slope and in the direction parallel with the slope, respectively.

More or less, the simple model has larger variation in the direction perpendicular to the slope, the average behavior is approximately same as experiment. It may be said that the simple model evaluates the experiment on the conservative side, anyway.

Collapse Test of Rocks

Next, we performed the simulation for collapse test of rocks by using the simple model. The experiment is shown in Figue.9 in which rocks were deposited in a box and collapsed by moving the wall of the box suddenly. The arrival positions of rocks ware measured. Rocks used in the experiment were 50 kg.

The particle number in this simulation is 177. The restitution coefficient of particles is assumed as 0.48. The snap shots of the simulation results are shown in Figure 10.

Figure 11 compares the distributions of stopped rock positions by the experiment and the simulation on the simple model. The comparison of the cumulative distributions of stopped rock positions is shown in Figure 12. The simulation accords with the experiment.

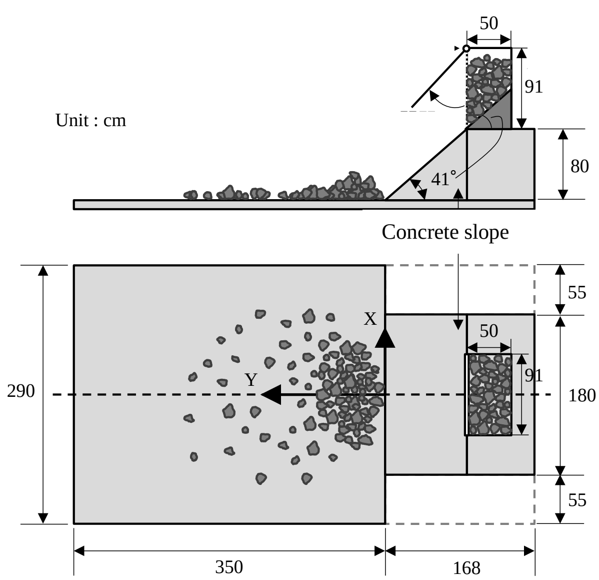

Figure 9. Experiment apparatus.

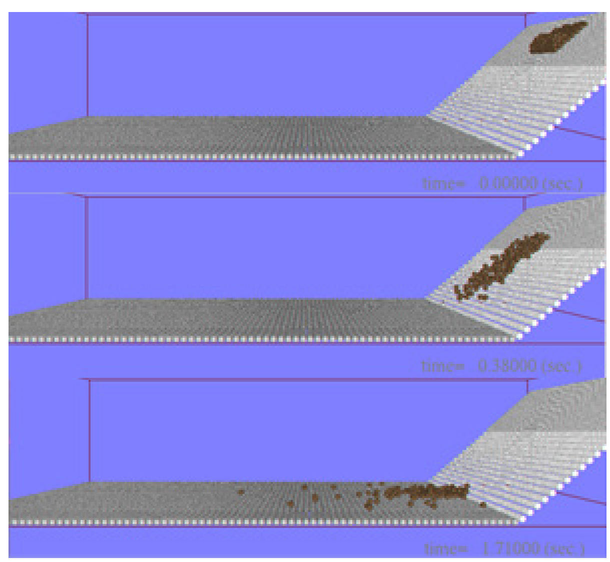

Figure 10. Snap shots of simulation results

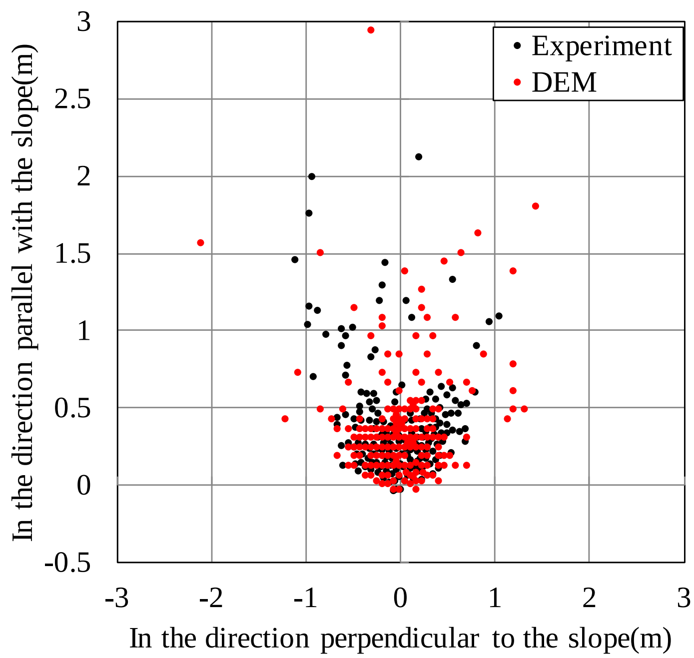

Figure 11. Comparison of distributions of stopped rock positions by experiment and simulation

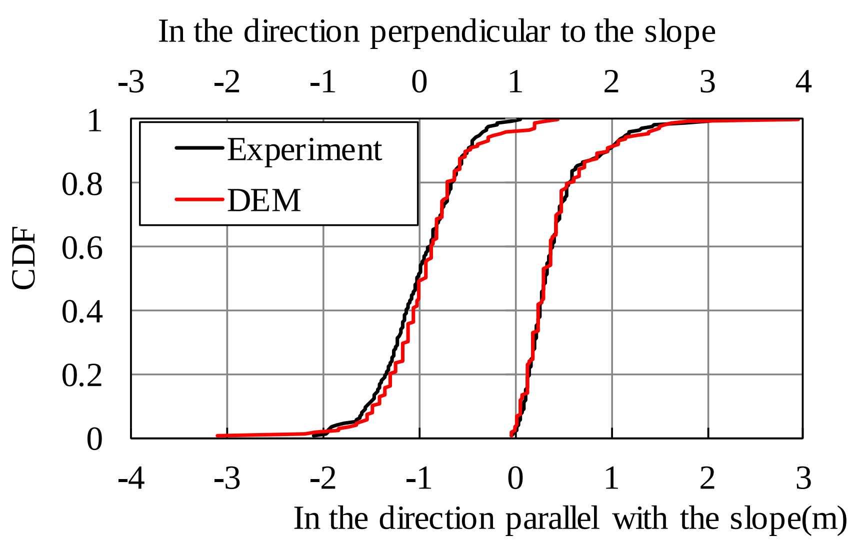

Figure 12. Comparison of cumulative distributions of stopped rock positions

Conclusions

We introduced the numerical simulation of a simple model which can evaluate the effects of slope collapse and rock fall from unexpectedly large earthquakes. Upon constructing the numerical model, we confirmed that verification result of our simulation is independent of simulation code.

In general, the realistic geometry of rocks is very complex and hard to model accurately. We think that the significance of this study is to express the irregular nature of rock dynamics by assigning roughness on the slope and the ground plane and setting a rock of simple geometrical property, instead of realistically and accurately modeling the complex geometry of a rock.

In our numerical model, we set grid points in XY plane coordinate at the same interval as the diameter of rock ball. By placing balls of the same diameter in that grid point and fixing the balls referring to Z coordinate of local slope or site, we can express the boundary fairly well. Thus, because model setting is easy, analysis time can be shortened based on simultaneous computing.

We stochastically evaluate the traveling location of rocks by synthesizing stochastic behavior of rock collision along the slope and the ground plane. Specifically, we synthesized behavior of a single rock drop test in the experiment.

Next, based on the model parameters determined above, say roughness 2r, we performed the numerical simulation of rock-fall along the slope, and compared the distribution of traveling distance of each analysis. As the result, the simple model can represent experiment results fairly well.

Furthermore, we performed the numerical simulation based on the simple model for the experiment of falling of multiple rocks. As the result of comparison of the distribution of traveling distance of rocks, we could confirm that the simple model can synthesize the experiment results fairly well stochastically.

Therefore, this suggests that our numerical approaches can predict traveling distances of rock-fall and their fluctuations.

Acknowledgments

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