Excavation simulation analysis of shallow tunnel in multilayered ground by DEM

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It is difficult that to set a clear standard concerning the design, because tunnels are excavated in various geotechnical conditions. Therefore, in general, the design is carried out still experientially, so it is required that analytical method that can appropriately reproduce the mechanics behavior on the natural ground. In this study, we tried excavation simulation analysis of shallow tunnel in multilayered ground using DEM, and the purpose of our research is established the analytical simulator in multilayered ground. Then, the focus of our research is actual collapse accident of tunnel, and we examined the presence of the collapse by setting conditions of underground water and the invert support, etc. We decided the analytical parameters by trying the simulation analysis of biaxial compression test using DEM, before we start the excavation simulation. As a result of the simulation, an analysis model has collapsed when underground water exists and non-closing invert as the actual phenomenon.

1. INTRODUCTION

Recently, the importance of urban tunnels aimed at effective land use increases by concentration of urban functions and overcrowding population. However, sandy soil grounds that consist of alluvium and diluvium are widely distributed in the urban part and the outskirts of Japan, and behaviors of those grounds are not clearly understood. It is very important to predict a subsidence of ground surface that is the biggest problem when excavating a shallow tunnel in urban parts, and to estimate the effect to the underground structures, etc. for the purpose of adequately conducting a countermeasure work at the early stage. And they are related directly to shortening the term of works and a reduction of the cost in the entire construction. We think that the prediction and the evaluation of these problems beforehand will propose a more rational design than the one that has been performed empirically in the past.

In general, an analysis method used for tunnel designing and initial evaluation of ground behavior is mainly continuum analysis such as FEM (finite element method). When excavating shallow tunnels in the poorly-lithified sediment ground, the important thing is how to evaluate the slipping behavior on the ground. However, the FEM which is the continuum analysis has a fault that it can not accurately express the slipping behavior on the ground. On the other hands, DEM (distinct element method) which models the ground as an aggregate of the minute particles can evaluate the slipping behavior because this method is a discontinuous analysis that can reproduce a behavior of the formation of shear planes on the ground. Then, in this study, taking an advantage of two dimensional DEM, we tried to simulate tunnel excavation in multilayered ground, using collapse accidents of shallow tunnel which occurred under construction in Japan. Moreover, we tried in this study to clarify the collapse mechanism, and aimed to establish the analytical simulator that enables rational design and construction of urban tunnels.

2. ANALYSIS METHOD

(1) DEM

DEM is an analysis method devised by P.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.

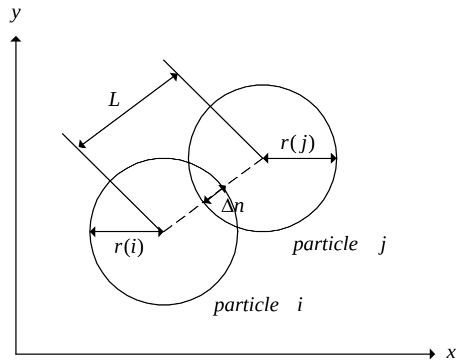

Figure1. The relationship between the particles

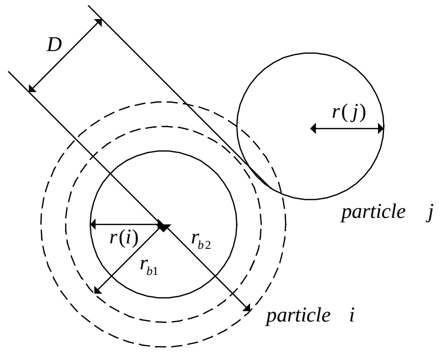

Figure2. The region where the bonding force acts

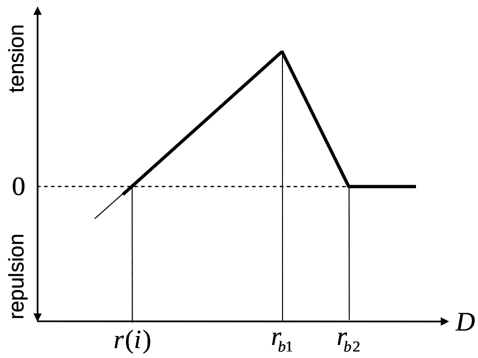

Figure3. The force between the particles

Table1. The value of ground physical properties

	γ (g/cm^3)	c (kPa)	ϕ (deg)
ta	1.54	34.1	9.6
tc-s	1.49	18.7	37.5
tc-c	1.57	8.1	37.1
ts	1.72	3.4	34.2
Nos1	1.97	48.0	34.2

γ : unit weight, c : cohesion, ϕ : internal friction angle

(2) Bonding force

In this study, we modeled supporting made of concrete 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.

$$F_{ij} = \begin{cases} K \cdot (D - r(i)) & (r(i) < D \le r_{b1}) \\ K \cdot \dfrac{(r_{b1} - r(i))(r_{b2} - D)}{r_{b2} - r_{b1}} & (r_{b1} < D \le r_{b2}) \end{cases} \quad (1)$$

where F_{ij} is the interparticle force between particle i and particle j, K is the spring stiffness, r_{b1} and r_{b2} is bonding radii.

3. THE COLLAPSE ACCIDENT OF SHALLOW TUNNEL

An analysis object in this study is the collapse accident of shallow tunnel which occurred under construction in Japan. This shallow tunnel is about 2,000 meters in the total length, and the average earth covering is about 8 meters. The collapse location is composed of the sand layer that has a comparatively high-stiffness (Nos1), sandy soil layer (ts), cohesive soil layer (tc-c), sandy soil layer mixing pumice stones (tc-s) and volcanic ash layer (ta) from the lowest position, and the upper side of the tunnel is used as a rice field.

It is supposed that the causes of this collapse accident were low earth covering, and distribution of tc-s and tc-c that have low-stiffness as the mechanical factors. Furthermore, as the inducible factors, there were facts that this location was unstable after excavating of invert, and that a large quantity of water was supplied to the surrounding ground for the purpose of drawing water to the rice field. Table1 gives values of ground physical properties in the collapse locations.

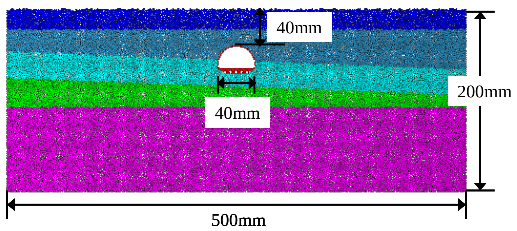

Figure4. The simulation model

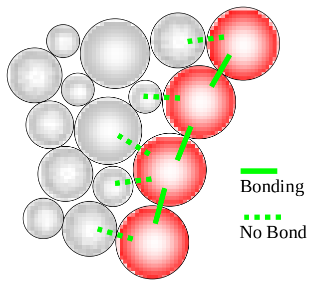

Figure5. The general of supporting particles

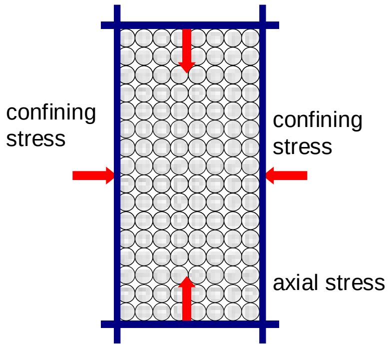

Figure6. Simulation of biaxial compression test

4. FLOW OF SIMULATION ANALYSIS OF TUNNEL EXCAVATION

(1) Establishment of simulation model of multilayer ground

In this study, we established the simulation model using packing simulation by fall method.

Afterwards, the particles in each layer were classified by colors, and the geotechnical conditions were reflected in the simulation model. Figure4 shows the simulation model, and the number of particles is 25657. In this model, red particles show the concrete supporting.

(2) Excavating method

The excavation was expressed by arranging particles in an empty part of tunnel of the simulation model established by packing, and by removing these particles in an arbitrary step. In this simulation analysis, the beginning of excavation is set at 300,000 steps because excavation started after the ground became static.

(3) Modeling of concrete supporting

When modeling the supporting made of concrete, it is necessary to give the characters as continuum to those particles. Then, in this study, we introduced the bonding theory which suggested by P.Mora, generated the bonding force defined as tensile force between particles, and formed an arch-like continuum. Figure5 shows the general description of supporting particles formed by the bonding force.

5. DECISION TECHNIQUE OF ANALYTICAL PARAMETERS

(1) Simulation analysis of biaxial compression test

Because the collapse location is composed of 5 layers, it is necessary to give different analytical parameters to each layer. In DEM, values of physical properties of simulation object are controlled by interparticle parameters. Then, in advance of simulation of excavation, 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 layer.

(2) Analytical conditions

Figure6 shows a pattern diagram of simulation of biaxial compression test. In this study, changing damping coefficient and friction coefficient of analytical parameters we tried the simulation to each layer 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. As seen in this result, these values and value of ground physical properties are almost the same although they are not completely identical (see Table1). Therefore, we decided to use these analytical

Table2. Analytical results of simulation analysis of biaxial compression test

Layer	The value of ground physical properties		analytical parameters		analytical results	
	c (kPa)	ϕ (°)	d (N・sec/m)	f (−)	c (kPa)	ϕ (°)
ta	34.1	9.6	145.00	0.08	34.40	10.74
tc-s	18.7	37.5	57.50	0.40	18.47	37.80
tc-c	8.1	37.1	4.25	0.40	8.15	38.93
ts	3.4	34.2	1.00	0.25	3.34	32.19
Nos1	48.0	34.2	120.00	0.50	48.29	34.32

c: cohesion, ϕ : internal friction angle, d: damping coefficient, f: friction coefficient

parameters for the simulation of excavation.

6. EXCAVATION SMULATION ANALYSIS

(1) Calculation of pore water pressure

The pore water pressure increased by the drawing water to an upper rice field , and underground water had existed from the levee crown of tunnel to the upper surface of the tc-c layer before the collapse. Therefore, it is necessary to add the pore water pressure as the outside power to the particle exists in this area. In this study, we decided to be act the pore water pressure calculated by the next formula on these particles.

$$u(i) = (Z(i) - Z_d)\cdot\gamma_w \quad (2)$$

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

(2) 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 excavation simulation analysis using an analysis model in the centrifugal acceleration place of 200G. As a result, it becomes possible to apply the physical properties obtained by simulation analysis of biaxial compression test to the tunnel excavation analysis.

Table3. analysis conditions

Case	invert	earth covering	cohesion of tc-s (kPa)	cohesion of tc-c (kPa)
1	non-closing	1.0D	18.47	8.15
2	closing	1.0D	18.47	8.15
3	non-closing	1.5D	18.47	8.15
4	non-closing	2.0D	18.47	8.15
5	non-closing	1.0D	49.24	8.15
6	non-closing	1.0D	18.47	38.28

Table3 shows the analysis condition. Case1 is the same condition as the actual phenomenon. In this study, we paid attention to cohesion in the tc-s and the tc-c that have low-stiffness, the earth covering, and the closing or non-closing invert, and did excavation simulation analysis. When underground water did not exist, the collapse was not caused in the condition of Case1.

(3) The result of analysis

Figure5 shows the displacement distribution of each Case. The tunnel collapsed in Case1 which assumed the actual phenomenon, and the collapse was not caused in Case2 in which invert was closed. Moreover, though the tunnel was transformed, collapse did not occur when assuming earth covering H=1.5D and 2.0 D(Case3,Case4). Thus,

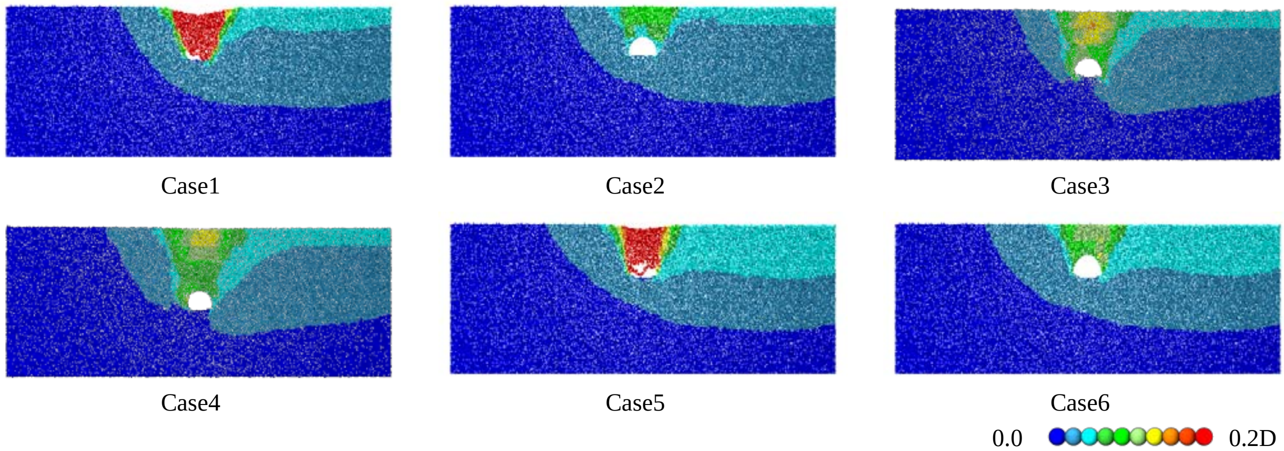

Figure7. displacement distribution(After settling displacement)

the factor of the collapse is thought to be a non-closing invert, and small earth covering. When paying attention to the tc-s and the tc-c, the tunnel collapsed in Case5 that increased cohesion in the tc-s that have low-stiffness, and the collapse was not caused in Case6 that increased cohesion in the tc-c. From these results, it is thought that the stiffness of the tc-c was lower to go through a tunnel. That is, it is estimated that the tunnel would not collapse if the stiffness of the tc-c were improved before excavation even though an excessive pore water pressure acted.

From figure8 to figure10 show comparison of displacement of Case1 and Case2. Figure8 shows the amount of the maximum ground subsidence according to time. The ground subsidence on the tunnel was controlled by closing of the invert. Moreover, the ground subsidence at the right of the tunnel when invert was closed and not closed was not change clearly from the displacement distribution. It is clear that the difference of both is started between 250,000step and 300,000step. The amount of the maximum ground subsidence of Case2 finally became -3.79 millimeter. As a result, it is necessary the invert should be closed until 250,000step in this analysis. However, it is difficult to appreciate the time of the analysis as real time at the present stage, and more research is requested.

Figure9 shows the amount of the levee crown displacement according to time. It is clear that the amount of the levee crown displacement changes steady. In other words, rapid displacement did not cause, and finally displacement became -1.95 millimeter. Figure10 shows the amount of the inside displacement according to time. Finally displacement became -0.11 millimeter. It is clear the tunnel is not transformed internally. This means the cutting face endures the lateral pressure and the shape of the tunnel is kept by closing of he invert.

7. CONCLUSIONS

This study analyzes the actual collapse accident of tunnel by using DEM, and we tried to clarify the collapse mechanism. Moreover, we tried the simulation analysis of biaxial compression test before the excavation simulation analysis, and decided an analytical parameter which can reproduce a physical properties of the each layer of the multilayered 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, a concrete supporting which is continuum was able to be modeled, and it was possible to analyze the excavation of tunnel which had the supporting.
2) We tried the simulation analysis of biaxial compression test using DEM before the excavation simulation analysis, and decided an analytical parameter. As a result, it became possible to model the natural ground that had arbitrary cohesion and the internal friction angle.
3) We analyzed an actual collapse accident of tunnel, and presumed the collapse mechanism. The collapse factor is ①undergrd water had existed from the levee crown of tunnel to the upper surface in the tc-c ②non-closeing invert ③earth covering is too small ④tc-c that have low-stiffness distributed. The opinion similar to the actual phenomenon was able to be obtained.

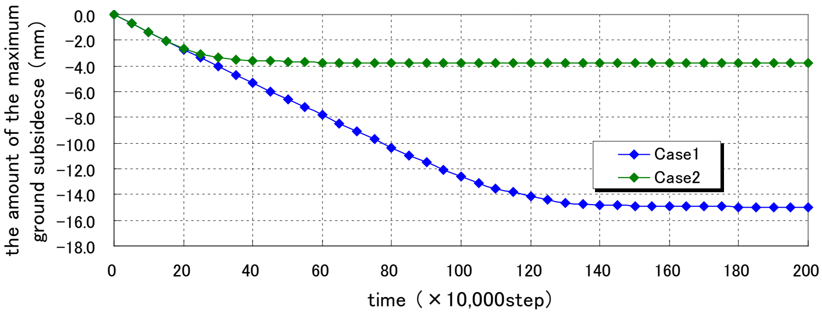

Figure8. the amount of the maximum ground subsidence

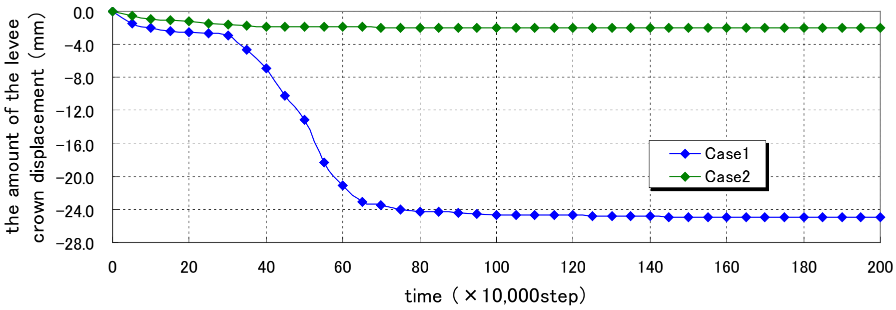

Figure9. the amount of the levee crown displacement

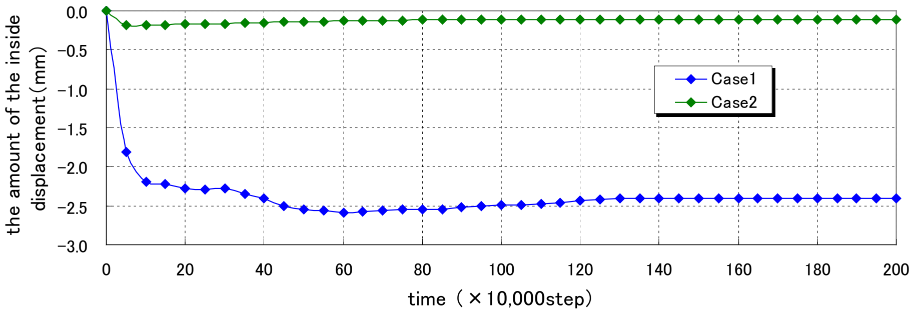

Figure10. the amount of the inside displacement

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