Simulation analysis of excavation of shallow tunnel in multilayered ground by DEM

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The collapse accident of shallow tunnel occurred under construction in Japan, and landslides of the volume of about 6,700 m^3 flowed into the tunnel. Geology of the collapse location is composed of 5 layers, and the upper side of the tunnel is used as field of rice. It is supposed that factors of this collapse accident were low earth covering, distribution of sandy soil layer and cohesive soil layer that are low-stiffness, and so on. However, its details are not clarified. In this paper, we try to clarify the mechanism of this collapse in modeling of ground composed of 5 layers using two dimensional DEM. In this analysis method, value of physical properties of simulation object is controlled by interparticle parameters. Then, in advance of simulation of excavation, we tried the simulation analysis of biaxial compression test by DEM, and examined the parameters that are expressible of the simulation object. Using this analytical condition, we tried to simulate excavation of the shallow tunnel, and to examine the differences of ground behavior by geological structures. As the result of this analysis, it is recognized that subsidence of ground surface is inhibited by improving the layers of low-stiffness.

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

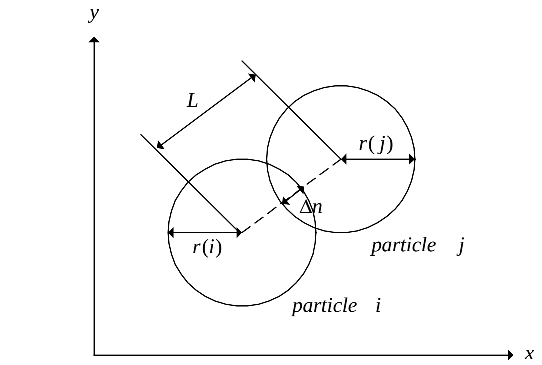


Figure1. The relationship between the particles

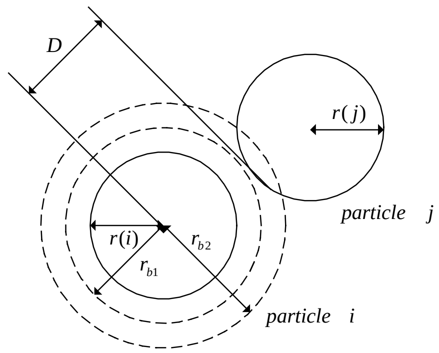


Figure2. The region where the bonding force acts

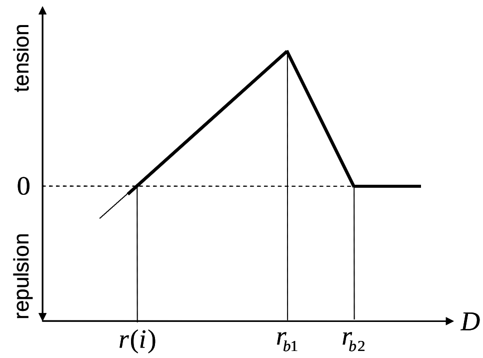


Figure3. The force between the particles

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

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 (Δn) by spring stiffness.

(2) Bonding force

Interparticle force is not only the repulsive force, when the model of granular material is applied to the solid like concrete. Then, the tensile force is expressed by introducing the bonding force in this study.

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.

$$F_{ij} = \begin{cases} K \cdot \Delta n & (D < r(i)) \\ K \cdot (D - r(i)) & (r(i) < D \le r_{b1}) \\ K \cdot (r_{b2} - D) & (r_{b1} < D \le r_{b2}) \\ 0 & (D > r_{b2}) \end{cases} \qquad (1)$$

where F_{ij} is the interparticle force between particle i and particle j, K is the spring stiffness.

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.

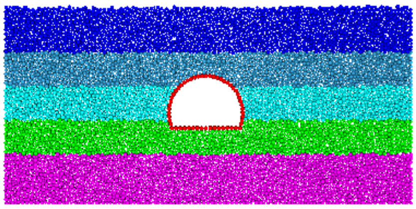


Figure4. The simulation model

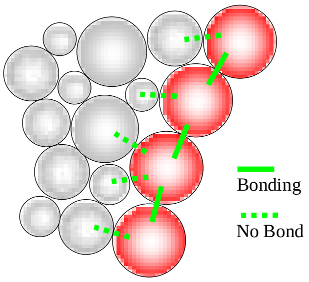


Figure5. The general of supporting particles

4. FLOW OF SIMULATION ANALYSIS OF TUNNEL EXCAVATION

(1) Establishment of simulation model

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 about 7500. In this model, red particles show the concrete supporting. The modeling method is described later.

(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 a static state.

(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.

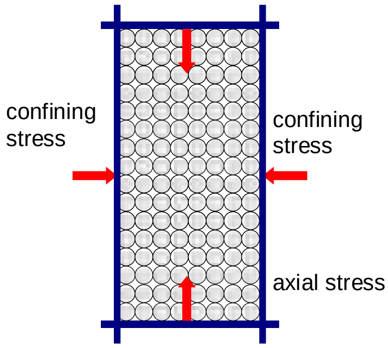


Figure6. Simulation of biaxial compression test

Table2. Analytical parameters and value of simulation analysis

	analytical parameters		value of simulation analysis	
	d (N・s/m)	f (-)	c (kPa)	ϕ (deg)
ta	500.0	0.0052	32.7	8.6
tc-s	200.0	0.30	18.7	35.1
tc-c	40.5	0.30	8.9	37.2
ts	2.0	0.25	3.5	36.3
Nos1	360.0	0.40	47.7	33.1

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

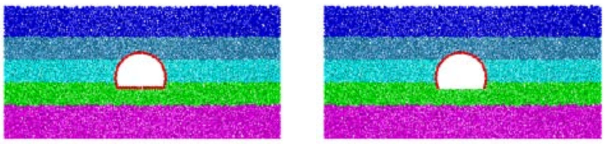
5. DECISION TECHNIQUE OF ANALYTICAL PARAMETERS

(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, value of physical properties of simulation object is 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, damping coefficient and friction coefficient of analytical parameters were changed, and 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 this simulation.



closing invert non-closing invert

Figure7. Simulation models

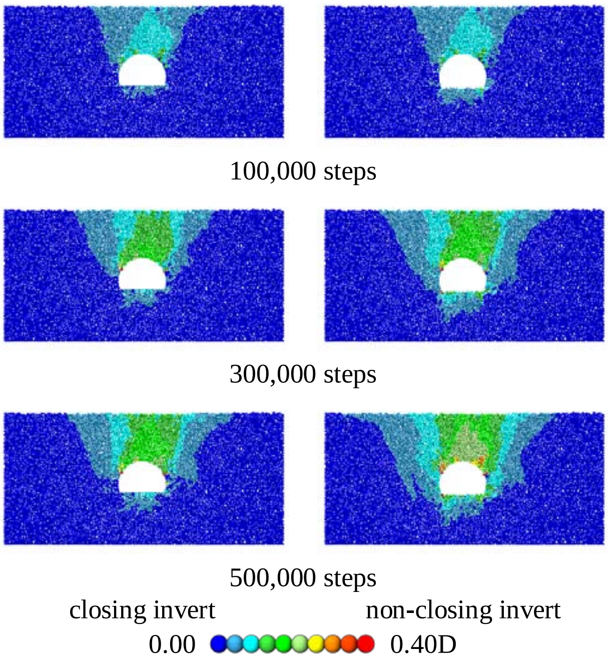


Figure8. The displacement distributions

(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 value but these are not completely corresponding (see Table1). Therefore, we decided to use these analytical parameters for the simulation of excavation.

6. SIMULATION OF EXCAVATION

(1) Examination of closing effect of invert

As one of the factors in the collapse accident, it is supposed that the collapse location was unstable after excavating of invert. In this simulation analysis, we tried to examine the closing effect of invert by using two simulation models shown in Figure7.

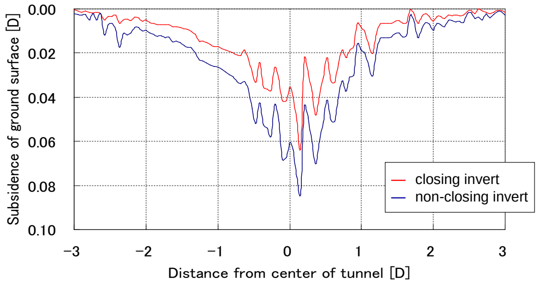


Figure9. The shape of subsidence of ground surface

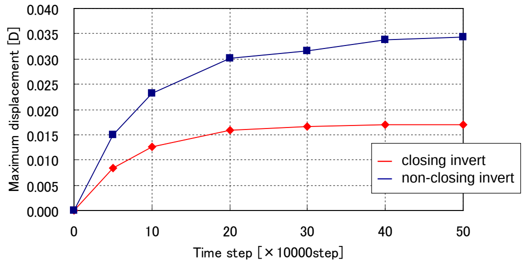


Figure10. Transition of the maximum displacement

(2) Analytical results

Figure8 show the displacement distributions that are one of the analytical results. In these figures, it is shown that displacement magnitude grows as the color of particles changes from blue into red. From this result, it is recognized that the deformation of ground of around on the tunnel and the batholith part is inhibited by closing invert.

Figure9 shows the shape of subsidence of ground surface in closing invert and non-closing invert. As seen in this result, subsidence of ground surface is inhibited by closing invert. Figure10 shows the maximum displacement of batholith part according to passage of time. From this result, it is recognized that the maximum displacement is decreased by about 50% by closing invert. In short, the collapse location where invert had not been close was delicate state, and it is said that this is one of the factors in the collapse accident.

(3) Examination of geological structures

Geology of the collapse location is composed of 5 layers, and sandy soil layer and cohesive soil layer that are low-stiffness are distributed. In this simulation analysis, we tried to examine about effect that the layers of low-stiffness exert on the collapse by using two simulation models shown in Figure11. In these simulation models, yellow particles show the layer that stiffness is improved. Table3 gives the analytical parameters changed in this simulation analysis.

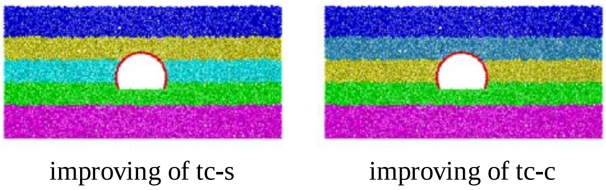


Figure11. Simulation models

Table3. Changed analytical parameters

	before improving			
	d (N・s/m)	f (-)	c (kPa)	ϕ (deg)
tc-s	200.0	0.30	18.7	35.1
tc-c	40.5	0.30	8.9	37.2
	after improving			
	d (N・s/m)	f (-)	c (kPa)	ϕ (deg)
tc-s	250	0.35	26.4	36.0
tc-c	100	0.35	17.3	37.2

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

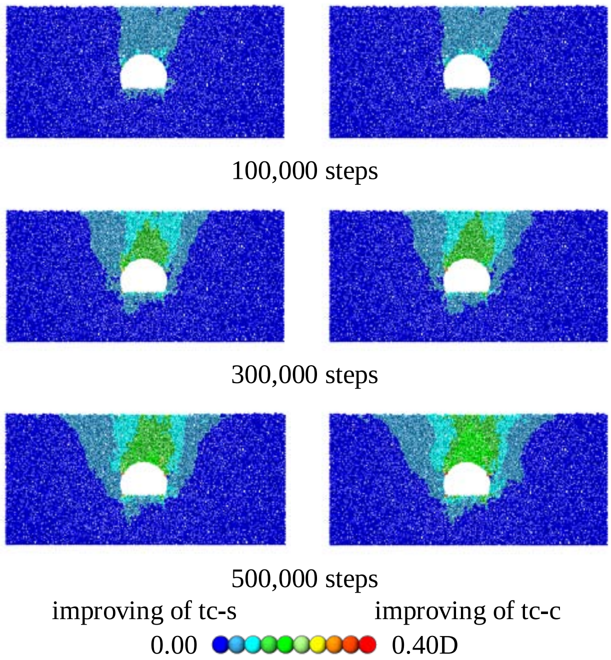


Figure12. The displacement distributions

(4) Analytical results

Figure12 show the displacement distributions that are one of the analytical results. In both cases, the results that deformation on the tunnel is mainly inhibited were obtained compared with before stiffness was improved. However, there is hardly a difference between case of improving tc-s and case of improving tc-c, we think that it is necessary to set the analytical parameters.

Figure13 shows the shape of subsidence of ground surface in before improving stiffness and after improving stiffness. Similar can be said from this figure. Figure14 shows the maximum displacement of batholith part according to passage of time. Though a big effect was not seen for the batholith part, the maximum displacement is decreased by about 28% by improving layers of low-stiffness. From these results, it is supposed that strength of the tunnel was not able to endure the water pressure with a large quantity of water supply to the surrounding ground because of these low-stiffness layers.

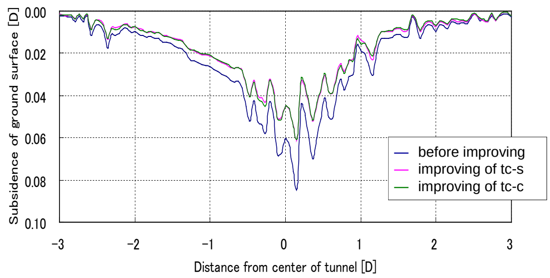


Figure13. The shape of subsidence of ground surface

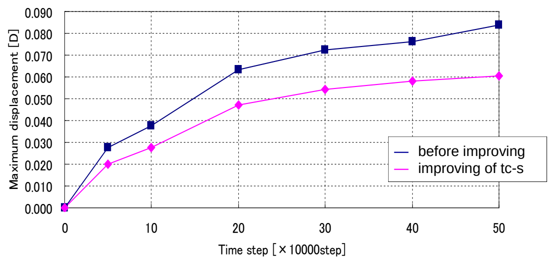


Figure14. Transition of the maximum displacement

7. CONCLUSIONS

In this study, analytical parameters were decided from simulation analysis of biaxial compression test, and the excavation of shallow tunnel in the multilayered ground was simulated by two dimensional DEM. Knowledge obtained by this study is stated as follows.

In simulation analysis of biaxial compression test, various grounds were able to be expressed by changing damping coefficient and friction coefficient.

Furthermore, as the results of simulation of excavation, it is recognized that the collapse location where invert had not been close was delicate state, and this is one of the factors in the collapse accident, and subsidence of ground surface is inhibited by improving the layers of low-stiffness.

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