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INVESTIGATION OF CYLINDRICAL SPECIMEN COLLAPSE BEHAVIOR ON THE EXPERIMENT AND 3D SMOOTHED-PARTICLE HYDRODYNAMIC ANALYSIS

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ABSTRACT: Smoothed-particle hydrodynamics (SPH) is a computational method used to simulate the dynamics of continuum media, such as solid mechanics and fluid flows. Much research has been conducted using this method to simulate the collapse behavior of soils; however, most of this research has focused on two-dimensional SPH analysis. There is currently little research into modelling the collapse behavior of soil using three-dimensional SPH analysis. Therefore, this paper presents the results of a collapse behavior study of cylindrical sand specimens, comparing experimental results with a three-dimensional SPH analysis. The experiments were conducted by pulling a cylindrical container from a column of sand and measuring the dimensions of the resulting diffusion cone. The frictional properties of the table surface and the rate of pulling were varied to determine their effects and compare analysis results. The diffusion cone geometries determined by SPH analysis showed good consistency with the observed experimental results, suggesting promising application of three-dimensional SPH analysis to the modelling of soil collapse behavior.

Keywords: SPH analysis, Cylindrical specimen, Collapse behavior, Decomposed granite

1. INTRODUCTION

Traditionally, finite element method (FEM) analysis has been widely used as a representative stress-deformation analysis method for in-situ soils. The FEM analysis method consists of a series of small elements, each of which is defined by a linear function, collectively describing the properties of an object by combining the discrete behavior of these many small regions. However, while FEM analysis is widely used in many different applications, other analysis methods are typically used to model large deformation problems. Among these methods, smoothed-particle hydrodynamics (SPH), a continuum analysis method, is a type of analysis used to express large deformations, including in geotechnical engineering applications. Several dissertations have relied upon two-dimensional SPH analysis for geotechnical engineering applications [1], [2].

In this study, sand column specimen collapse behavior is both experimentally evaluated and numerically analyzed using three-dimensional SPH analysis, and the shapes of the resulting diffusion cones are compared to validate the use of SPH analysis.

2. EXPERIMENTAL CONDITIONS

2.1 Outline of Experiment

Fig. 1 illustrates an outline of the experiment. The material used was a Masa soil, that is

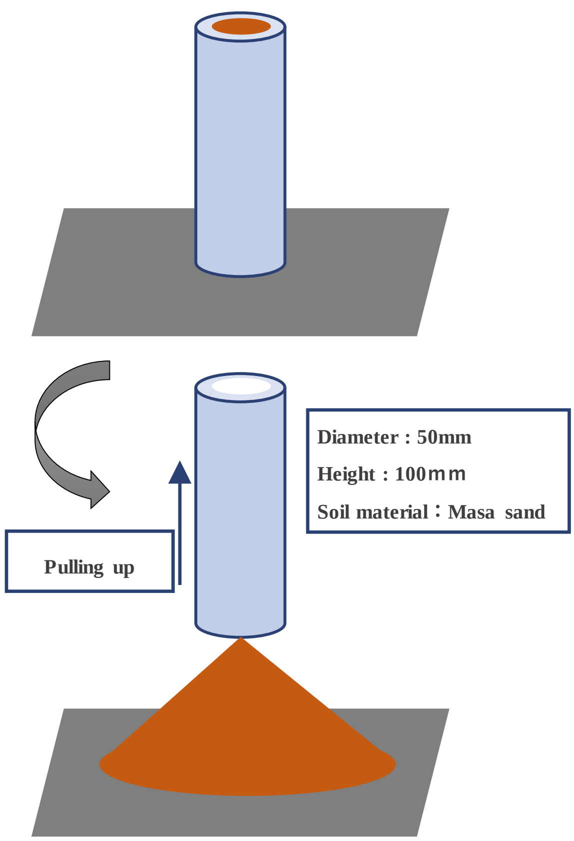

Fig.1 Outline drawing of experiment of pulling up cylindrical sands

decomposed granite soil obtained from Shigaraki, packed in a cylindrical container with an inner diameter of 5 cm and a height of 10 cm. This cylindrical container was connected to a threaded rod that was used to pull the cylinder up vertically. Fig. 2 shows a photograph of the equipment during the experiment.

Because the cylinder was pulled up manually, the velocity of pulling varied. To capture the pulling velocity during the experiment, the pulling time was measured by a 40-fps video camera, and the mean pulling velocity was calculated by dividing the displacement by the time it took to raise the cylinder.

If the velocity at which the container is pulled is too fast, the friction between the cylindrical specimen and the container becomes a dominant cause of dynamic deformation. In this study, the friction between the specimen and the container was minimized to the extent possible by applying an electrostatic discharge spray to the inside of the container. Based on the parameters of the spray, the ideal pulling velocity was targeted at 50 cm/s to minimize the remaining friction between the sand and the cylinder. Target pulling velocities of 50, 40, 30, 20, and 10 cm/s were then experimentally applied, and each experiment was conducted four times for each different pulling velocity.

To account for the influence of friction between the table surface and the specimen as it diffused, two different table surface materials were used for each set of test parameters: ultra-high molecular weight polyethylene (UHMWPE), widely used for sliding surfaces in biomaterials such as artificial joints and industrial materials because of its superior wear and corrosion resistance, and a

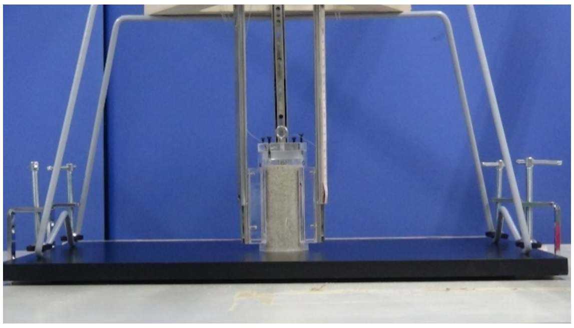

Fig.2 Experimental equipment

decorative board with a general surface coating.

The resulting diffusion cones of the collapsed specimens were quantified using two dimensions: the maximum diffusion diameter and the maximum height. The maximum diffusion diameter is defined as the diameter of the base of the diffusion cone and is shown in Fig. 3. The maximum height is the height of the diffusion cone and is shown in Fig. 4. The analytical and experimental results were then compared using these two dimensions for the two types of table surfaces, and the effect of friction was determined with respect to the applied pulling velocity. The experimental procedure employed was as follows:

1. The experimental instruments were placed on the table surface.
2. The electrostatic diffusion spray was applied to the table surface and the inner wall of the cylindrical container.
3. The sand was prepared in the cylindrical container.
4. The container was pulled upward manually as constantly as possible at the target rate.

Fig. 3 Maximum diffusion diameter

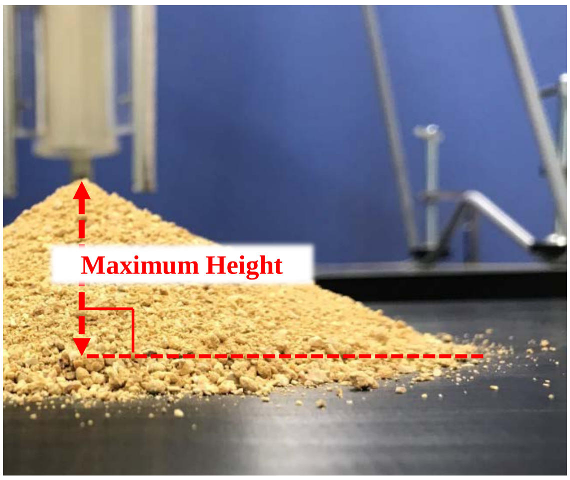

Fig.4 Maximum height and
the boundary for Maximum diffusion diameter

5. The maximum diffusion diameter and maximum height of the diffusion cone were then measured.

2.2 Material Parameters

Table 1 provides the material parameters of the Shigaraki decomposed granite. The internal friction angle ϕ and Young's modulus E were determined from triaxial compression test results transferred as per Moriyoshi [3] from the stress-strain curve. As the specimens used in this study were air-dried, the cohesion c = 0 kN/m^2.

Table 1 Material parameters of Shigaraki decomposed granite

Parameters	Variables	Units	Values
Unit weight	γ	kN/m^3	14.7
Young's modulus	E	MN/m^3	2.309
Poisson's ratio	ν	—	0.33
Cohesion	c	kN/m^2	0.0
Internal friction angle	ϕ	*deg*	32
Dilatancy angle	ψ	*deg*	0.0

3. NUMERICAL ANALYSIS

3.1 Analysis Conditions

The experimental arrangement was numerically analyzed in three dimensions using an SPH analysis program created by Bui [1]. The state at which the displacement converged after the specimen was loaded with its own weight was taken as the initial state. Table 2 provides the SPH method parameters used for the analysis.

Table 2 Parameters of the SPH simulation

Parameters	Variables	Values
Initial Particle diameter	dx	2.5 mm
Smoothing length	h	3.0 mm
Initial smoothing length	kh	6.0 mm
Parameter for boundary condition	β	1.75
Number of particle	n	3160

The model used in the analysis is shown in Fig. 5. The bottom of the specimen was set as Z = 0 cm, at which location the bottom layer of real particles was used for the first step of the analysis inside a circle with a radius of 2.5 cm in the XY plane. Considering the axial symmetry of the cylinder, a cross section consisting of one quarter of the section of the whole cylinder was analyzed to reduce the computational complexity.

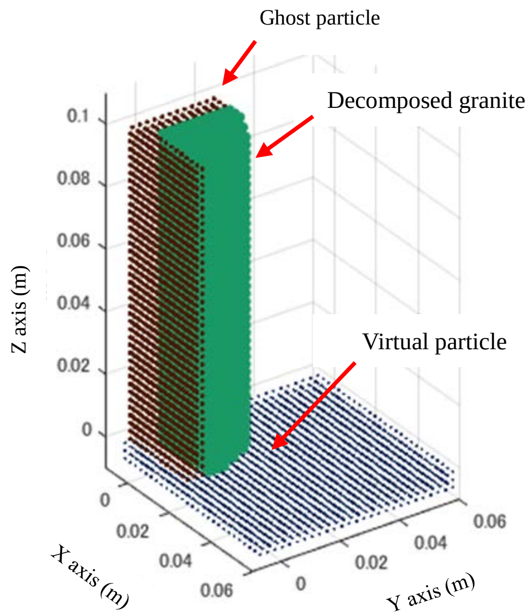

Fig.5. Outline of simulation case

Real particles were stacked from the bottom to a height of 10 cm. Three layers of boundary particles were distributed on the bottom surface to support the real particles, and three layers of ghost particles were arranged at the boundary between the quarter-cylinder specimen and the XZ and YZ planes.

The maximum value β_{max} of the coefficient β_0, related to the relative velocity between the real particles and the boundary particles, was set to 1.75 to prevent particles from getting too close to the boundary. Bui et al. [1] recommend that β_{max} be set between 1.5 and 2. It was confirmed by preliminary testing prior to conducting the SPH simulation that the value of β_{max} influences the analysis result, so this constant value was selected by more detailed examination.

The boundary conditions selected to simulate the pulling of the cylindrical container were determined to reflect the pulling velocity using ghost particles. The ghost particles were initially placed around the specimen circumference and the lifting of the container was then simulated by sequentially removing these ghost particles from the bottom upward. In this process, the distance from the bottom surface to the lower edge of the circumferential ghost particles was defined as *TR*.

By increasing *TR* by Δ*TR* each step, the raising rate of the experimental container could be expressed.

4. RESULTS AND DISCUSSION

4.1 Confirmation of Analytical Symmetry

In this section, the results of the three-dimensional SPH analysis are evaluated to ensure appropriate symmetry in the circumferential direction. Fig. 6 depicts the horizontal diffusion of the simulated specimen particles when the container is instantaneously removed, thus the rate at which TR was increased was infinite. The color map depicts the degree of displacement of each particle.

Fig. 7 and 8 depict the cross-sectional diffusion of the simulated specimen particles, in which the angle indicates the degree of rotation from the model y axis towards the x axis.

Fig. 9 depicts a superposition of the cross-sectional diffusion at 45 and 60 degrees shown in Figs 7 and 8, respectively, for the instantaneous cylinder removal case, generated by ImageJ [4], an image processing software package used at the National Institute of Health. Fig. 7 is processed into a red fluorescent image and Fig. 8 is processed into a blue fluorescent image, and these are superimposed. Thus, overlapping points are displayed in purple. The results in different directions are in good agreement, demonstrating that there is almost no difference in particle diffusion with circumferential location.

4.2 Effects of Different Pulling Velocities

In this section, the distribution predicted by the SPH analysis is compared with that observed in the experiments. Fig. 10 is a typical example of the resulting three-dimensional particle diffusion after removing the cylinder, as determined by analysis. Table 3 provides a comparison between the maximum diffusion diameter, maximum height, and pulling velocity of the experimental (A) and analytical (B) results, in which the models and the experiments show generally good agreement.

Fig. 11 depicts relationship between the pulling velocity and the resulting experimental and analytical maximum diffusion diameters. Regression curves have been added to approximate the correlation between pulling velocity and maximum diffusion diameter and aid comparison. Clearly, the maximum diffusion diameter and pulling velocity are positively correlated in both the experimental and analytical results. Additionally, it can be observed that the total variation in diffusion diameter with pulling velocity is particularly large

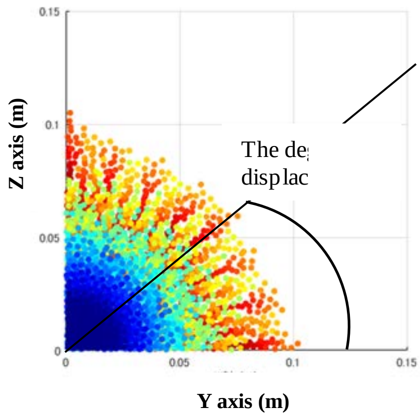

Fig.6 Displacement when the experiment container is instantaneously removed

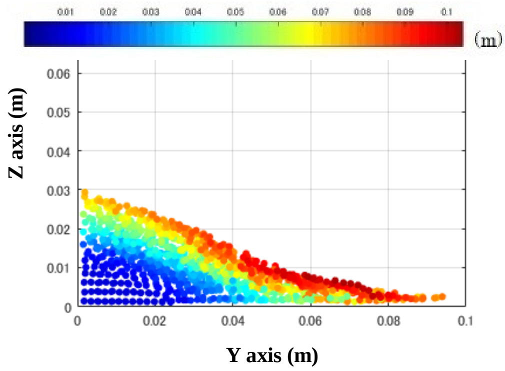

Fig.7 Displacement of 45°

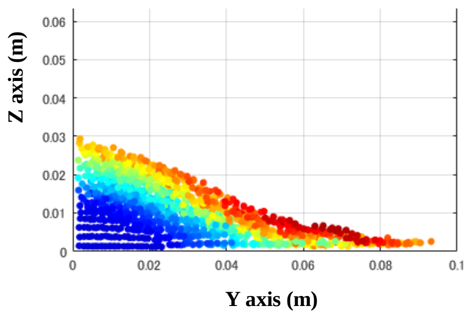

Fig.8 Displacement of 60°

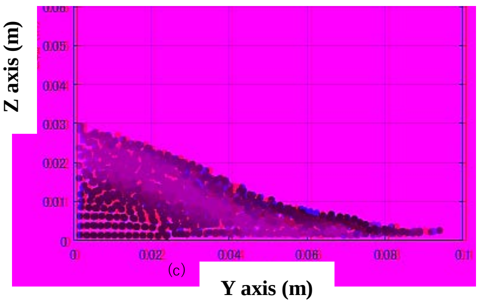

Fig.9 Superposition of the displacement diagram

for the UHMWPE board, yet the shape of the regression curves for the UHMWPE and decorative boards are similar. For both table surface materials, the diffusion diameter increases with the pulling rate. Finally, note that the regression curves for the experimental data and the regression curve for the analytical data are quite similar.

Fig. 12 depicts the relationship between the pulling velocity and the resulting experimental and analytical maximum height of the diffusion cone. At a pulling velocity greater than 10 cm/s, the maximum height is nearly constant regardless of the table surface material, but when comparing the regression curves, the use of the UHMWPE plate (which has a smaller coefficient of friction) generally results in a smaller maximum height. Though the analysis results also indicate a nearly constant maximum height at pulling velocities greater than 10 cm/s, the maximum height predicted is smaller than the experimentally determined values. It is inferred from this result that because the table surface friction is neglected in the analysis, the smaller the table surface friction, the smaller the maximum height of the diffused cone.

Clearly, though quantitatively small differences in diffusion cone geometry were obtained, qualitatively speaking, when comparing the shapes of the regression curves, the SPH analysis very nearly reproduced the observed experimental behavior.

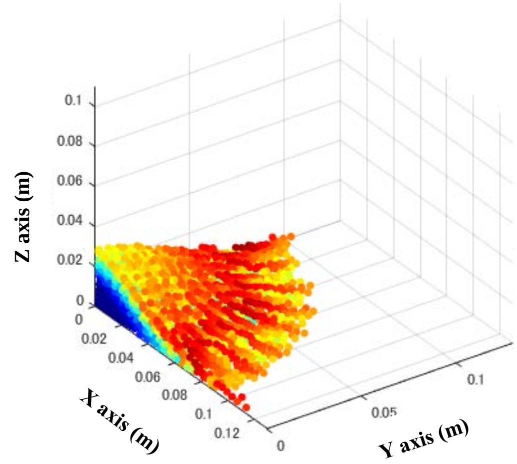

Fig.10. An example of analysis result

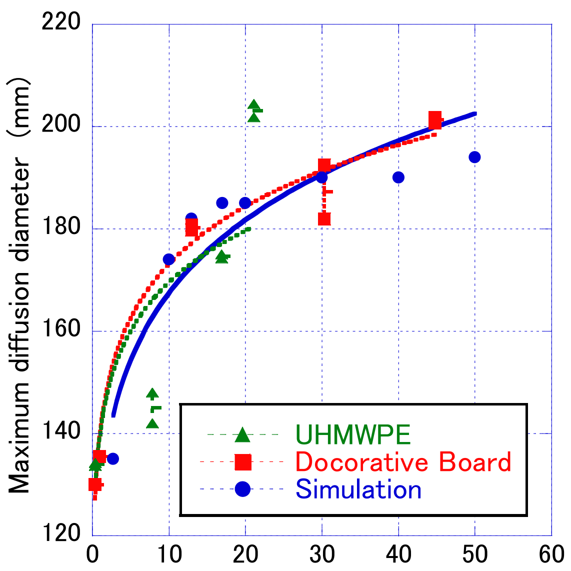

Fig.11 Relationship between pulling velocity and maximum diffusion diameter

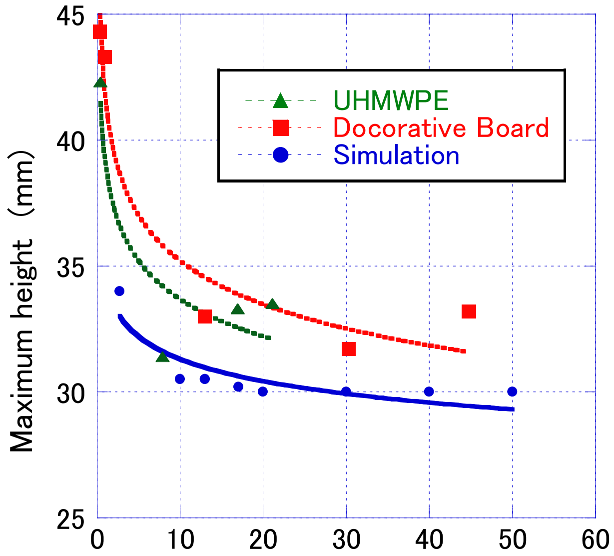

Fig.12. Relationship between pulling velocity and maximum height

Table 3 Comparison of analytical and experimental results

Exp. no.	Max. diffusion diameter (mm)			Max. height (mm)	Pulling velocity (cm/s)
	X axis	Y axis	Ave.		
A-1	—	—	194※	30.0	50.0
B-9	202	201	201	33.2	44.8
A-2	—	—	190※	30.0	40.0
B-4	182	193	187	31.7	30.3
A-3			190※	30.0	30.0
B-1	195	186	191	39.3	24.5
B-7	204	202	203	33.5	21.1
A-4	—	—	185※	30.0	20.0
A-5	—	—	185※	30.2	17.0
B-8	175	175	174	33.3	16.9
A-6	—	—	182※	30.5	13.0
B-10	181	180	180	33.0	13.0
B-2	148	142	145	31.4	7.9
A-7	—	—	174※	30.5	10.0
A-8	—	—	135※	30.4	2.7
B-5	136	136	136	43.3	0.9
B-3	134	134	134	42.3	0.4
B-6	130	130	130	44.3	0.3

Note: A: Analytical case; B: Experimental case

5. CONCLUSION

In this study, the collapse behavior of a simple cylindrical specimen was reproduced and analyzed using an SPH analysis accounting for the physical properties of the experimental samples. A parametric study was then conducted by changing the pulling velocity of the cylindrical container. By comparing the results of the experiment and analysis, the accuracy of the three-dimensional SPH analysis method was verified. The following conclusions were obtained:

1) It was confirmed that the diffusion cone shape of a cylindrical specimen after collapse differs depending on the table surface material and the container pulling velocity.
2) It was confirmed that the three-dimensional SPH analysis of a cylindrical specimen provides consistent and circumferentially symmetric results, yielding particle displacements that were nearly the same value in different angular directions.
3) It was confirmed that the change in pulling rate could be accurately expressed by the three-dimensional SPH analysis in terms of changes in the diffusion cone geometry.
4) The results of the three-dimensional SPH analysis and the experiments provided roughly the same maximum diffusion diameters for different pulling velocities, indicating that the accuracy of the three-dimensional SPH analysis is high.
5) When the pulling velocity was relatively slow, the same values for maximum height were obtained from both the three-dimensional SPH analysis and the experimental results, and when the velocity was high, the maximum height predicted by the SPH analysis was smaller, but qualitatively similar in trend to that determined by experiment.

In future work, the authors will investigate the effects of a wider variety of table surfaces and cylinder friction conditions, conduct further verification of the SPH method, and attempt to apply it to the analysis of slopes and tunnels.

6. REFERENCES

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