Studying Parameters for Changing the Initial Particle Arrangement of Distinct Element Analysis in Earthquake Response Based on Slope Analysis

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BACKGROUND

◆ The level of the design for earthquake ground motion for nuclear power plants increasing

← The influence of the Great East Japan Earthquake

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◆ Deterministic approach is in the regulation whereas Probabilistic Risk Assessment (PRA) is a voluntary activity by corporations.

▪Slope failure around nuclear power plants

→The events that accompany earthquakes in PRA

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SEISMIC RISK ASSESEMENT FLOWCHART FOR ROCK SLOPES

Probabili
hazard a

（Nakajima et al, 2018）

Two Steps

Step1: Evaluation of stability of the surrounding slopes

Step2: Evaluation of the effect on nearby structures by falling rocks

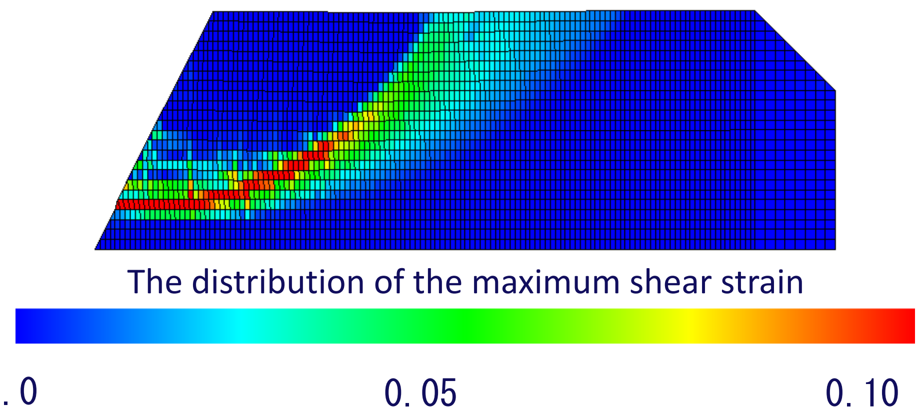
ANALYTICAL METHOD IN STEP1

◆ Step1: The seismic stability of the surrounding slope

→ The equivalent linear analysis is used.

The equivalent linear analysis（Yoshida et al, 2015）

→ The time history nonlinear analysis is researched.



The time history nonlinear analysis（Ishimaru et al, 2015）

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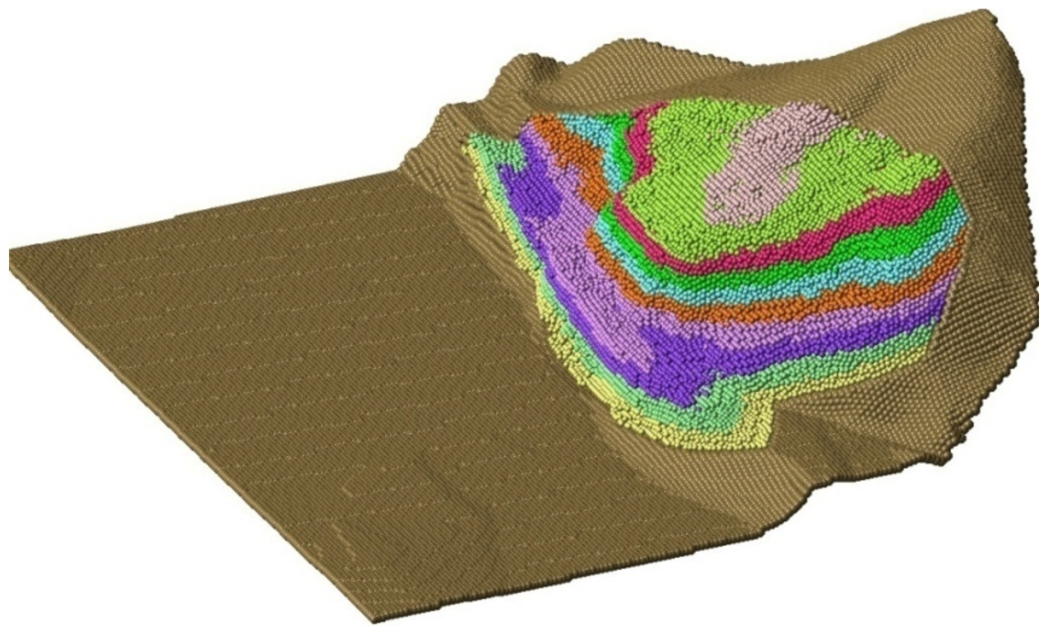
ANALYTICAL METHOD IN STEP2

◆ Step2: The effect on nearby structures by falling rocks

→ The DEM is a particle-scale analysis method.

It can evaluate large deformations or failures easily compared to the FEM.



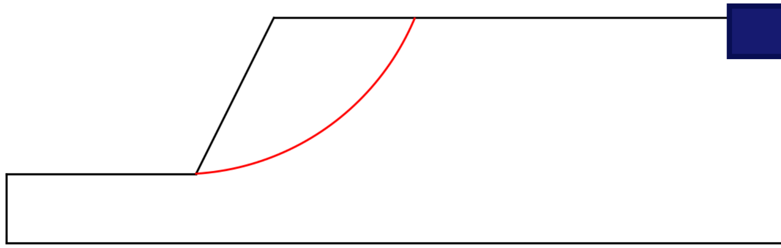
Analysis of slope failure（Tochigi et al, 2013）

TASK

Step1:The seismic stability of the surrounding slope

◆ FEM

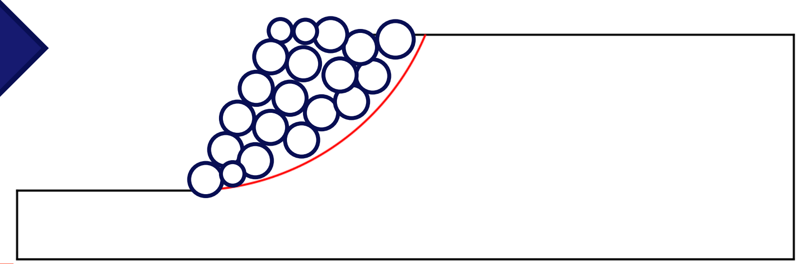
- Judging whether slopes failure or not
- Identifying failure region



Step2:The effect on nearby structures by rock movement

◆ DEM

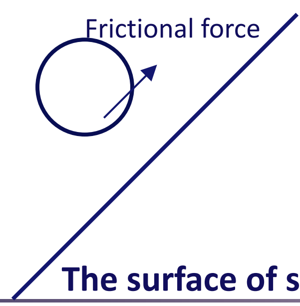
- Evaluation of large deformation or failures



It may have the excessive conservative margin.

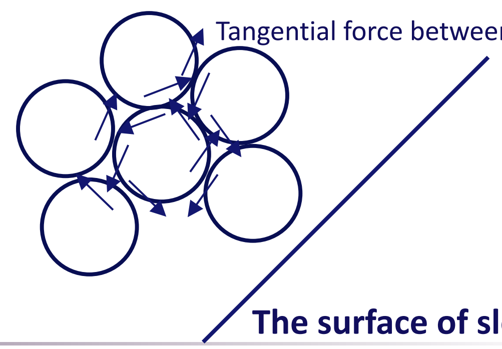
Ex1. Friction coefficient is 0.

A DEM particle



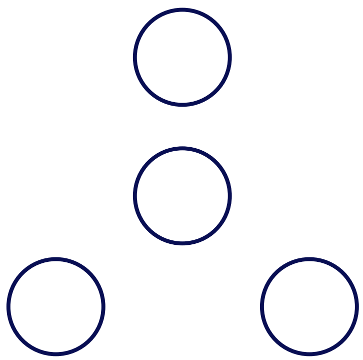
Ex2. Residual strength between particles is 0.

DEM particles



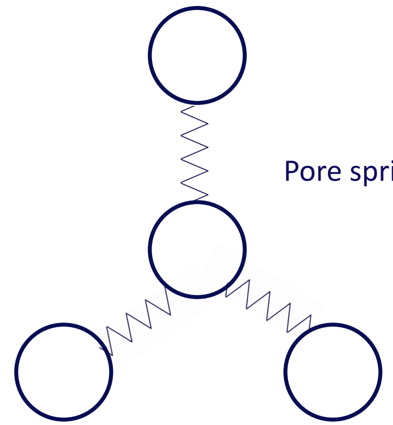
EXTENDED DEM（EDEM） CONCEPT

DEM



・Particles are not connected
if particles don't touch each other.

EDEM



・Particles are connected by pore springs even if particles don't touch each other.
・By setting tensile strength and the shear and turning off the pore spring if the pore force exceed their strength, the progressive failure of slopes can be modelled.

EDEM may be effective for developing a seamless analytical approach including the transition from continuum to dis-continuum of slope.

DEM PARAMETERS

DEM Parameters

Geometric Parameters	Strength-Deformation Parameters
・Fabric Tensor ・The Average Coordination Number, etc.	・Spring Coefficient ・Viscous Damping Coefficient ・Friction Coefficient ・Rolling Friction Coefficient, etc.

If EDEM is applied in seismic risk assessment flowchart of rock slopes, all parameters can be raised and they need to be given uncertainty.

EXISTING RESEARCH OF DE-ANALYSIS

◆ However, there are a few researchers focusing on the statistical patterns of analysis results by many initial particle arrangements of the EDEM.

⬇

If there are defect of parameters realized,

aleatory variability and epistemic uncertainty will not be able to be modelled fully in seismic risk assessment flowchart for rock slopes.

AIM

We investigated two elements below.

- The applicability of DE-analysis to a shaking model table test
- The statistical pattern of failure timing and region by various kinds of initial particle arrangements

SHAKING TABLE MODEL TEST

Geo-material

Stainless particles : Iron sand : Water = 40 : 30 : 1

Stainless particles	Iron sand
	

Physical property obtained from laboratory test results

Physical property	Value
Wet unit weight [kg/m^3]	4.20×10^{3}
Poisson ratio [-]	9.00×10^{-2}
Static elastic modulus [MPa]	$1.36\cdot\sigma^{1.03}$
Initial shear elastic modulus [MPa]	$34.44\cdot\sigma^{0.32}$
Tensile strength [kPa]	0.5
Peak shear strength [kPa]	$7.0+\sigma\cdot\tan40.9^{\circ}$
Residual shear strength [kPa]	$2.05\cdot\sigma^{0.69}$

σ [kPa] ; cofining pressure

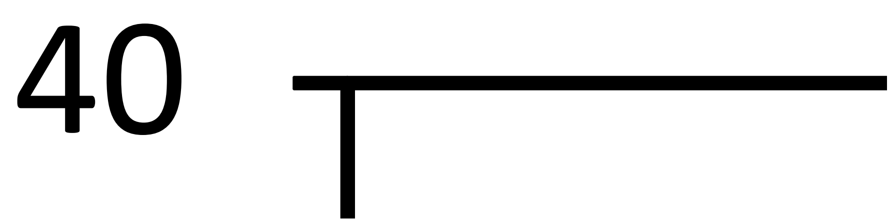
SHAKING TABLE MODEL TEST

<u>The scale of the slope model</u>

Full Length : 0.9m
Height ： 0.26m
Slope gradient ： 1:0.5

<u>Experimental condition</u>

・The model was shaken in 16 stages at input acceleration.
・The input acceleration was a sinusoidal waveform with the main section consisting of 20 waves at a frequency of 20Hz.



<u>The horizontal acceleration measured at the bottom of the soil bin during the third stage of the shaking table model test</u>

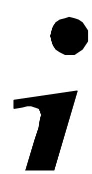
DISTINCT ELEMENT METHOD FOR SOFT ROCK

The motion of each soil element is expressed by the following equations of motion.

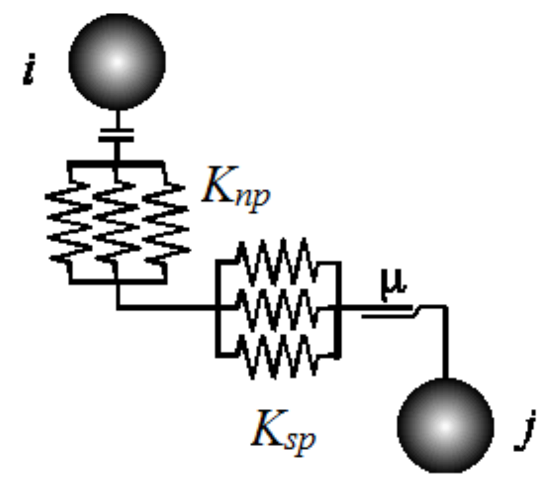
$$\frac{d\boldsymbol{P}}{dt} = \sum \boldsymbol{F} \qquad \frac{d\boldsymbol{L}}{dt} = \sum \boldsymbol{N}$$

$\boldsymbol{P}$ represents linear momentum, $\boldsymbol{F}$ stands for the acting on the soil element,
$\boldsymbol{L}$ is angular momentum, $\boldsymbol{N}$ stands for the torque acting on the soil element.

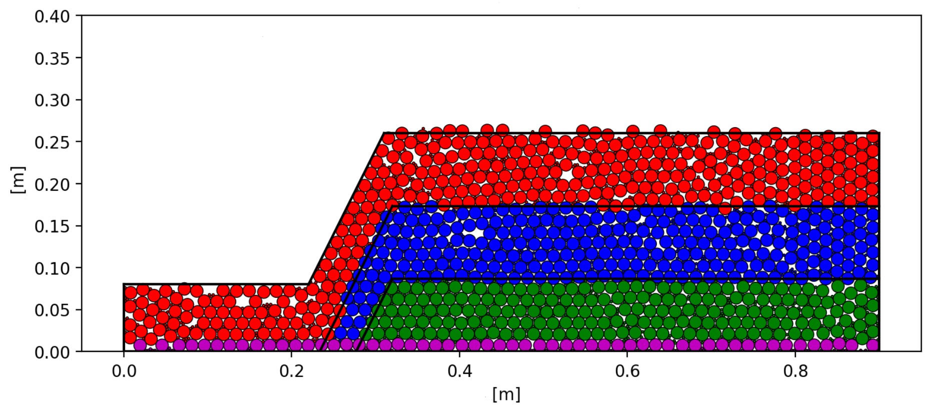
Contact model



Parallel bond model



DISTINCT ELEMENT METHOD FOR SOFT ROCK



An example of the analytical model of slope

・The boundary condition

・The front and the back are modeled as a rigid wall.

・The bottom of the soil bin, shown in purple in the figure, are fixed.

◆ 50 models of changing initial particle arrangements were prepared.

◆ Each model is composed of two kinds of particles whose diameters are 3mm and 15mm.

DISTINCT ELEMENT METHOD FOR SOFT ROCK

DEM parameters for the force between particles

Layer number	First	Second	Third
Wet unit weight [kg/m^3]		4.20×10^3	
Normal spring coefficient [N/m]	4.25×10^7	5.51×10^7	6.51×10^7
Tangential spring coefficient [N/m]	1.92×10^7	2.48×10^7	2.93×10^7
Normal pore spring coefficient [N/m]	1.28×10^5	1.65×10^7	1.95×10^7
Tangential pore spring coefficient [N/m]	5.76×10^4	7.44×10^4	8.79×10^4
Normal damping ratio [%]		3	
Tangential damping ratio [%]		3	
Inter-particle friction angle [°]		34	

◆DEM parameters are determined by laboratory tests.

※Spring coefficient, pore spring coefficient and shear strength→The plane strain compression test

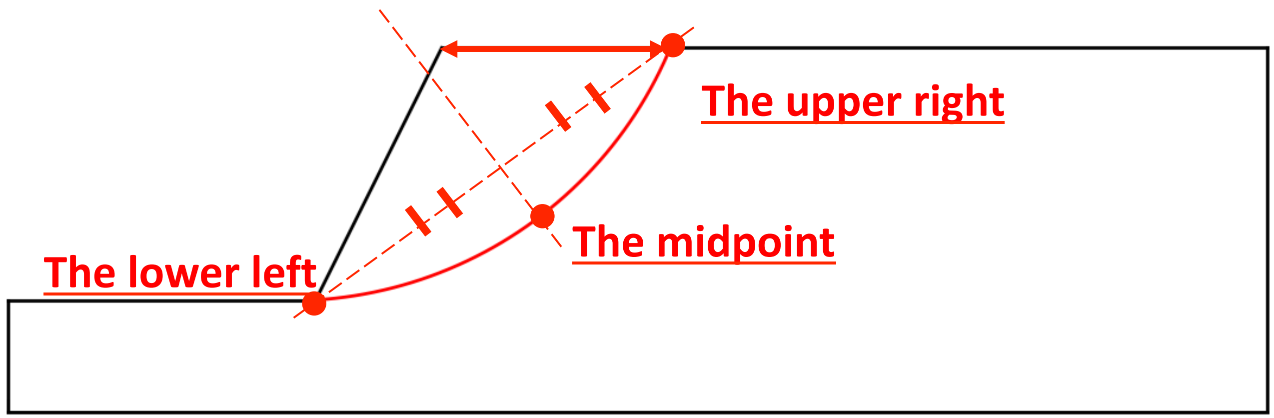
※Dynamic friction coefficient→Cyclic tri-axial test

※Tensile strength→The uniaxial tension test

HOW TO DETERMINE FAILURE TIMING AND REGION

- 1) excluding particles whose movements are more than the threshold, considered as falling
- 2) defining the particle on the upper right of the remaining particles at the left of the foot of the slope as the lower left of slip line
- 3) defining the particles on the upper left of the remaining particles at the right of the top of the slope as the upper right of slip line
- 4) determining that one of the particles at the slope surface and around the perpendicular bisector between the two points is the midpoint of slip line
- 5) defining the slip line as the line which passes its lower left point, upper right, and midpoint

※The horizontal distance used as the index for the size of failure region.



RESULTS（FAILURE TIMING AND REGION）

Failure timing

Experimental result

10

- The statistical model was normal distribution based on statistical hypothesis testing.
- The mode was close to the experimental result.
- The mean was also close to the experimental result.

Failure region

Experimental result

20

- The statistical model was log-normal distribution based on statistical hypothesis testing.
- The mode was close to the experimental result.
- The mean was also close to the experimental result.

- The results of statistical analysis of simulations were close to the experimental result.

RESULTS（SLIP LINES）

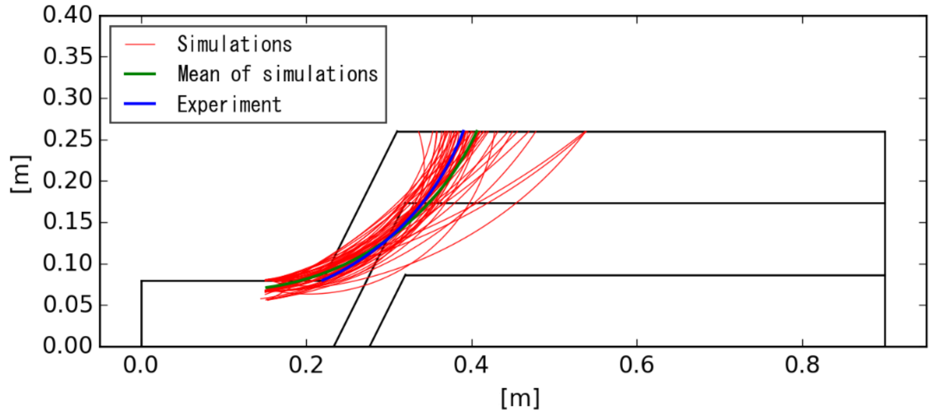


Figure1

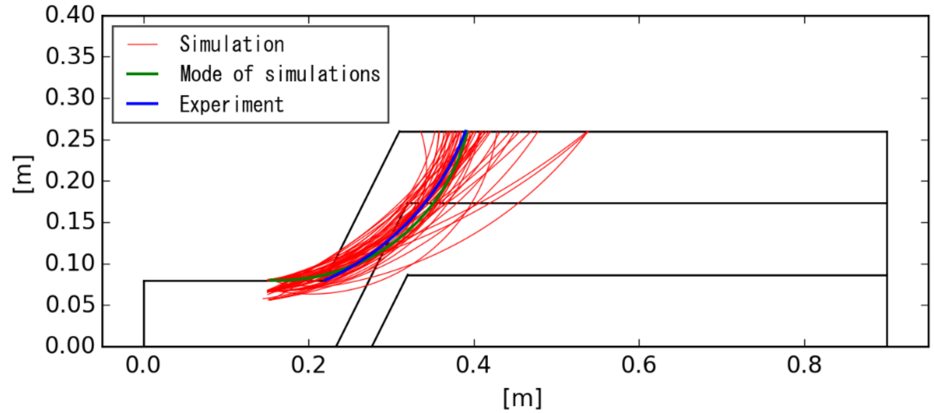


Figure2

The Distribution of the slip lines in the experiment and numerical analysis.

・Red lines・・・・・ Simulation lines, Blue line・・・・・・ Experiment slip line,
Green line・・・・・ Mean of simulations or Mode of simulations

※"Mean of simulations" in Figure1 is defined as the line which passes the mean of each lower left point, midpoint, upper right.

※"Mode of simulations" in Figure2 is defined as the line which passes the mode of each lower left point, midpoint, upper right.

・The results of statistical analysis of simulations were close to the experimental result.

DISCUSSION

◆ The EDEM is effective.

→・A stability analysis can be performed before a slope failure.

・Experimental result may be interpreted based on the statistical analysis by the initial particle arrangements given that strength-deformation parameters are fixed.

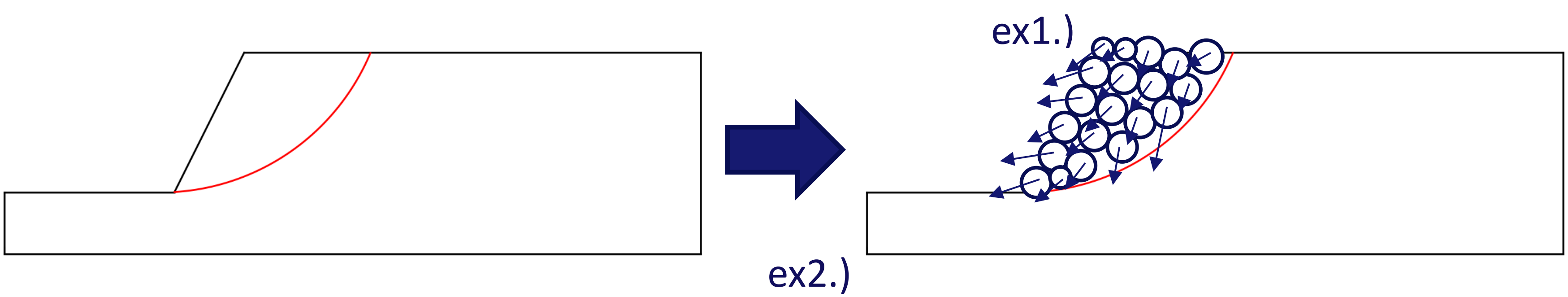
・ Organizing conceptually, it shows DE-analysis result is prescribed by two parameters which are different from each other below.

DE-analysis result	=	Strength-Deformation Parameters effect	×	Geometric Parameters effect

・Next, it is needed to conduct DE-analysis parameterizing both strength-deformation parameters and geometric parameters for each uncertainty correctly.

DISCUSSION

- There is **a realistic information on the failure region** in EDEM.
  - ex1.) The velocity of the particles at the moment the slope fails
  - ex2.) The transition of the particles while the slope fails



▪Existing approach can be improved.

① Including the velocity of the particles at the moment the slope fails
② Analyzing the earthquake response of slope seamlessly

DISCUSSION

The sequence of events from slope failure

$$P_{f\_ijkl} = P_{0i} \times P_{1j} \times P_{2k} \times P_{3l}$$

P_{0i} : The exceedance probability of the peak ground acceleration i of the earthquake
P_{1j} : The probability of occurrence of scenario j of slope failure
P_{2k} : The probability of rock movement reaching reactor building
P_{3l} : The probability of falling rocks causing a failure in the reactor building

- P_{1i} and P_{2k} can be calculated seamlessly by EDEM.
- The next step is to evaluate the seismic failure probability of P_{3l}.

CONCLUSION AND FUTURE WORKS

CONCLUSION

- The probability distribution of the failure timing was found to match normal distribution.
- The failure region showed log-normal distribution.
- Experimental result may be interpreted based on the statistical analysis by the initial particle arrangements given that strength-deformation parameters are fixed in EDEM.

FUTURE WORKS

- The next step is to evaluate the seismic failure probability of the reactor building.

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