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Division III

A PRACTICAL EVALUATION METHOD FOR THE IMPACT RESPONSES OF A PROJECTILE AGAINST SURFACE SOIL

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ABSTRACT

We conducted a simulation analysis using a three-dimensional FEM for a drop-weight impact test in which weights were dropped on a reinforced concrete slab specimen covered with buffering materials, with an aim of establishing a numerical analysis method that is able to handle collision events, such as crash, penetration, and denudation which underground structures might be subject to. First, we conducted a parametric study to investigate yield criterion of buffering materials (sandy soil and gravel) based on the Mohr-Coulomb criterion, focusing on the dilatancy angle of the material. However, the deformation of the buffering material in the test was not simulated well by conventional FE analysis, and therefore we introduced a Smoothed Particle Hydrodynamics (SPH) model to describe the large deformation of the buffering material. Furthermore, we proposed a hybrid model of SPH and FEM in order to evaluate vibration of the soil more accurately, and determined a SPH modeling region required for the analysis.

INTRODUCTION

The Sept.11, 2001 terrorist attacks on the US have drown public attention to the potential for an airplane crash risk to nation's important facilities, including nuclear power plants. In Japan, the new regulatory requirements for nuclear power plants were established in 2013, which require nuclear power plants to be robust and can withstand against an airplane crash. As a result, Specialized Safety Facilities are going to be built supplementarily in nuclear power plant sites and some of them are underground.

However, the impact force resistant design for the underground facilities are generally performed conservatively without considering the resistant capacity of surface soil upper and around the facilities, because the quantitative evaluation of surface soil behaviour such as penetration or scraping against impact force is under developing stage.

In this study, a practical evaluation method regarding impact force of a projectile, penetration or scraping depth of surface soil is being discussed for the rational impact force resistant design of underground facilities, using 'Large-scale drop-weight impact test of sand cushion and gravel cushion' (Yamaguchi *et al*, 2014) as a base.

FE Analysis for Simulation of the Drop-Weight Impact Test by using Mohr-Coulomb Elastic-Plastic Configuration Rule

We conducted a simulation analysis for a drop-weight impact test using the Mohr-Coulomb yield criterion, which is considered as the most basic and prevalent in the constitutive laws describing failure of surface soil materials. In this study, we assumed that impact force and penetration or scraping depth are defined by relationship between slip line and plastic strain-increment direction after shear yielding zone was formed in the soil. As the plastic strain-increment direction is defined by the dilatancy angle of the soil, we focused on the dilatancy angle and investigated how to set it.

Analysis FE Models for the Drop-Weight Impact Test

In order to verify the validity of the crash analysis using the Mohr-Coulomb yield criterion, a FEM analysis was performed for the drop-weight impact test of Yamaguchi *et al.*. In this test, a metal weight of 5 tons was dropped from a height of 5 meters on the specimen, which is a reinforced concrete slab of 5m square and 500mm thick covered with buffering materials (sand or gravels) of 500mm thick, and then the impact and the penetration quantity of the weights were measured. Table 1 shows the test cases that was applied, and Figure 1 illustrates the analysis model (one-quarter symmetric model), where the buffering materials are modeled as a Mohr-Coulomb elastic-plastic material, and for the others, as elastic bodies. The software package we used was LS-DYNA 9.0.

Table 1: Test Cases for Simulation Analyses

	Thickness of Buffering Material [mm]	Drop Height [m]	Input Energy [kJ]	Thickness of Compaction [mm]
Gravels	500	5	245.2	250 + 250
Sandy Soil	500	5	245.2	250 + 250

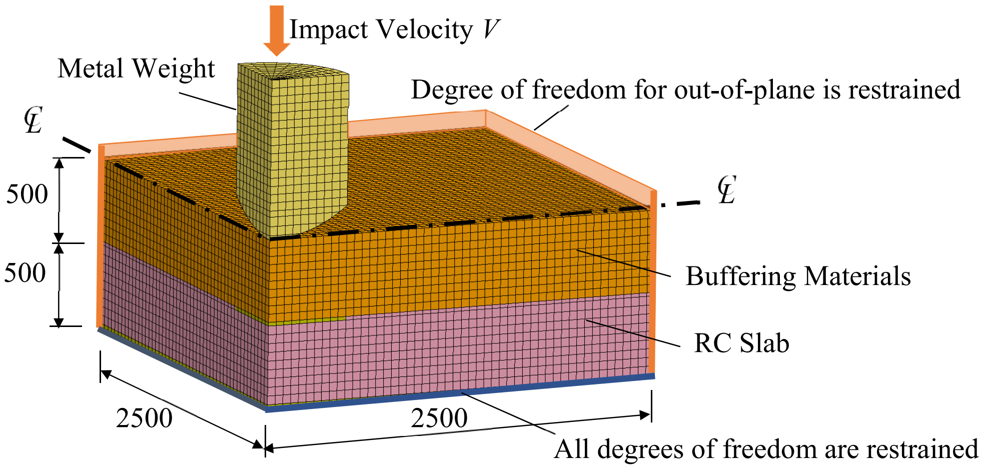


Figure 1. Analysis Model [unit: mm]

Consideration of Determination of parameters of Material Constitutive Equation

The Mohr-coulomb yield function f can be written as the following equation based on principal stress formulation. This function regards compressive stress as positive.

$$f = \tau - c - \sigma_n \tan\varphi \tag{1}$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2}\cos\varphi \tag{2}$$

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\sin\varphi \tag{3}$$

where φ is the internal friction angle, τ is the shear stress, c is the cohesion, σ_n is the normal stress on a plane that shear stress acts on, σ_1 is the maximum principal stress, and σ_3 is the minimum principal stress.

Since N-values and the values of φ had not been clear, we regarded the values of φ of sandy soil and gravels as 35 degrees and 45 degrees respectively by giving them the values of φ of sandy soil and gravels that is provided for in the Japanese Fire Service Act. Moreover, we calculated N-values based on the values of φ, and determined the Young's modulus E from the N-values referring to Japanese AIJ Recommendations for Design of Building Foundations.

$$N = \frac{(\varphi - 20)^2}{20} \text{ [unit of } \varphi \text{ : degree]} \tag{4}$$

$$E = 2.8N \text{ [kN/m}^2\text{]} \tag{5}$$

Representative values of Poisson's ratio and c are generally known for each material. In this study, Poisson's ratio of approximately 0.3 and c of 0 are employed for sandy soil.

Dilatancy angle ψ is the angle between slip line and plastic strain-increment direction in simple shear. At ground failure event, plastic deformation occurs nearly parallel to the slip line and its volume change is relatively small, therefore, non-associated flow rule is assumed to be relevant in this case.

Plastic potential g is written as the following equation using dilatancy angle.

$$g = \tau - c - \sigma_n \tan\psi \tag{6}$$

In this study, results of triaxial compression tests conducted in known study are used to calculate based on the following equation in order to research the possible range of ψ. The result of research is shown in Table 2.

$$\psi = \sin^{-1}\left(\frac{\beta}{-2+\beta}\right),\ \beta = \frac{d\varepsilon_v}{d\varepsilon_a} \tag{7}$$

where ε_v is volumetric strain, and ε_a is axial strain. Note that the equation is arranged considering ψ as a constant instead of a variable due to the average dilatancy characteristics.

In this research, sandy soil and gravels tend to show ψ of 5 to 15 degrees, which indicates occurrence of plastic strain-increment nearly parallel to slip line in ground and rocks as well as in metallic materials. Regarding this result, the uniform dilatancy angle of 10 degrees is assumed in this study.

Table 2. Bibliographic Survey on ψ

Reference	Specimen	ψ [degree]
Yamauchi *et al.*	Sand	2.7 ~ 13.3
Takahashi *et al.*	Gravel	6.7 ~ 13.3
Nakagawa	Gravel	7.5 ~ 15.0
P. A. Vermeer	Sand	15
	Gravel	12.0 ~ 20

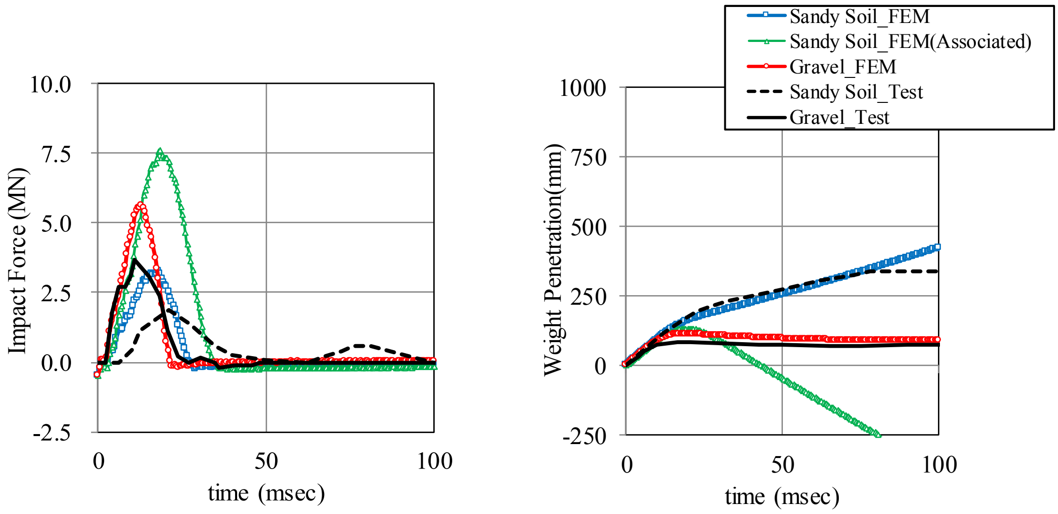
Determination of parameters of Material Constitutive Equation and Analysis Results

Parameters and conditions used in analyses are shown in Table 3. Analyses were performed for 100msec from just before the impact of drop-weight. Analysis results are shown in Figure 2. Each result shows slightly overestimated impact force but rather accurate penetration depth of drop-weight reproducing experimental tendency.

Results using associated flow rule are also expressed in the figure for comparison. Deformation diagram of sandy soil at 50msec is shown in Figure 3. Associated flow rule does not express the phenomenon in terms of impact force and penetration depth of drop-weight. Especially, associated flow rule showed the results that the drop-weight bounced at a shallow depth when originally drop-weight should deeply penetrate, which may lead to non-conservative design.

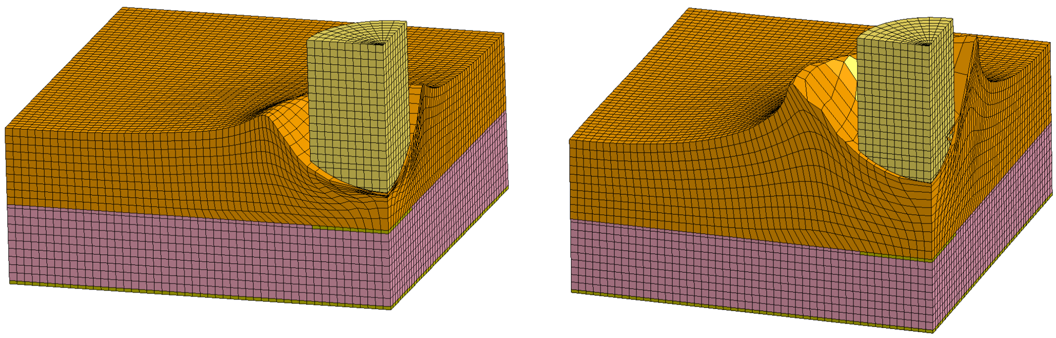
Table 3: Case of Experiments for Simulation Analyses

		FE Model for Sandy Soil	FE Model for Gravel
Buffering Materials	Material	Sandy Soil	Gravel
	φ (degree)	35.0	45.0
	Elastic Modulus (MN/m^2)	31.5	87.5
	Poisson's Ratio	0.3	0.3
	ψ (degree)	10	10
	c (kN/m^2)	0.0	0.0
	Density (t/m^3)	1.6	2.2
RC Slab	Elastic Modulus (MN/m^2)	20,000	
	Poisson's Ratio	0.167	
	Density (t/m^3)	1.96	
Steel	Elastic Modulus (MN/m^2)	206,000	
	Poisson's Ratio	0.3	
	Density (t/m^3)	7.85	
Boundary Condition between Drop-Weight and Buffering Materials		Contact Definition: Penalty Method Coefficient of Friction: 0	
Boundary Condition between Buffering Materials and RC Slab		Rigid Connection by Sharing Nodes	
Initial Velocity of Drop-Weight (m/sec)		9.90285 downward (Equivalent to the speed when dropped from height of 5m)	
Mass of Drop-Weight (t)		5.0* (5.0/4 in this case because the model is one-quarter in size)	



(a) Impact Force (b) Penetration Depth of Drop-Weight

Figure 2. Analysis Result (Time History)



(a) ψ =10° (Non-associated) (b) ψ =35° (Associated)

Figure 3. Deformation Diagram of Sandy Soil Model (Magnification 1.0, at 50*msec*)

Simulation Analysis of Drop-weight Impact Test Using SPH-FE Hybrid Model

FE analysis performed in this study showed reasonable results for impact forces and penetration depths which reproduce the tendency of the test results. However, the results could not reproduce the actual deformation, for instance, buffering materials elements at the tip of drop-weight were crushed and distorted. Also, the deformation mode became crater-like shape. This may due to the incapability of elements following large deformation at impact event by conventional FEM.

Regarding above mentioned problems, Smoothed Particle Hydrodynamics (SPH) evaluated in our past study was applied to the drop-weight impact test and the usability of the method were evaluated.

Analysis Model for SPH

SPH analysis was performed for the drop-weight impact test of Yamaguchi *et al.* as in the FE Analysis. Analysis model (one-quarter symmetric model) used in this study is shown in Figure 4. The region of buffering materials is modelled by SPH particles due to large deformation is expected. The region of RC slab was modelled by FE model. Buffering materials are modelled as Mohr-Coulomb elastic-plastic materials, and others as elastic materials. Analysis conditions are the same as pre-studied FE analysis models.

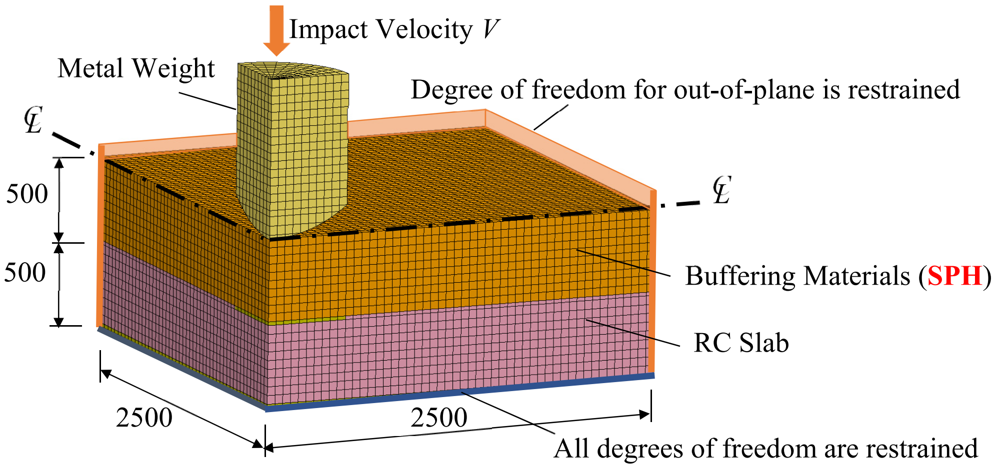
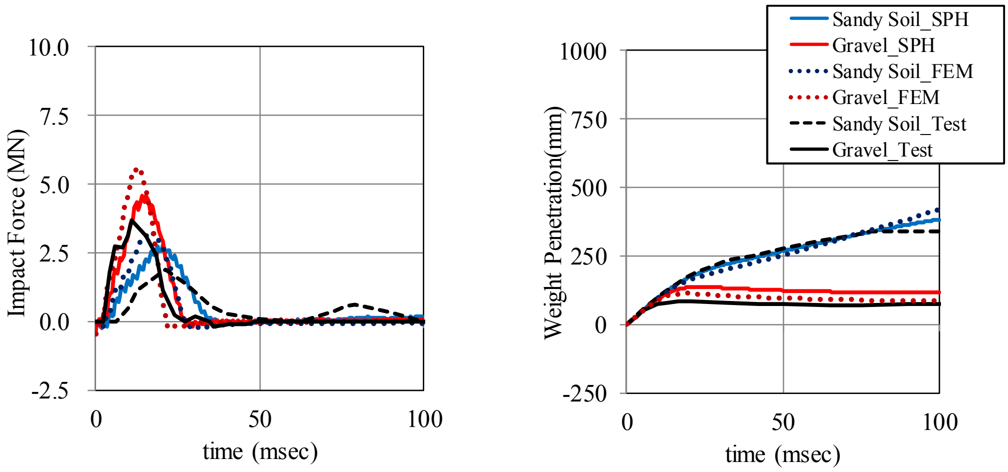


Figure 4. Analysis Model for SPH [unit : mm]

Analysis Results for SPH Model

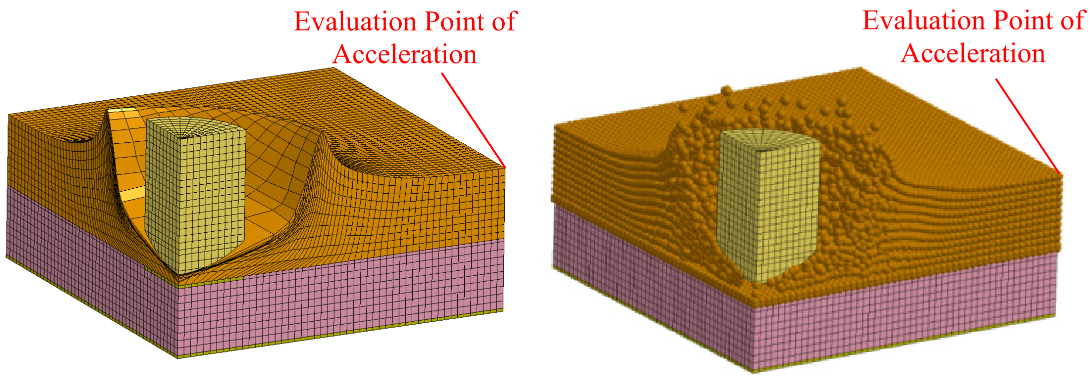
Analysis was performed for 100msec from just before the impact of drop-weight. Time history responses of impact force and penetration depth are shown in Figure 5. Both impact force and penetration depth of drop-weight have reproduced the test tendency well. Deformation diagram of sandy soil model at 100msec is shown in Figure 6. While buffering materials elements at the tip of drop-weight are crushed and showed unnatural deformation in FE model, penetration of drop-model was well expressed, and sandy soil portion was scattered upwards in SPH model. From the above results, SPH model is capable of evaluating impact force and penetration depth of drop-weight as well as FE model, in addition, it is also able to evaluate deformation modes.

However, SPH model has some demerits. The accelerogram in vertical direction at evaluation point of acceleration in Figure 6 is shown in Figure 7. Acceleration response of SPH model does not include high frequency component, and the phase at peak is delayed. The reason for above is that weighted averaging of surrounding particles is used in SPH method to solve a motion equation, which causes resolution declines of deformation compared to FE method.



(a) Impact Force (b) Penetration Depth of Drop-Weight

Figure 5. Comparison of SPH Model Analysis Results and Test Results (Time History)



(a) FEM (b) SPH

Figure 6. Deformation Diagram of Sandy Soil Model at 100*msec* (Magnification 1.0)

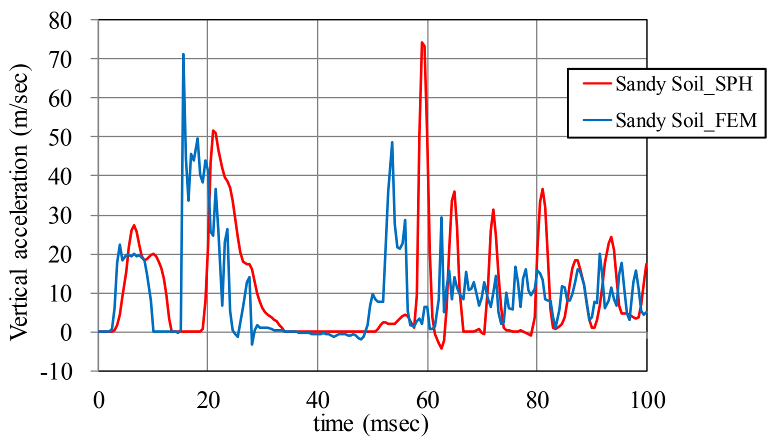
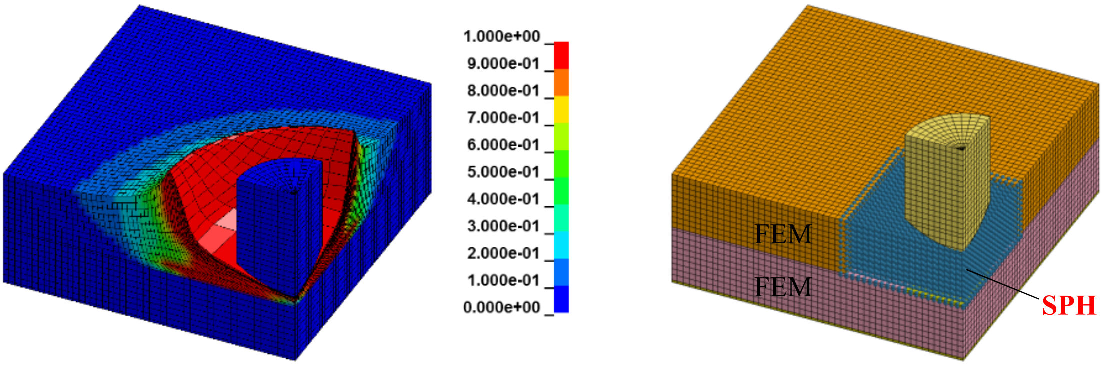


Figure 7. Accelerogram of SPH Model and FE Model at Evaluation Point (Vertical Direction)

FE Model with Partially Employed SPH

It is desirable to employ a reasonable modeling technique which secures high resolution as for vibration, in order to evaluate the transmission of vibration through ground properly. Therefore, a hybrid model in which SPH method was applied to the region where large deformation is expected, FEM to the rest of model was analysed (hereinafter referred to as "SPH+FEM"). In this study, "large deformation" is defined as maximum shear strain exceeding 1.0: the region was set as shown in Figure 8.



(a) Maximum Shear Strain Contour (Magnification 1.0 at 100*msec*)

(b) SPH Applied to Region with Large Strain

Figure 8. FE Model Diagram with SPH Method Applied to Region with Large Strain

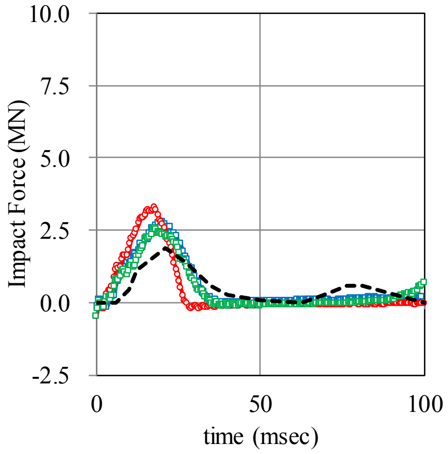
Time histories of impact force and drop-weight penetration depth of SPH + FEM are shown in Figure 9. Impact force shows nearly the same results as in SPH model. As for drop-weight penetration depth, reproducing of test results was mostly achieved; however, final deformation obtained in SPH + FEM was slightly larger than in SPH model. Regarding larger deformation, it can be said that more conservative results are obtained by this method. Deformation diagrams at 100msec using SPH + FEM and SPH model are shown in Figure 10 (a). As shown in this figure, SPH + FEM can express drop-weight penetration depth as well as in SPH model. Accelerograms are shown in Figure 10 (b). SPH + FEM shows the tendency nearly equal to the accelerogram in FE model, including high-frequency component.

From above study, rational simulation can be achieved considering merits and demerits of both SPH and FE methods by using both methods appropriately.

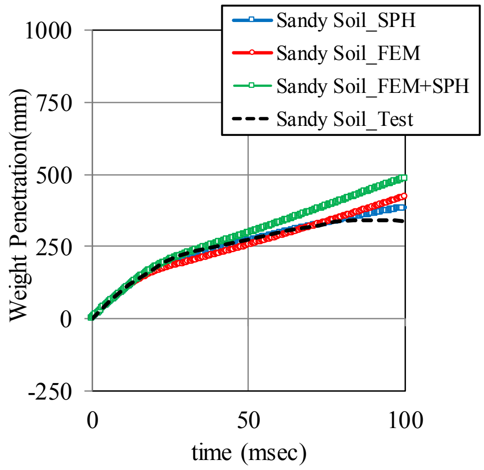
CONCLUSION

In this study, simulation analyses for a drop-weight impact test using the Mohr-Coulomb yield criterion, especially focusing on the setting method of dilatancy angle were conducted. As a result, dilatancy angle of soil materials was approximately 10 degrees. Simulation analysis for a drop-weight impact test with dilatancy angle of 10 degrees was capable of reproducing the test tendency well.

Subsequently, in order to improve the reproducibility of large deformation, impact analysis using SPH method was performed. Applicability of hybrid model of SPH and FEM was investigated; SPH model was improved as a result of the investigation. However, FE analysis is necessary to determine the size of a region to where SPH method is applied at this moment and therefore modeling requires time and effort. Furthermore, applicability of the model with penetration angle other than vertical direction or impact at higher speed range is not considered in this study. These will be future subjects.

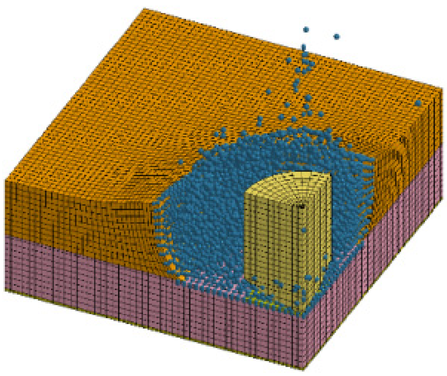


(a) Impact Force

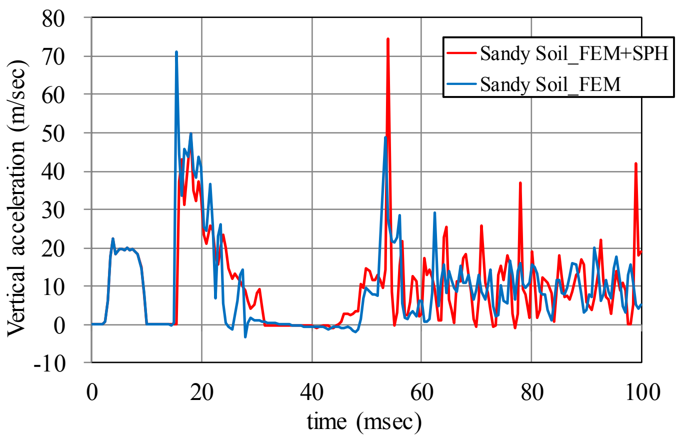


(b) Penetration Depth of Drop-Weight

Figure 9. Comparison of Analysis Results for SPH + FEM and SPH Model (Time History)



(a) Deformation Diagram
(Magnification 1.0, at 100*msec*)



(b) Accelerogram

Figure 10. SPH + FEM Analysis Results

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