Slope failure simulation analysis caused rainfall on road slope by DEM

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In our country, it is reported that there are a lot of cases which the slope failure is caused by the rainfall. Then, the purpose of our study is to analyze slope failure simulation caused by rainfall on fill slopes by DEM. Especially we focus on the real field. And, we regarded a decrease of clod strength as a decrease of frictional coefficient on this analysis. As a result, we have been able to calculate the decreasing rates of frictional coefficient and the start speeds of three cases that had different ways of groundwater's rising. From this result, it is recognized that the decreasing rate of the Case3 was the largest, and the start speed and move distance were also large. So, when it is heavy rain, we should take note it in Case3, and we can say that the possibility of influencing the inhabited area under the slope is high at collapse.

1. INTRODUCTION

Recently, examples of slope failure due to rainfall are still constantly being reported. ; National Highway No.168 Yoshino-gun Nara(2004), Niigata Tokamachi(2005), National Highway No.136 Shizuoka Izu(2007). Especially on the road slope, care must be taken in the planning stage because the degree of fill or material properties or location affects its strength, durability, and disaster resistance.

If slope failure including the road slope occur, it will induce landslides and mudflows, which can be damages to life or property, and to structures such as railways and roads. Therefore, it is socially important to develop preventive measures for these.

Moreover, for the collapse of road slope that we focus on for our research, junction between cut earth and fill will be discontinuous surface on the soil. And, the fills slip and are likely to destroy because rain water or spring water flow into them from the natural ground. Such a slipping collapse especially, it is ruled by the discontinuity surface in the direction of the dip slope. But the collapse mechanism of the complexity has not been necessarily completely clarified. Then, from such a background, in our research, we carry on slope failure simulation caused rainfall on road slope by DEM (Distinct Element Method), and we aimed to evaluate appropriate soil's physical properties in flooding, and examine the influence that its properties of soil give to the slope failure.

2. ANALYSIS METHOD

(1) DEM

DEM is an analysis method devised by P.A.Cundall, and the analysis object is mainly discontinuous body of rock mass and ground. This method analyzes the dynamic behavior of rock mass considering the simulation object as an aggregate of the minute particles. Interparticle force is generated by setting a virtual spring, making it possible to calculate acceleration, velocity and displacement with the use of the force and to track the behavior of particles. The microscopic relationship between the particles is shown in Figure1. In this analysis method, interparticle force is calculated by multiplying the contact distance by spring stiffness.

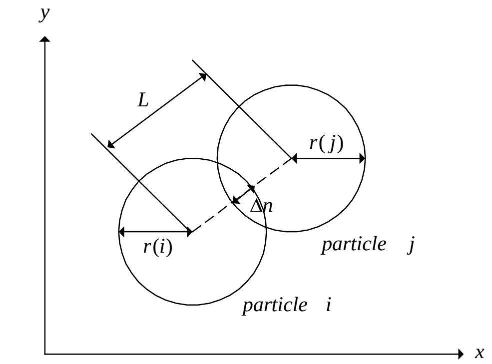

Figure1. The relationship between the particles

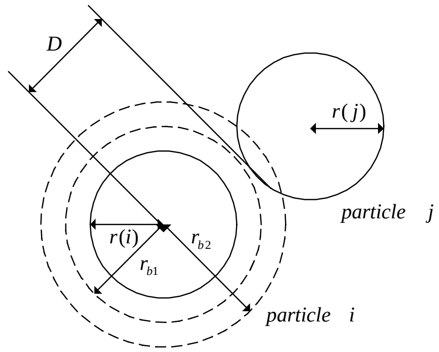

Figure2. The region where the bonding force acts

(2) Bonding force

In this study, we modeled bedrock of slope by introducing interparticle force called bonding force into the normal and tangential directions. The outline of the bonding theory is described as follows.

Figure2 shows two kind of bonding radii of rb1 and rb2. rb1 shows the distance in which the bonding force comes to the yield, and rb2 shows the distance in which the binding force breaks. In short, the bonding force increases from contact point r to rb1, and it decreases from rb1 to rb2. In addition, the bonding force is broken at rb2. At this time, the value of the tensile force is zero (see Figure3). The repulsive force and the bonding force can be formulated as follows.

$$F_{ij} = -F_{ji} = K\Delta n \tag{1}$$

$$F_{ijb} = \begin{cases} K \cdot (D - r(i)) & (r(i) < D \le r_{b1}) \\ K \cdot \dfrac{(r_{b1} - r(i))(r_{b2} - D)}{r_{b2} - r_{b1}} & (r_{b1} < D \le r_{b2}) \end{cases} \tag{2}$$

where F_{ij} is the repulsive force between particle i and particle j, F_{ijb} is bonding force between particle i and particle j, Δn is overlap of particles, K is the spring stiffness, r_{b1} and r_{b2} is bonding radius.

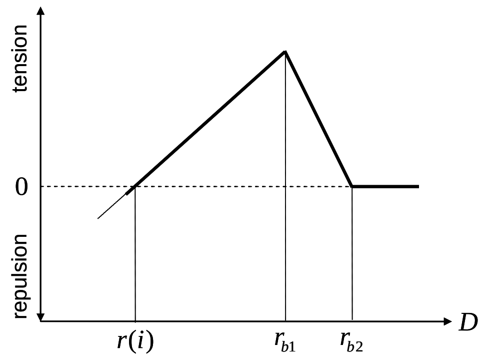

Figure3. The force between the particles

3. THE ROAD SLOPE FAILURE

An analysis object in this study is the failure of fill slope which was established in 2004. Additionally, such a new establishment fill is unstable in strength.

The whole road including the old one has collapsed by continuous rain since the day before. The collapse scale is that the maximum width is about 50m, the slope length is about 105m, and the amount of the collapse soil is about 19,000m^3. As for the geological situation of the slope, this slope is composed of fill, valley sediments, and sandstone shale alternation of strata. In addition to these, for terrain, it was a section where underground water gathered easily because this slope is located in a valley. As a result, most of the fill collapsed.

4. CREATING OF ANALYTICAL MODEL

In this study, we constructed simulation model by using drop method packing simulation. After we cut the model of rectangular shape after packing to slope shape, we colored these particles due to differences in physical properties, and we reflected the geological conditions to the simulation model.

We show cross section of a site (see Figure4) and simulation model (see Figure5), and specification of the analytical model (see Table1). Where, red particles mean fill, orange particles valley sediments, and white particles bedrock.

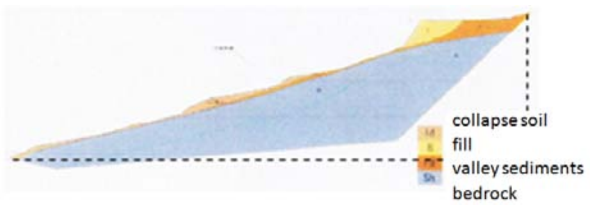

Figure4. Cross section of a site

Figure5. The simulation model

Table1. The specification of analytical model

The total number of particles		7520
Particle radius	maximum	0.14cm
	minimum	0.06cm
Model scale	The direction of x-axis	45.3 cm
	The direction of y-axis	12.6cm

5. DECISION TECHNIQUE OF ANALYTICAL PARAMETERS

(1) Simulation analysis of biaxial compression test

Because this slope is composed of fill and valley sediments and sandstone shale alternation of strata, it is necessary to give different analytical parameters to each ground. In DEM, values of physical properties of simulation object are controlled by interparticle parameters. Then, in advance of simulation of slope failure, we tried the simulation analysis of biaxial compression test by DEM, and decided the analytical parameters that are expressible of cohesion and internal friction angle of each ground.

(2) Analytical conditions

Figure6 shows a pattern diagram of simulation of biaxial compression test. In this study, changing only the spring stiffness of analytical parameters, we tried the simulation to each ground using two kinds of confining stresses. In addition, cohesion and internal friction angle were decided from the failure criteria of Mohr-Coulomb obtained from this simulation.

(3) Analytical results

Table2 gives the analytical parameters and value of simulation of biaxial compression test. Because we didn't get real ground's parameters, we gave properties of general soil to fill. About valley sediments, we gave about twice the strength of the fill from boring data. But, as seen from this result, these values and value of ground physical properties are almost the same although they are not completely identical. Therefore, we decided to use these analytical parameters for the simulation of failure.

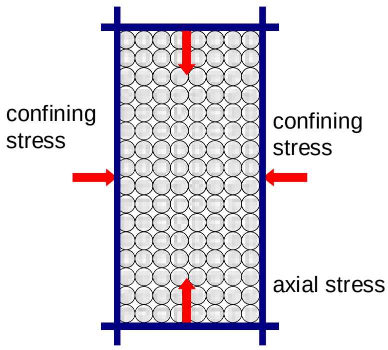

Figure6. Simulation of biaxial compression test

6. FAILURE SMULATION ANALYSIS

(1) Consideration the effect of rainfall

Most of the fill at this site collapsed because pore pressure increased by supplied groundwater in the fill by the rain that had continued since the day before. Therefore, it is necessary to consider a decrease of clod strength by pore pressure to the particle exists in this saturated area. In this study, for these particles, we act the frictional coefficient calculated from the stability formula by Fellenius shown the following.

$$Fs = \sum_{i=1}^{n} \{c_i l_i + (W_i \cos\alpha_i - u_i l_i)\tan\phi_i \} / \sum_{i=1}^{n} W_i \sin\alpha_i \qquad (3)$$

where c:cohesion of slip plane, φ:internal angle of slip plane, u:average pore pressure of split pieces, l:slip plane's length of split pieces, W:clod weight of split pieces, α:slip plane's inclination of split pieces.

Table2. Analytical results of simulation analysis of biaxial compression test

Geology	Density(g/cm^3)	The value of ground physical properties		Analytical parameter		Analytical result	
		c(kPa)	φ(°)	spring stiffness (kN/m)		□c(kPa)	φ(°)
				v	s		
fill	1.65	0.1～0.5	30～35	3000	1100	0.938	34.615

c:cohesion, φ:internal angle, v:vertical spring, s:shear spring

(2) Calculation of pore pressure

The formula (3) mentioned above required the value of the pore pressure. Then, in this study, as shown in the following, we decided to make the hydrostatic pressure work on these particles calculated by the next formula.

$$u(i) = (Z(i) - Z_d)\cdot \gamma_w \quad (4)$$

where $u(i)$ is hydrostatic pressure which works on particle$i$, $Z(i)$ is depth from ground level to particle$i$, Z_d is depth from ground level to ground water level, γ_w is Unit volume weight of water.

(3) Analytical conditions

According to Nishimura's report, when a geometrical similar model of 1/n of the real is put on the centrifugal acceleration place of nG, the vertical stress acts on the model and the real becomes equal. That is, if the tunnel excavation analysis that assumes the centrifugal acceleration place is done, it becomes possible to generate the load level equal with a real tunnel that has the earth covering of several meters in the reduced scale tunnel analysis models put on place of nG. In this study, to reproduce the actual phenomenon, we decided to do the slope failure simulation analysis using an analysis model in the centrifugal acceleration place of 300G. As a result, it becomes possible to apply the physical properties obtained by simulation analysis of biaxial compression test to the slope failure analysis. Next, we describe the setting of the groundwater level. We set three cases that had different ways of groundwater's rising. Case1 is the drain conditions and drained groundwater from the bottom edge of the fill slope, Case2 and Case3 are the non-drain conditions and groundwater accumulates in horizontal and in parallel directions to slope. Figure7 shows the details of how to increase the groundwater. In addition, the frictional coefficients in each case to be used in the analysis (calculation results of formula (3)) are shown in Table3.

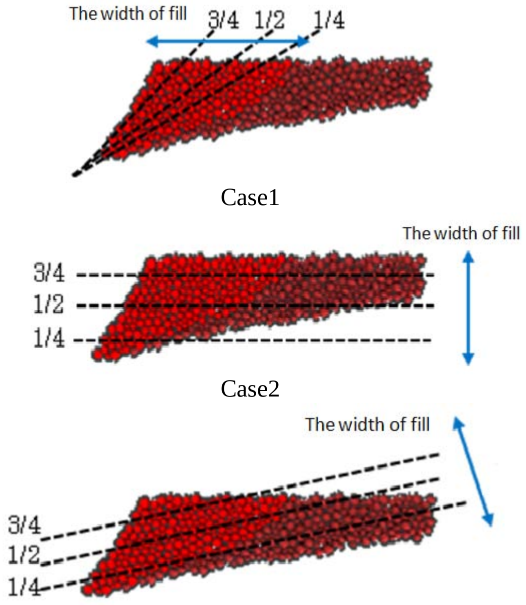

Figure7. Increasing process of groundwater

Table3. The frictional coefficient after lowering

	Level 1/4	Level 1/2	Level 3/4
Case1	0. 30	0. 21	0. 13
Case2	0. 48	0. 29	0. 13
Case3	0. 21	0. 10	0. 06

(3) The result of analysis

Figure8 shows state after the collapsed in each case. As a result, all cases failed to reach the shape of decay shown in Figure4. Of all cases, most closed to the actual phenomena in Case3-3/4 with the highest decreased frictional coefficient and the case where all of the fills are saturated although not mentioned here were the closest. Furthermore, in Case3, it is understand that collapse soil fell a long distance in any case of groundwater. As a consideration by here, it was found that frictional coefficient was influenced by how groundwater rises.Then, in Case1, it was the case where its collapse had a difficulty proceeding because unsaturated clod prevented the progression of the collapse. Second, Figure9 shows each case's velocity of collapse soil . Here, start speed of Case2 with the lowest decreased frictional coefficient was latest of all cases when the groundwater level is 1/4.

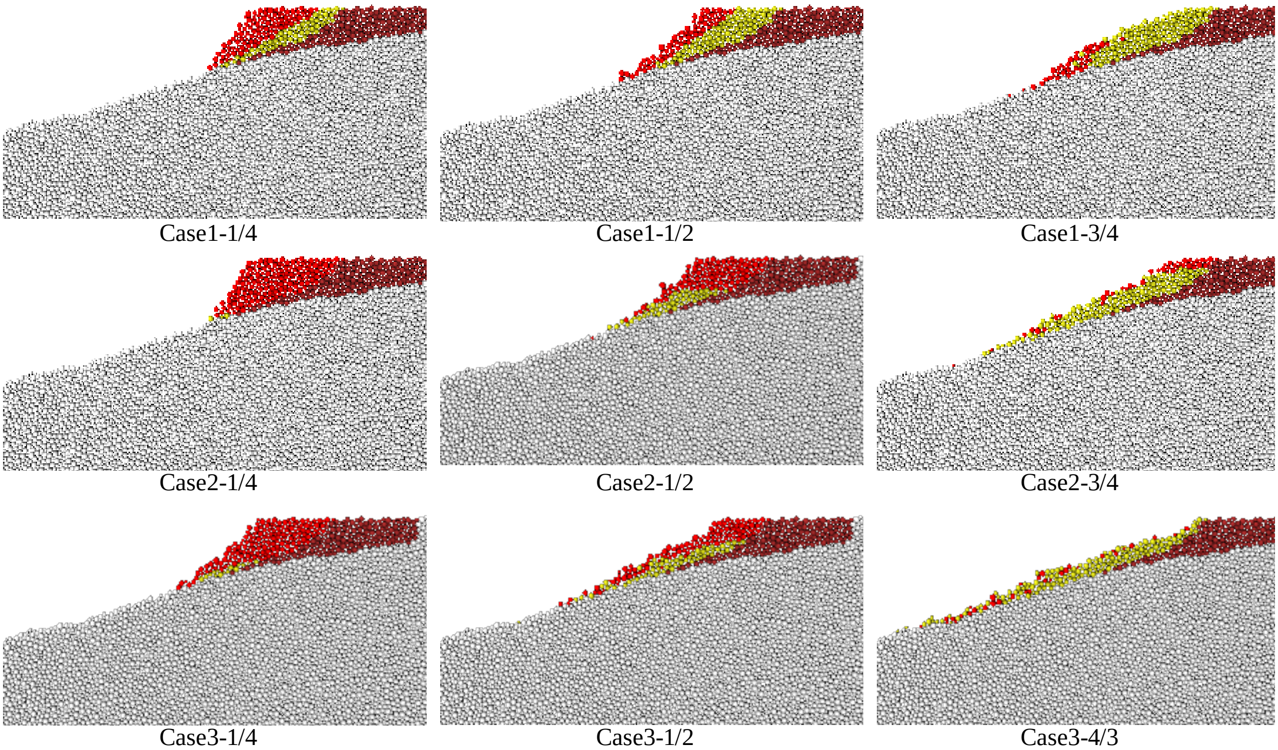

Figure8 Slope shape after it collapsed

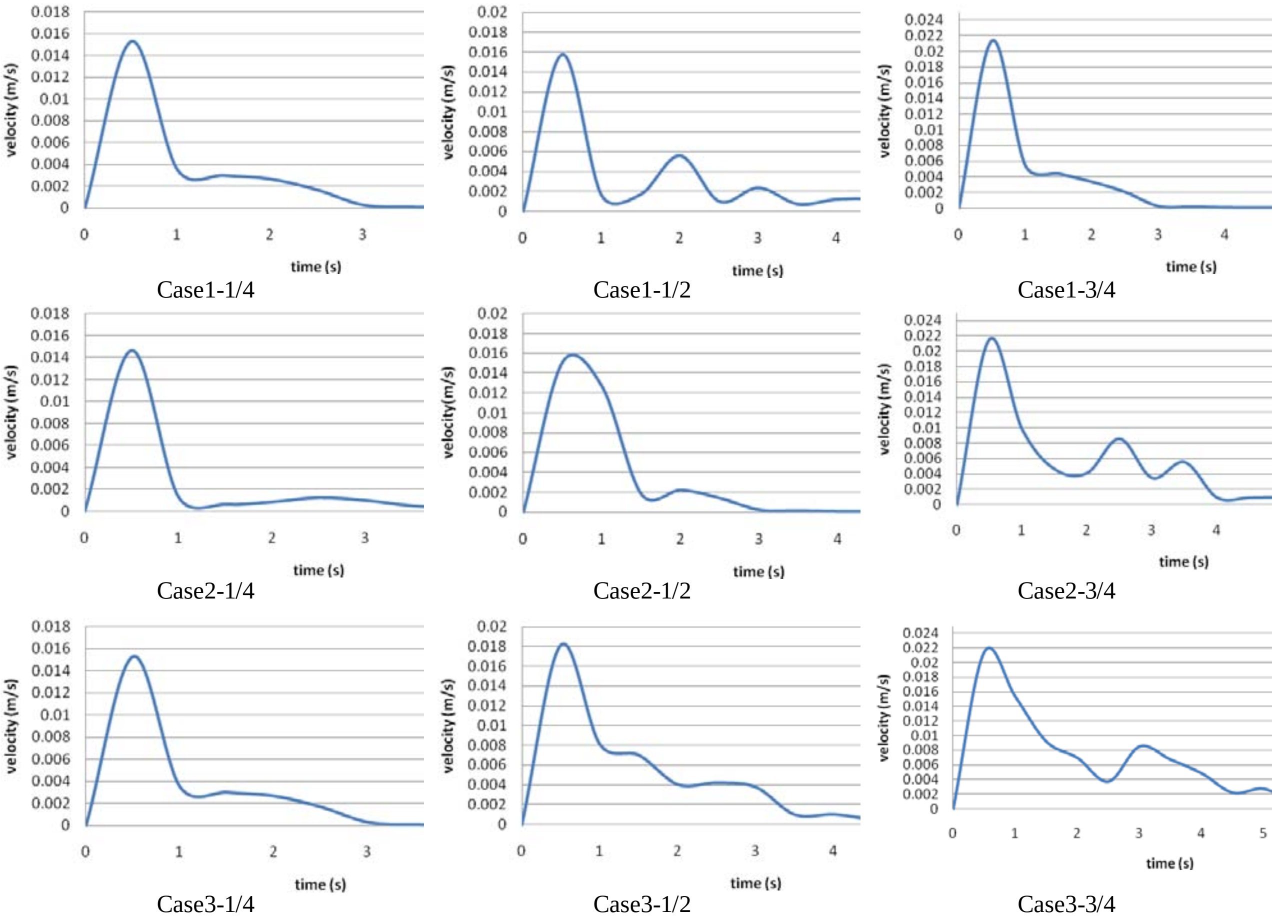

Figure9 Velocity of collapse soil

For this, we excluded this from consideration because we thought it was a factor that the saturated particles were little. Moreover, when the groundwater level is 1/2, start speed of Case3 with highest decreased frictional coefficient was large. But, when the groundwater level is 3/4, we could not confirm the major change.

7. CONCLUSIONS

This study analyzes the failure of actual slope by using DEM, and we tried to clarify the collapse mechanism caused by decrease of clod strength. Moreover, we tried the simulation analysis of biaxial compression test before the failure simulation analysis, and decided an analytical parameter which can reproduce a physical properties of the each ground. The summary of the result achieved in this study is shown as follows.

1) The bonding force was introduced into DEM, and the program that was able to analyze both continuum and discontinuous body was constructed. As a result, bedrock which is continuum was able to be modeled, and it was possible to analyze the natural slope such as actual site.

2) We tried the simulation analysis of biaxial compression test using DEM before the failure simulation analysis, and decided an analytical parameter. As a result, it became possible to model the natural slope that had arbitrary cohesion and the internal friction angle.

3) From the stability formula, we were able to consider as the effect of pore pressure by rainfall as a decrease of frictional coefficient.

4) For analysis that focused on actual slope failure, although we could not obtain the groundwater level that caused slope failure, we could obtain decreasing rate of clod strength and behavior of collapse in each cases.

5) From 4), we could estimate the dangerous slope among Case1~Case3.

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