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Experimental Study on Soil Penetration Evaluation Against Rigid Missile Impacts (2) Evaluation and Simulation Analyses of Test Results

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ABSTRACT

The objective of these series of studies is to evaluate soil penetration behavior against rigid missile impacts. This paper shows the evaluation and simulation analyses based on the test results obtained by the previous paper Part 1.

First, compared to the test results, the penetration equations into the soil proposed by Young (1969) are considered to conservatively evaluate for the penetration depth into the soil. In addition, regarding the relationship between penetration depth and impact velocity, Young's formula defined in the low-speed range show good agreement with the test results.

Next, the simulation analyses based on test results are performed using the CEL (Coupled Eulerian Lagrangian) modelling method. Numerical results to model homogenous dry fine sand by Eulerian element show quite good agreement with the test results. For example, simulation analyses can trace the skidding behavior observed in low impact angle tests. Regarding the relationship between penetration depth and impact velocity, numerical results using the CEL method also show good agreement with the test results that is similar to Young's formula defined in the low-speed range.

INTRODUCTION

Present structural evaluations for underground structures against missile impacts in Japan conservatively consider the penetration depth into the soil against rigid missile impacts using the empirical equation proposed by Young, C.W (1969) called Young's formula in the following, because there are no assessment methodologies for soil impacts in NEI07-13 [Revision 8P] (2011). But the detailed information and the influence are not clear regarding the soil properties and the impact angle in the test data for Young's formula.

Based on the above background, this paper first shows the applicability of Young's formula compared to the maximum penetration depth into the soil evaluated from many penetration tests into the soil against rigid missile impacts with varied soil properties, impact angles and impact velocities obtained by the previous paper Part 1.

Next, simulation analyses based on typical test results are performed using the CEL (Coupled Eulerian Lagrangian) modelling method. Validation of the above numerical method is also confirmed through those simulation analyses from the viewpoint of future real-scaled numerical experiments.

EVALUATION

In this section, the applicability of Young's formula is shown compared to the maximum penetration depth into the soil evaluated from many penetration test into the soil against rigid missile impacts with varied soil properties, impact angles, and impact velocities obtained by the previous paper Part 1.

Young's Formula

Young's formula to evaluate the penetration depth into the soil against rigid missile impacts is the empirical equation proposed by Young, C.W (1969) with variables such as soil constant, nose performance coefficient, missile weight, missile cross-sectional area, and impact velocity shown in equation (1) and equation (2).

$$\begin{aligned} &Z = 0.53SN(W/A)^{0.5}\ln(1+2V^2\times10^{-5}) \\ &V < 200\,ft/s \end{aligned} \tag{1}$$

$$\begin{aligned} &Z = 0.031SN(W/A)^{0.5}(V-100) \\ &V \geq 200\,ft/s \end{aligned} \tag{2}$$

Here,
Z : Penetration depth into the soil (ft)
S : Soil constant
N : Nose performance coefficient (Spherical shape: 0.65)
W : Missile weight (lbf)
A : Missile cross-sectional area (in^2)
V : Impact velocity (ft/s)

For the features in Young's formula, while equation (1) defined as the smaller impact velocity shows that penetration depth into the soil increases lognormally relative to the square of the impact velocity, equation (2) defined as the larger impact velocity shows that penetration depth into the soil increases linearly relative to impact velocity. Therefore, the sensitivity on penetration depth to impact velocity in equation (1) is smaller than that in equation (2), and the transition point between equation (1) and equation (2) is determined based on a lot of test results.

In addition, while penetration depth into the soil increases linearly relative to the soil constant in both equation (1) and equation (2), a qualitative and very limited classification table for various soil types is only given to decide soil constant values. In particular, the relationship between the soil constant and soil material properties such as soil density, soil stiffness and soil strength, is not clear in Young, C.W (1969). For example, the soil constant for fine sand used in this study is supposed to be 8 to 12 (median 10). As a reference, the soil constant for coarse sand and gravel is supposed to be 2 to 3 (median 2.5) and the soil constant for medium to coarse sand is also supposed to be 4 to 6 (median 5). The above soil constant values are given by Bernard, R.S. and Creighton, D.C. (1979).

Comparison and Discussion with Test Results

Comparison of penetration depth into the soil obtained by test results and Young's formula is shown in Figure 1. Penetration depth into the soil obtained by test results is evaluated to be the maximum penetration depth. The penetration depth into the soil obtained by Young's formula is calculated from three soil constant values of S=2.5, S=5.0 and S=10.0.

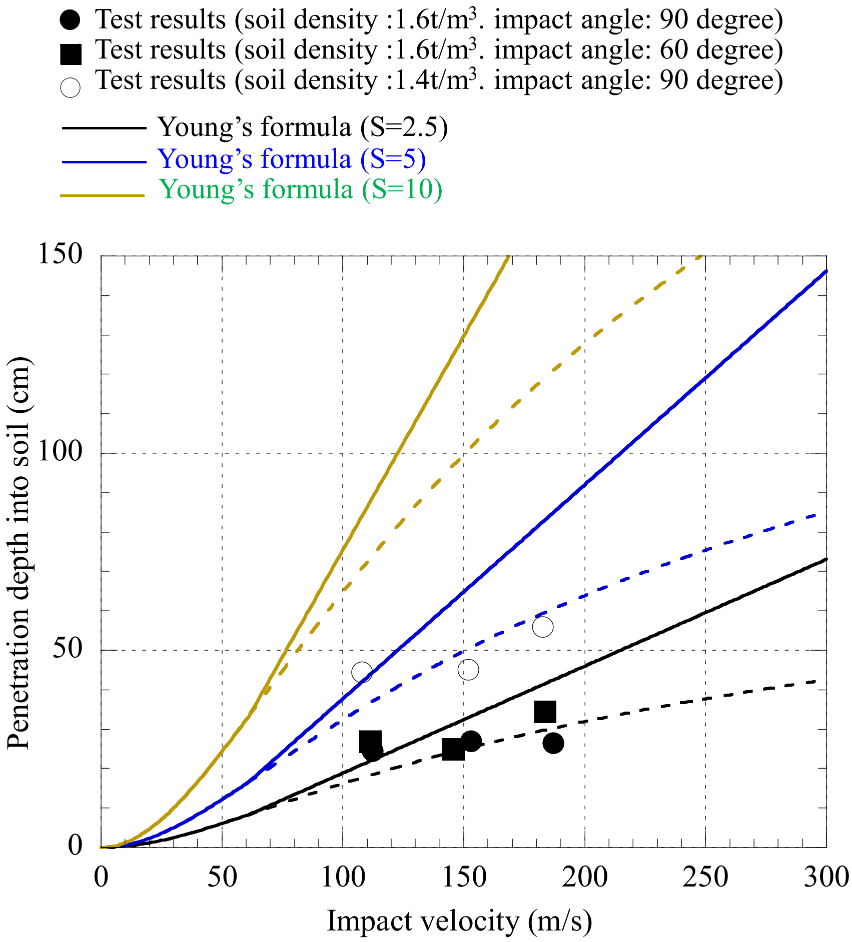


Figure 1. Comparison of penetration depth into the soil obtained by test results and Young's formula.

As a result, penetration depth into the soil obtained by test results for soil density of 1.6t/m^3 with compaction is slightly smaller than that by Young's formula calculated from the soil constant value S=2.5 corresponding to coarse sand and gravel according to the classification table by Bernard, R.S. and Creighton, D.C. (1979).

On the other hand, the penetration depth into the soil obtained by test results for soil density of 1.4t/m^3 without compaction is slightly smaller than that by Young's formula calculated from the soil constant value S=5.0 corresponding to medium to coarse sand according to the classification table by Bernard, R.S. and Creighton, D.C. (1979).

The above reason is why Young's formula is supposed to be derived conservatively and the grain diameters of the soil in real scale are converted to 10 to 20 mm corresponding to medium to coarse sand based on the scaling law shown in the previous paper Part 1 while homogenous dry fine sand in a grain diameter of 0.2 to 0.4 mm is used for soil specimens in penetration tests against small-scaled rigid missile impacts.

As a reference, the penetration depth into the soil obtained by Young's formula calculated from only equation (1) defined in smaller impact velocity is shown in a broken line. Comparing to Young's formula calculated from only equation (1) and the test results, transition point between equation (1) and equation (2) given in Young's formula seems to be greater impact velocity. Therefore, Young's formula is supposed to be derived conservatively regarding the transition point.

SIMULATION ANALYSES OF TEST RESULTS

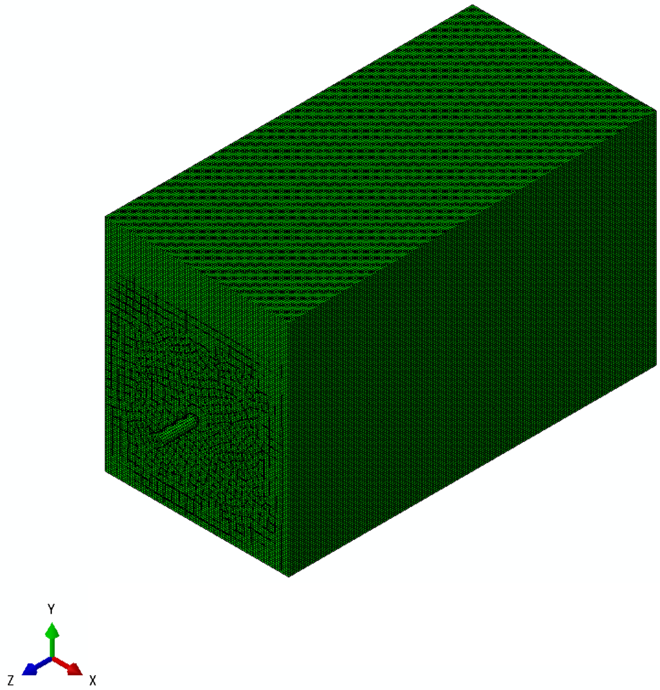
In this section, simulation analyses based on typical test results are performed using the CEL (Coupled Eulerian Lagrangian) modelling method. Validation of the above numerical method is also confirmed through those simulation analyses from the viewpoint of future real-scaled numerical experiments.

Numeral Method and Numerical Model

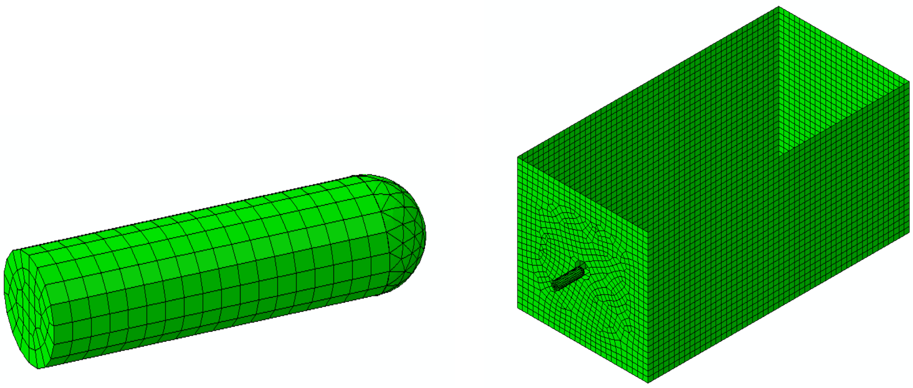
The numerical method for simulation analyses based on typical test results is used with the CEL modelling method that can trace fluid behavior of homogenous dry fine sand in the tests more accurately and can give relatively smaller sensitivity to element or grid size than the particle method such as the SPH (Smoothed Particle Hydrodynamics) modelling method.

It is suitable for the CEL modelling method to simulate the problems regarding large deformation, fractures, and penetration that are not numerically treated in the Finite Element modelling method because the CEL modelling method can consider material deformation as not necessary to avoid the skewness and distortion of elements that become general controversial problems in finite element modelling.

In the simulation analyses, homogenous dry fine sand is modelled by the Eulerian element and the rigid missile is modelled by the Lagrangian rigid solid element. Also, a reservoir for containment of the soil specimens is modelled by the Lagrangian rigid shell element. Numerical models for simulation analyses are shown in Figure 2.



(a) Whole numerical model



(b) Missile model (Left) and reservoir model (Right)

Figure 2. Numerical models for simulation analyses.

Material Property of the Soil Specimen

Soil specimens for simulation analyses are supposed to be basic soil cases such as soil density of 1.6 t/m^3 with compaction. Material constitutive characteristics for the soil are subjected to the Mohr-Coulomb plastic model and the material properties are shown in Table 1. Furthermore, for the case of an impact angle of 20 degrees, the internal friction angle is set to be a smaller value than given in Table 1 considering the smaller weight of the surface layer of the soil.

Table 1: Material properties of the soil specimens.

Soil density (t/m^3)	Young's modulus (kN/m^2)	Poisson's ratio (-)	Cohesive strength (kN/m^2)	Internal friction angle (degree)
1.6	5.00×10^4	0.4	0	20

Simulation Cases and Numerical Code

As described before, simulation analyses are performed with basic soil cases such as soil density of 1.6 t/m^3 compacted and an impact angle of 90 and 20 degrees as shown in Table 2. Commercial finite element code Abaqus2017 HF5 is used as a numerical code for simulation analyses.

Table 2: Simulation Cases.

Test Case	Impact velocity (m/s)	Impact angle (degree)	Soil density (t/m^3)
1	187	90	1.6
2	153	90	1.6
3	112	90	1.6
7	185	20	1.6
8	110	20	1.6

Outline of Simulation Results

Simulation results with the CEL modelling method for typical simulation cases are shown in the following. Simulation results for test case #1 are shown in Figure 3 and Figure 4 regarding penetration behaviors of missiles into the soil and the maximum principal strain distribution of the soil. The simulation result of an impact angle of 90 degrees shows that the missile penetrates into the soil not only in the horizontal direction but also in the vertical direction that is similarly observed in the test results.

Next, the simulation result for test case #7 is shown in Figure 5 regarding the penetration behavior of missiles into the soil and the maximum principal strain distribution of the soil. The simulation result of an impact angle of 20 degrees shows that the missile is skidding on the soil that is similarly observed in the test results.

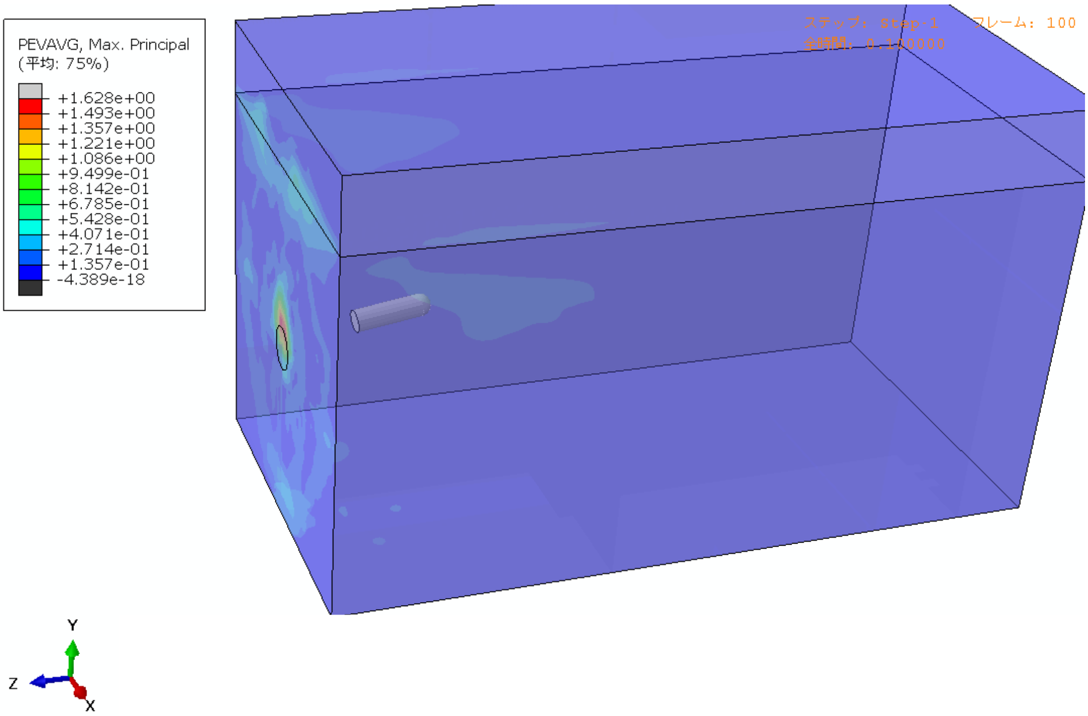


Figure 3. Penetration behavior of missiles into the soil in the termination time of analysis and maximum principal strain distribution of the soil.
(Test case #1, time 0.1 s)

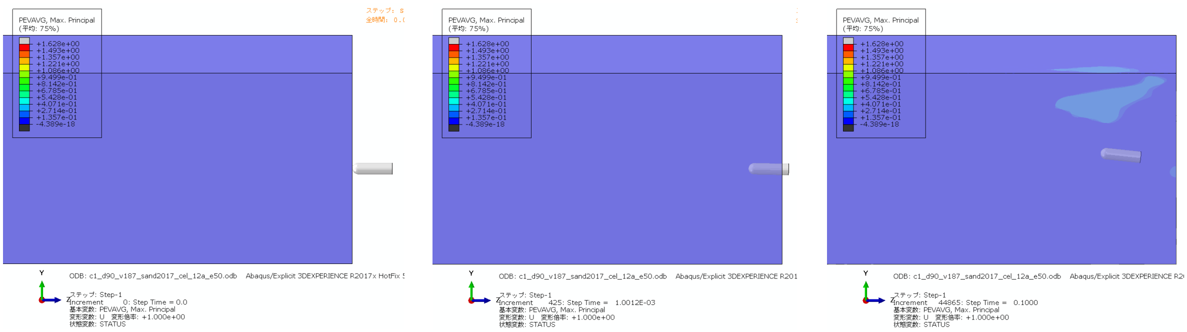


Figure 4. Snapshots of penetration behavior of missiles into the soil in the termination time of analysis and maximum principal strain distribution of the soil.
(Test case #1, time 0 s: Left, time 1 ms: Middle, time 0.1 s: Right)

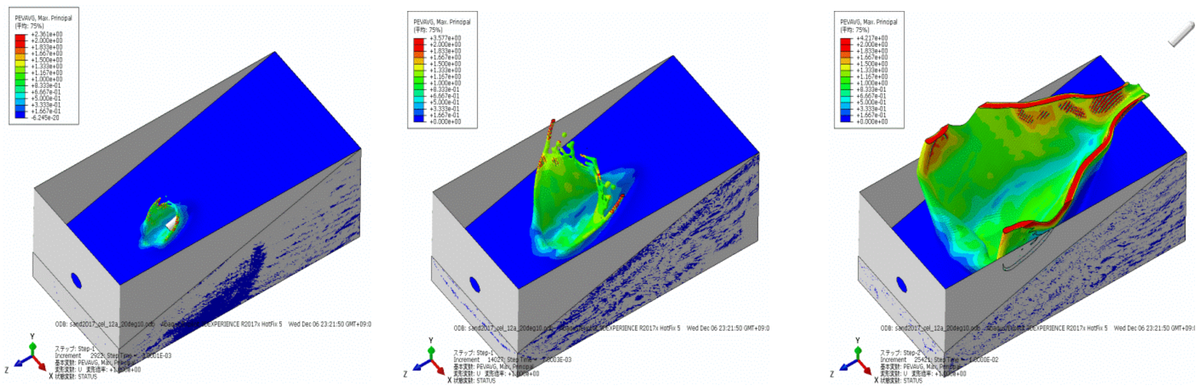


Figure 5. Snapshots of penetration behavior of missiles into the soil in the termination time of analysis and maximum principal strain distribution of the soil.
(Test case #7, time 3 ms: Left, time 7 ms: Middle, time 10 ms: Right)

Comparison and Discussion with Test Results

Comparison of the penetration depth into the soil obtained by the test results and simulation results with the CEL modelling method is shown in Table 3. As a result, simulation analyses can trace overall failure patterns of the soil in test results with satisfactory accuracy considering the various uncertainties in the severe nonlinearity of the soil specimens, although the penetration depth into the soil in simulation results is slightly smaller than that in the test results.

Table 3: Comparison of penetration depth into the soil obtained by test results and simulation results.

Test Case	Penetration depth into the soil (cm)					
	Test results			Simulation results		
	Horizontal	Vertical	Maximum	Horizontal	Vertical	Maximum
1	21.0	5.5	26.5	19.3	4.1	23.4
2	24.0	3.0	27.0	17.4	3.1	20.5
3	21.0	3.0	24.0	13.6	2.0	15.6
7	Skidding			Skidding		
8	Skidding			Skidding		

Furthermore, as reference, a comparison of the residual velocity of the missiles obtained from test results and simulation results with the CEL modelling method is shown in Figure 6. Note that residual velocity of missile obtained by test is evaluated from high-speed video when an additional test is performed with streaky scale at back-end missile. As the result, while the simulation result shows good agreement with the test result until the time when the residual velocity of the missile drastically decreases, the residual velocity of the missile from the test results is slightly greater than that from the simulation analysis after that time. That is thought of as the one of the reasons why the penetration depth into the soil in simulation results is slightly smaller than that in the test results.

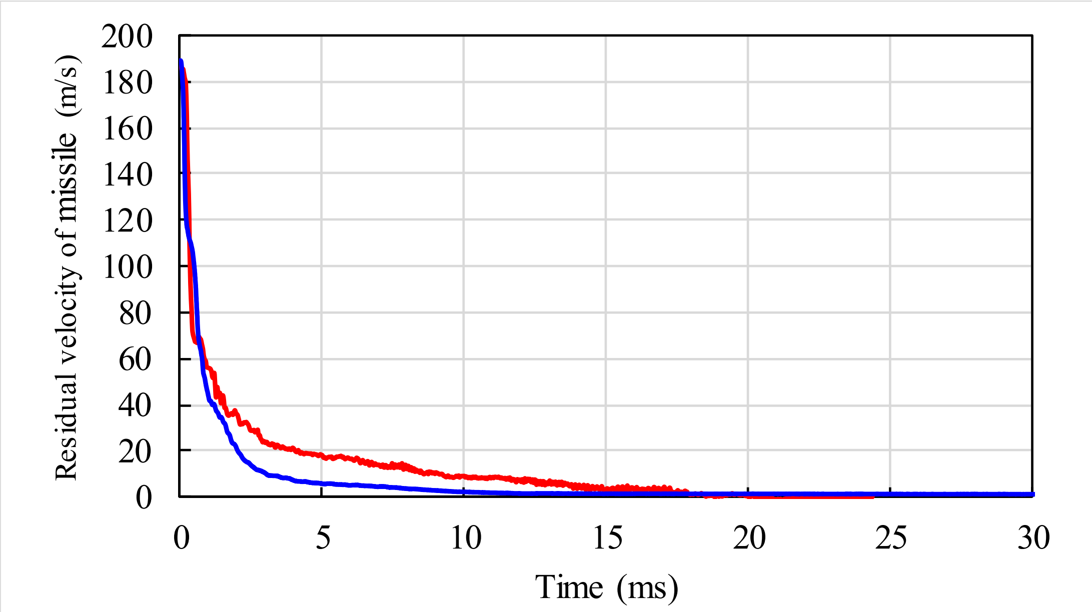


Figure 6. Comparison of residual velocity of missile.
(Test case #1, Red line: test result, Blue line: simulation result)

CONCLUSION

The objective of these series of studies is to evaluate soil penetration behavior against rigid missile impacts. This paper shows the evaluation and simulation analyses based on the test results obtained by the previous paper Part 1.

First, compared to test results, the penetration equations into the soil proposed by Young (1969) are conservatively evaluated for the penetration depth into the soil. In addition to that, regarding the relationship between penetration depth and impact velocity, Young's formula defined in the low-speed range show good agreement with the test results.

Next, simulation analyses based on the test results are performed using the CEL (Coupled Eulerian Lagrangian) modelling method. Numerical results to model homogenous dry fine sand by Eulerian element show quite good agreement with the test results. For example, simulation analyses can trace the skidding behavior observed in the low impact angle tests. Regarding the relationship between penetration depth and impact velocity, numerical results using the CEL method also show good agreement with the test results that is similar to Young's formula defined in the low-speed range.

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