



SEISMIC EVALUATION OF CIRCULAR SHAFT IN CENTRIFUGAL LOADING TEST USING 3D PRINTER MODEL AND IN REPRODUCTION ANALYSIS

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ABSTRACT

Critical civil engineering structures in nuclear power plants are generally designed so that the structure maintains its elastic state even during a large earthquake. In this research, centrifugal loading test of an underground shaft, a 3D printer model made of nylon 12, which has enough tensile strength, and reinforced bolts was manufactured to allow the model to exhibit elastic behavior even in a large earthquake, and its reproduction analysis was performed. In this paper, the effects of earth pressure and total horizontal force on structures during an earthquake were investigated and the validation of analysis in relation with soil and structure during a large earthquake was evaluated. The dense ground of an actual nuclear power plant was simulated with a dense sandy soil in the centrifugal loading test.

DESIGN OF 3D PRINTER MODEL MADE OF NYLON12

The main purpose of this study is to evaluate the loads such as soil pressure and inertial forces acting on structures that behave within the elastic range during earthquakes. Therefore, a 3D printed model of a circular shaft used in this study was created using nylon 12, which provides sufficient strength to simulate the shaft. Since nylon 12 is lighter and less rigid than the reinforced concrete, which is the actual structural material, it was combined with steel to design it to have approximately the same weight and rigidity as reinforced concrete.

The drawings and photos of the 3D printed model are shown in Figure 1. Additionally, the weight and rigidity achieved by combining nylon 12 with steel, as shown in Figure 1, are compared to the case where the model is made of reinforced concrete in Table 1. The 3D printed model of the shaft, created using nylon 12, was made to be roughly equivalent in weight by combining reinforcement steel plates and bolts, and its rigidity was adjusted to be approximately 50% of the initial rigidity of reinforced concrete, considering the non-linearity of reinforced concrete.

Figure 2 (b) shows the 3D analysis model of this PO test. The material properties used in this analysis are shown in Table 2. In the same way as PO test, the bottom end of this model was fixed, and horizontal concentrated force was loaded at the top end of the model. Figure 2 (c) shows the deformation of the 3D analysis model.

Figure 2 (d) shows the comparison of load-displacement relationships between PO test and 3D analysis of this test. At the 1st PO test, nonlinear behavior was seen because of the loosening of the bolts at the bottom end. At the 2nd PO test, by modifying the fixing method, linear load-displacement relationship was obtained appropriately. In this test, it was confirmed that the load-displacement relationship was consistent between the test and the analysis.

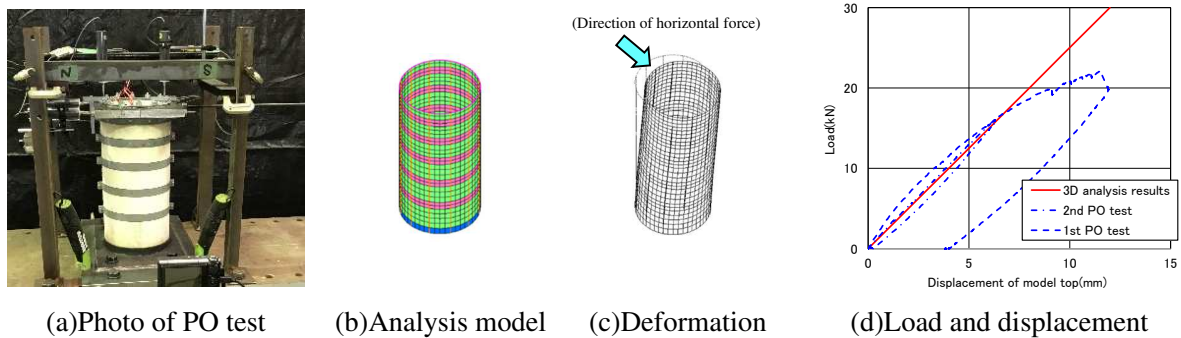


Figure 2. A photo and analysis results of a PO test

Table 2. Material properties used in PO analysis

	Young modulus E [N/mm ²]	Poisson's ratio ν	Density γ [t/m ³]
Nylon12 (Side wall of shaft)	1,710	0.354	0.99
Steel (Flat steels, Steel flange, Bottom plates and bolts)	200,000	0.30	7.85

CENTRIFUGAL LOADING TEST

The centrifugal load test was conducted at a 1/30 scale of the actual model, under a 30G centrifugal field. As shown in Figure 3, the experimental model consists of a circular shaft created by using a 3D printer and placed at the center of the soil. The shaft is surrounded by a dense sand layer (relative density $D_r = 90\%$) to simulate the typical ground conditions in which nuclear power facilities are constructed. The shaft model was installed on a cement-improved soil simulating the foundation layer, and the surrounding sand layer was divided into a liquefiable layer from the base with a depth of 340mm in model scale and a non-liquefiable layer from the ground surface with a depth of 130mm. Earthquake motions were applied in the order of Kobe wave and Tokachi wave, as shown in Figure 4. The measured table accelerations for both Kobe and Tokachi waves were approximately 13.9m/s^2 and 15.2m/s^2 at maximum in prototype scale, respectively. Measurements included acceleration, excess pore water pressure, displacement, earth pressure, structural strain, and acting load on the structure, with results recorded at various points shown in Figure 3.

Acceleration time histories for the ground and shaft are presented in Figure 5. A spike-like response, which is a characteristic response due to cyclic mobility in the saturated layer, was observed for both Kobe and Tokachi waves. The time histories of excess pore water pressure ratio (E.P.W.P.R.) at representative points are shown in Figure 6. Comparing the results between Kobe and Tokachi waves, the negative pore water pressure is more significant after the influence of Kobe wave shaking, demonstrating the behavior of cyclic mobility peculiar to dense sandy ground. Figure 7 displays the relationship between shear stress calculated from the acceleration distribution in the depth direction of the ground and the shear strain calculated from the displacement distribution in the depth direction of the soil layer at the center of the liquefiable layer. Particularly in the case of Tokachi wave shaking, the stiffness recovered when shear strain exceeded 2%, forming a reverse S-shaped curve, indicating a behavior characteristic of dense sandy ground. As previously mentioned, the excess pore water pressure ratio during shaking exceeded 1 throughout the liquefiable layer, generally indicating liquefaction, but the maximum shear strain remained around 3%.

Figure 8 shows the horizontal displacement distribution of the shaft, while Figure 9 illustrates the strain response time histories at the base of the shaft. The maximum horizontal displacement of the shaft was approximately 200mm, which corresponds to about 1.4% of the shaft height. Residual displacement was around 20mm, which is a small value, about 0.14% of the shaft height. The strain occurring at the base of the shaft reached a maximum of approximately 1700 μ , which is considerably smaller than the yield strain (approximately 10900 μ). This confirms that the structural response remained within the elastic range as intended by this experiment.

In Figure 10 a scatter plot of the ratio of inertial force to the total shear force acting on the shaft is shown. The total shear force is the sum of the horizontal loads from two load cells, while the inertial force is calculated by multiplying the mass of the shaft and potentiometers by the acceleration measured with accelerometers installed on the shaft. The percentage of inertial force to the total shear force is approximately 15% for both Kobe and Tokachi wave excitations, indicating that the inertial forces are relatively small, and the contribution of external loads, such as earth pressure, to the total shear force is significant.

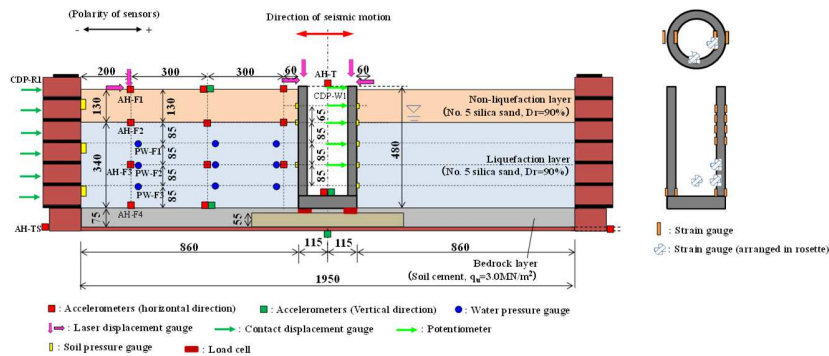


Figure 3. Model settings and arrangement of sensors of centrifugal loading test (1/30 model scale, unit: mm)

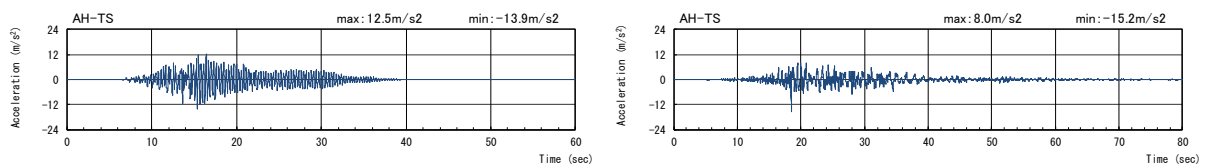


Figure 4. Measured table acceleration (left : Kobe, right : Tokachi)

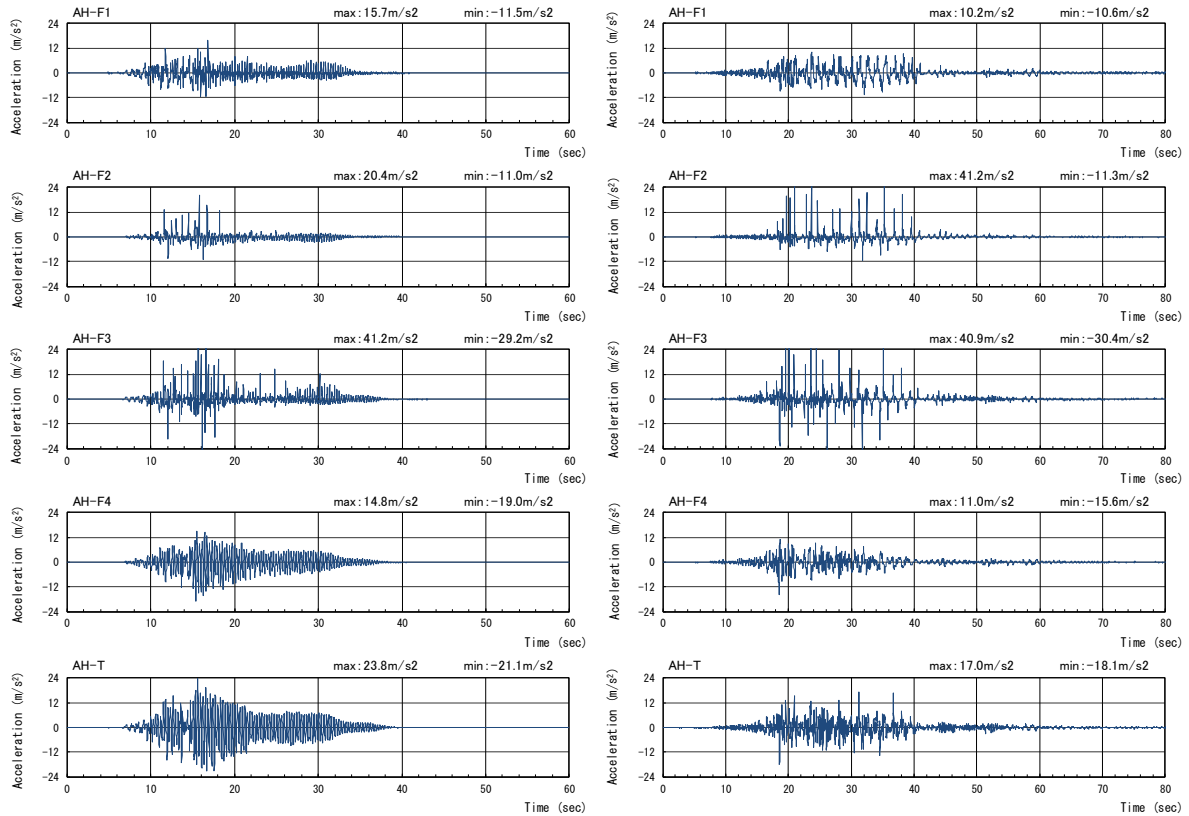


Figure 5. Time histories of acceleration at the points indicated in Figure.3
 (left : Kobe, right : Tokachi)

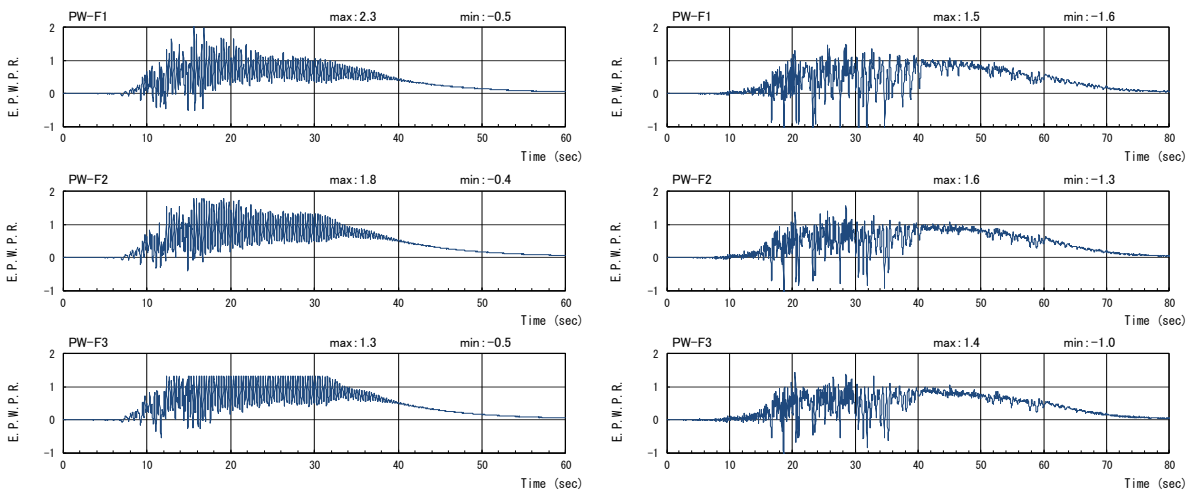


Figure 6. Time histories of excess pore water pressure ratio at the points indicated in Figure.3
 (left : Kobe, right : Tokachi)

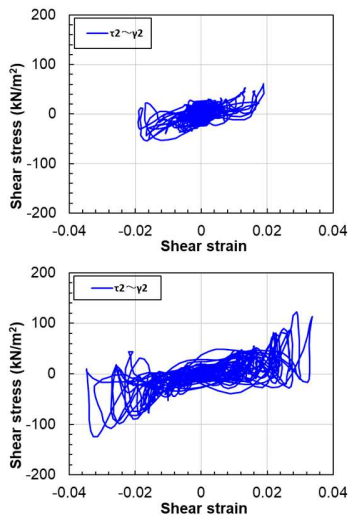


Figure 7. Shear strain – shear stress relationship (upper: Kobe, lower: Tokachi)

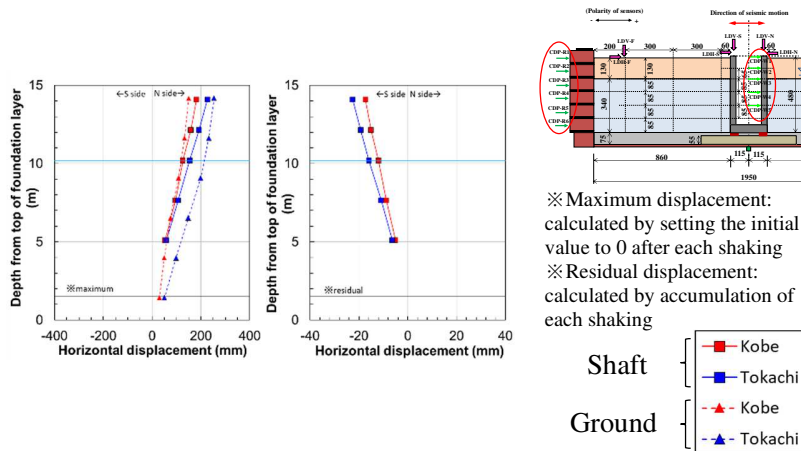


Figure 8. Maximum and residual horizontal displacement of circular shaft

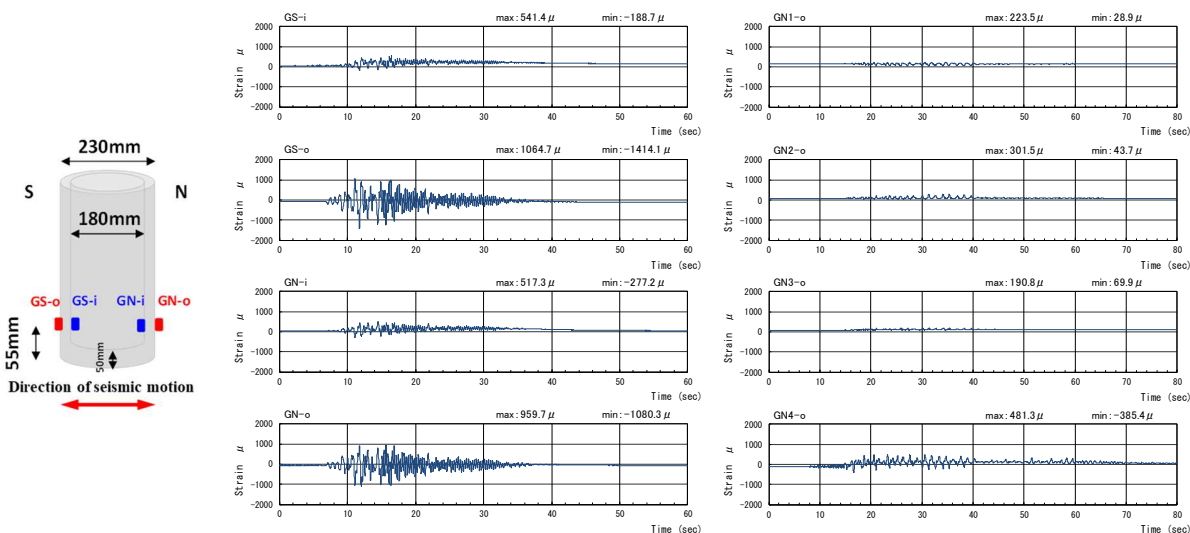


Figure 9. Time histories of vertical strain at the bottom of circular shaft (left : Kobe, right : Tokachi)

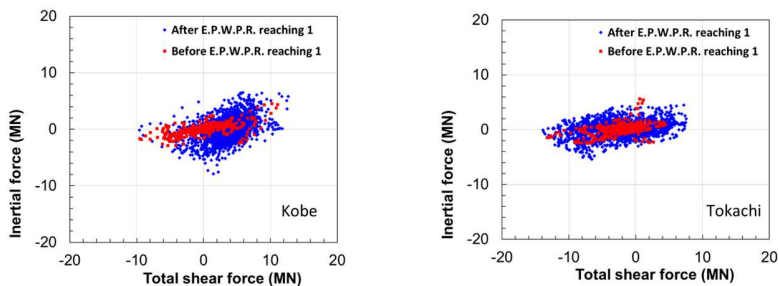


Figure 10. Relation between total shear force and inertial force

REPRODUCTION ANALYSIS OF CENTRIFUGAL LOADING TEST

The reproduction analysis was carried out using a 2D FLIP, and the analysis program used was FLIP ROSE 7.3.0. The analysis model is shown in Figure 11, and the parameters for the ground are presented in Table 2. To model the liquefaction characteristics of the sand foundation, a cocktail glass model that can represent the dissipation of excess pore water pressure was employed. The results of fitting based on the parameters in Table 2 are shown in Figure 12.

The acceleration time histories for the ground and shaft are presented in Figure 13. Although the analysis exhibits slightly smaller pulse-like responses associated with cyclic mobility compared to the experiment, the overall response is generally in agreement. The time histories of excess pore water pressure ratio are shown in Figure 14. In the analysis of the Kobe wave, the average trend in the increase of excess pore water ratio can be captured with high accuracy. There is a slight difference in the dissipation process of the excess pore water pressure, which can be studied in the further analysis, such as setting of the hydraulic conductivity. On the other hand, in the analysis of the Tokachi wave, the amplitude and other aspects are well reproduced. This was achieved because the analysis for the Tokachi wave considered a change in material properties due to the compaction of the sandy ground with the Kobe wave shaking, and the parameters were adjusted accordingly. The material properties used in the Kobe wave analysis were fitted separately to a $Dr = 90\%$ element test, which may have slightly differed from the model ground characteristics.

The horizontal response displacements for the ground and shaft are shown in Figure 15. Both the time histories of displacement for the ground and shaft, as well as of horizontal displacement distribution in depth-direction, are accurately reproduced. Additionally, Figure 16 compares the time histories of horizontal shear force at the bottom of the shaft. In the analysis of the Kobe wave, the analysis tends to slightly underestimate the experiment, but in the case of the Tokachi wave, the difference between the analysis and experiment is small, and the accuracy of reproduction is generally high. As mentioned above, in the case of the Tokachi wave, the reassessment of parameters improved the reproducibility of ground acceleration responses, which is believed to have contributed to the improved accuracy of reproducing the horizontal forces acting on the shaft.

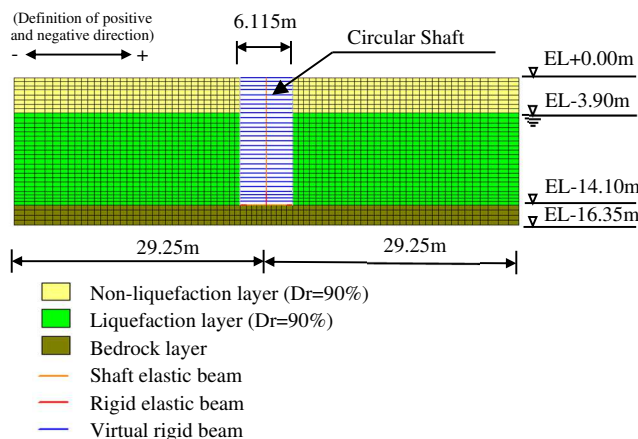


Figure 11. 2D reproduction analysis model
 (1/1 real scale)

Table 2. Soil parameter applied for reproduction analysis

Case	$r_{e,d}$	r_k	q_1	q_2	q_4	c_1
Kobe	0.2	0.6	20	1.4	1.0	1.9
Tokachi	0.1	1.2	15	1.5	0.8	1.7

($p_n = 98kPa$) Refer to Iai et al. (2011) for parameter description
 Some other parameters that are common: $G_m = 94300$ kPa, $\nu = 0.33$,
 $K_{L,U} = 246000$ kPa, $\phi_j = 59.1^\circ$, $m_{G/K} = 0.5$, $n = 0.431$, $h_{max} = 0.206$, $\phi_p = 32.0^\circ$,
 $r_{e,d}^s = 1.3$, $\varepsilon_s^{sm} = 0.27$, $S_1 = 0.005$, $\rho = 1.975$ μm^3

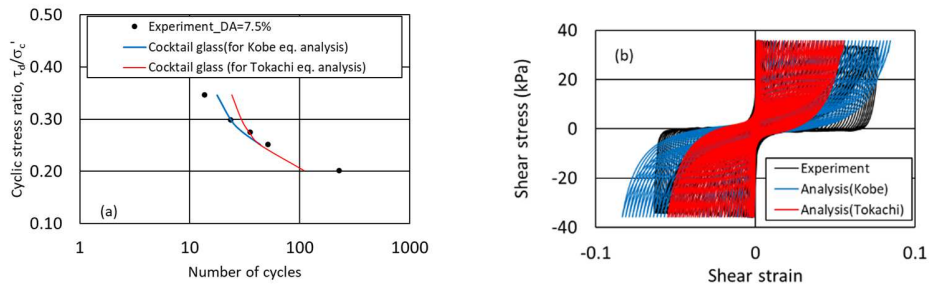


Figure 12. Result of parameter fitting

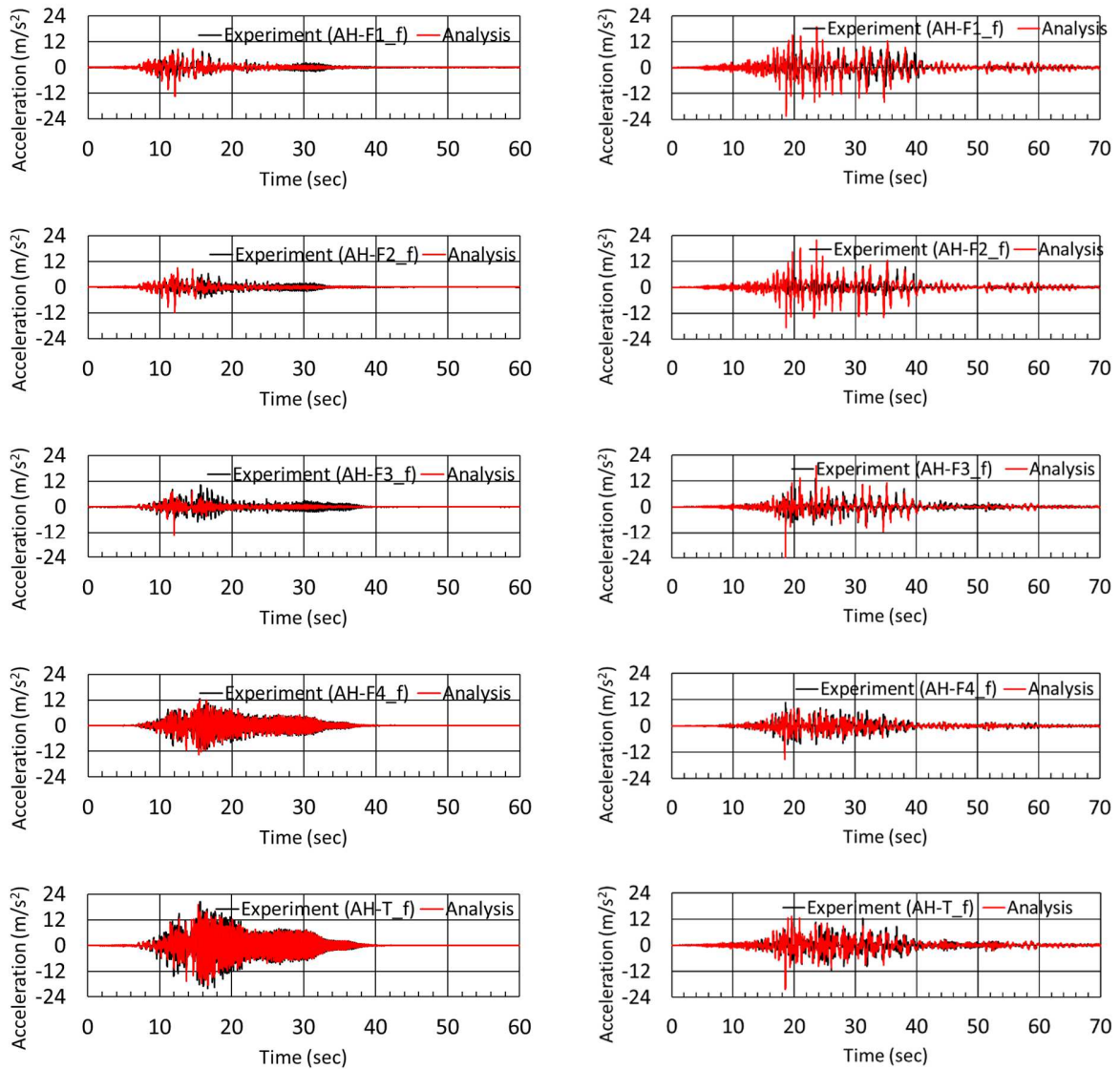


Figure 13. Time histories of acceleration of reproduction analysis compared to test (left : Kobe, right : Tokachi)

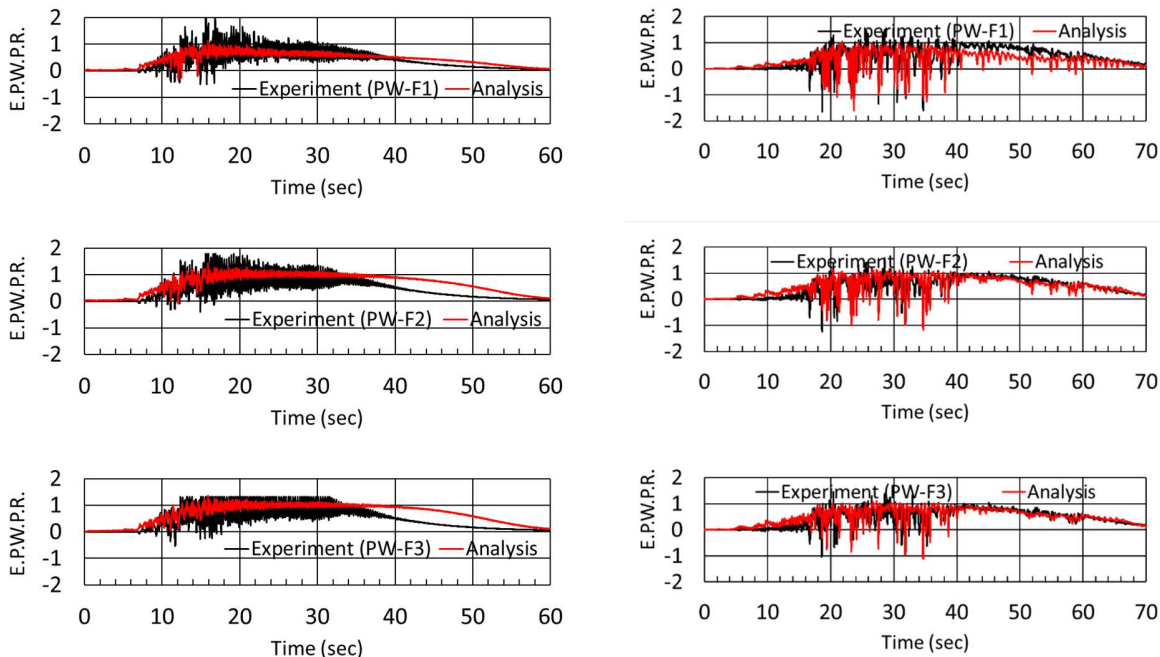


Figure 14. Time histories of excess pore water pressure ratio compared to test (left : Kobe, right : Tokachi)

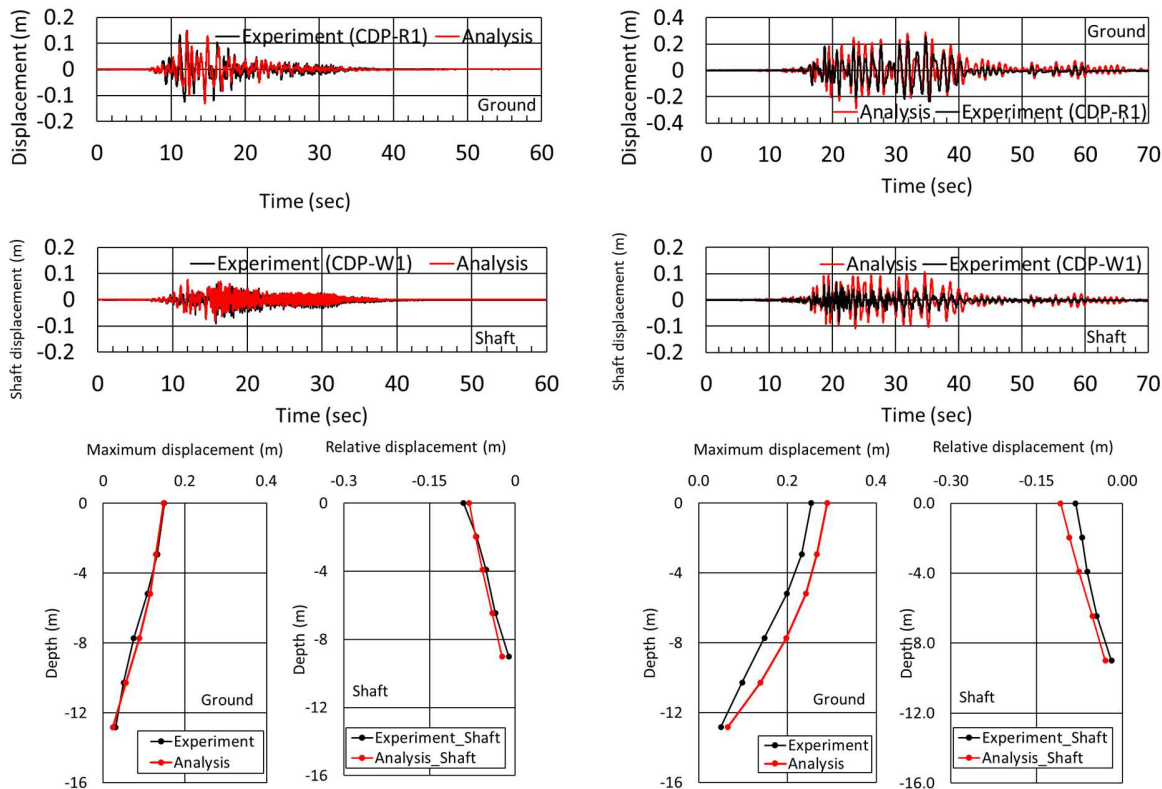


Figure 15. Displacement of ground and circular shaft (left : Kobe, right : Tokachi)

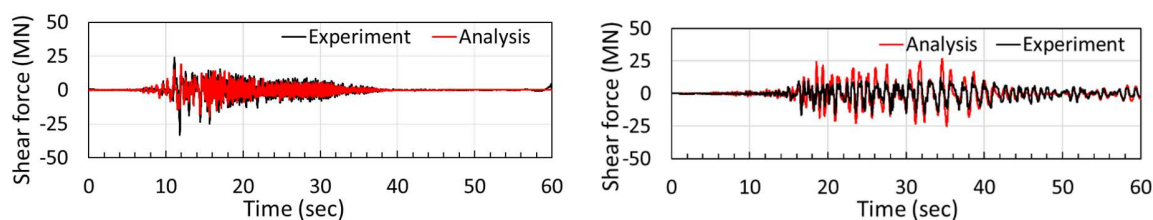


Figure 16. Time histories of horizontal shear force at the bottom of circular shaft
(left : Kobe, right : Tokachi)

CONCLUSIONS

By building a 3D printer model, we were able to confirm that even a complicated structure can be easily made, and that the rigidity and weight of the model can be adjusted by using nylon 12 and reinforcing steels. As the validation of analysis in relation with soil and structure, we were able to reproduce the behavior sufficiently even for liquefied ground of dense sand.

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