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SEISMIC ACTION CONTROL FOUNDATION OF TANK STRUCTURES

Shunichi. HIGUCHI[1] & Takashi. MATSUDA[2]
Department of Civil Engineering,
Technical Research Institute of OBAYASHI Co., Japan

SUMMARY

A high earthquake proof spread foundation for the tank structures named “Seismic action control foundation” was developed. “Seismic action control foundation” consists of a concrete slab and the improved ground under the slab utilizing the deep mixing method. “Seismic action control” effect is theoretically basing on the dynamic soil-structure interaction. In this study, performances of the “Seismic action control foundation” were investigated with both numerical analyses and experiment. Followings were found from the results.
(1) Up to 30 % of the base shear of the tank structure can be reduced by the “Seismic action control foundation”.
(2) It is able to reduce the area of “Seismic action control foundation” up to 50% without decreasing the effect of the seismic input reduction.

INTRODUCTION

Due to severe damage on urban functions experienced in recent great earthquakes, higher seismic performances of infrastructures and industrial facilities are preferred in seismic regions all over the world. However, this requires higher design seismic force and, therefore, provides higher construction costs.
The authors have proposed an economical method to reduce the seismic actions on the tank structures named “Seismic action control foundation” and shown its effectiveness on relatively stiff ground by the numerical analyses [1]. In this study, performances of the “Seismic action control foundation” on various site conditions are investigated with both numerical analysis and experiments.

CONCEPT OF THE “SEISMIC ACTION CONTROL” EFFECT

“Seismic action control foundation” consists of a slab foundation and the soil improvement (cemented soil block, hereafter) under the base slab as shown in Figure 1. This foundation focuses on the large volume liquid storage tanks (e.g. LNG storage tank). Both relatively stiff ground (equivalent to ground type II in JGA Standard [2] or soil profile type S_D in UBC [3]) and soft ground (equivalent to ground type IV or soil profile type S_E) are selected as the ground conditions of tank sites in this study. On these sites, piled foundations were usually selected as the foundation type of the LNG tanks in Japan.

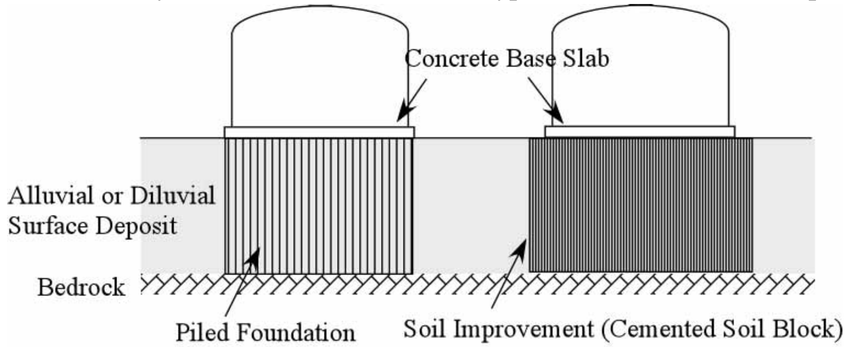


Figure 1 Piled Foundation and the "Seismic Action Control Foundation

"Seismic action control" effect is expected basing on the soil-structure interaction during the earthquake event due to the embedment of the foundation. This effect is known as the kinematic interaction, because of the difference of the stiffness between the cemented soil block and the soil around the foundation. Schematic mechanism of the soil-structure interaction is illustrated in Figure 2.

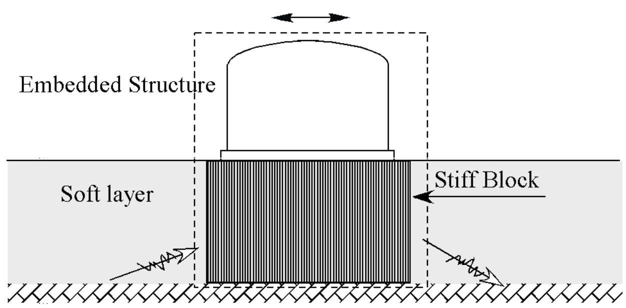


Figure 2 Schematic Mechanism of the Soil-Structure Interaction

NUMERICAL ESTIMATION

Purpose

Followings are the purposes of the numerical estimation.
(a) To investigate the effect of the "Seismic action control foundation"(SACF, hereafter) by comparing the seismic response of the tank with conventional designed foundation tank.
(b) To investigate the performance of the proposed foundation in terms of its dimension (improved area).

Procedure

FEM Code

Time history response analyses with an idealized LNG storage tank were performed in this study. Ax-symmetric FEM model was adopted for the calculation. The numerical program named "ABLE" [4] was utilized in this study. "ABLE" has the following features;
(a) The analysis is based on ax-symmetric FEM model and anti ax-symmetric forcing for horizontal vibration.
(b) Effects of the structure-liquid interaction can be considered.
(c) Effects of the soil-structure interaction can be considered.
(d) The analysis is based on time-history response.
(e) Non-linear effects of the soil can be considered.
(f) Radiation effect can be considered utilizing the energy transmitting boundary.

Model Tank

A 45,000m^3 LNG storage tank with Pre-stressed Concrete containment as shown in Figure 3 was adopted for the estimation. The dynamic characteristics of the inner steel tank are shown in Table 1. The tank is supported by the piled foundation, which has 392 steel piles with diameter of 800mm and 16mm thickness.

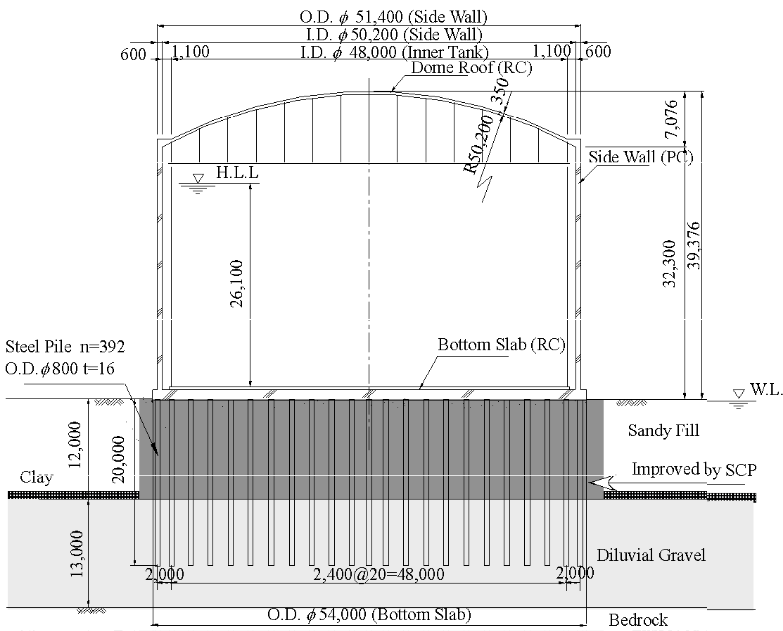


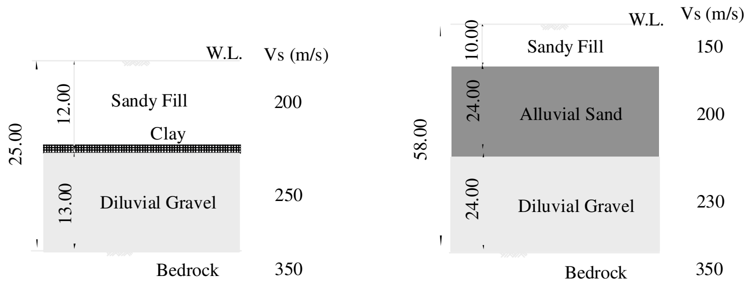
Figure 3 45,000m^3 LNG Storage Tank

Table 1 Predominant Periods of the Inner Steel Tank

	Sloshing Mode	Bulging Mode
T_s (sec)	7.36	0.30

Soil Conditions

Soil profiles of the tank sites are illustrated in Figure 4. In this figure, the Model A corresponds to the ground type II (S_D), and the Model B corresponds to the type IV (S_E), respectively. Predominant periods of the subsurface ground for seismic design at the free field are shown in Table 2. Non-linear characteristics of the soils were considered basing on the equivalent linear theory.



Model A (Type II/S_D) Model B (Type IV/S_E)

Figure 4 Soil Profiles of Subsurface Models

Table 2 Predominant Subsurface Periods

Model	A	B
Ground Type	II (S_D)	IV (S_E)
Period T_g (sec)	0.42	1.08

Design of Soil Improvement

Design strength of the cemented soil block under the slab was selected as q_{ud} (uni-axial compression strength) =500kN/m^2. For the FEM analysis, elastic modulus of the cemented soil block is estimated according to the relation proposed by Mori et.al. [5]. Which is

$$E = 1{,}000 q_u \qquad (1)$$

For the deep mixing method, safety factor of 3 is conventionally applied to the field strength of the cemented soil [6]. Therefore, elastic modulus were decided as E=1,500MN/m^2 in this analyses.

For the SACF, cemented soil block utilizing the deep mixing method is placed under the slab. Thickness of the cemented soil block is chosen as 13.0m in each model. Base of the cemented soil block is embedded into relatively stiff layer.

Pile Foundation

Constitutions of the pile foundations are summarized in Table 3. No piles are installed at the Model A, and smaller piles are used at the Model B for the SACF.

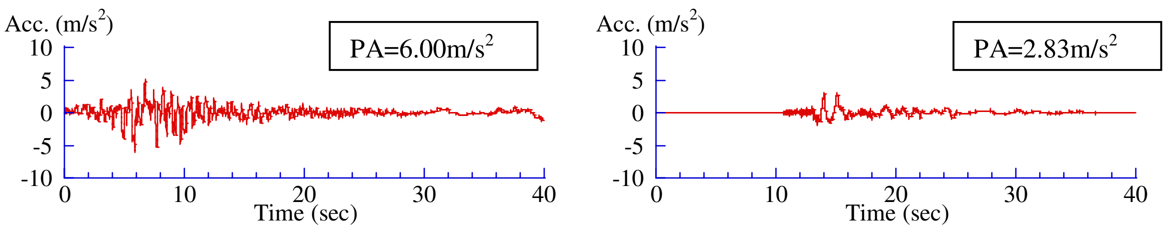
Table 3 Constitutions of the Pile Foundations

	Model A		Model B	
	Conventional	SACF	Conventional	SACF
Diameter (mm)	800	No piles are installed	800	400
Length (m)	20		58	58

Input Motion

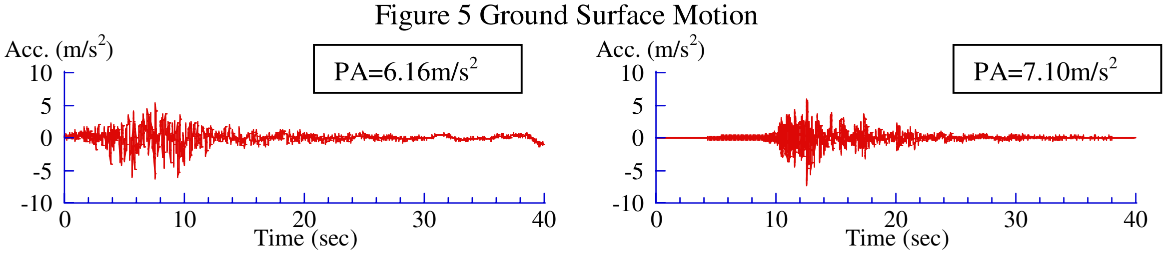
Acceleration time history at the ground surface for the Model A is shown in Figure 5(a). The original time history of JMA Kobe NS (1995) is modified to fit its response spectra with JGA standard's Safe Shutdown Earthquake (SSE, which corresponds to L2 in Japan.) spectral amplification factor [2]. Figure 5(b) corresponds to the ground surface motion for the Model B. Original time history of the Port Island EW (GL=0.0m) (1995) is used in this case.

Because these motions are defined at the ground surface, the input motions (bedrock motions) for FEM, as shown in Figure 6, were calculated by the reverse operation utilizing the program SHAKE [7].



(a) Modified JMA Kobe NS (1995) (b) Port Island EW (GL=0.0m; 1995)

Figure 5 Ground Surface Motion



(a) Modified JMA Kobe NS (GL=-25.0m) (b) Port Island EW (GL=-58.0m)

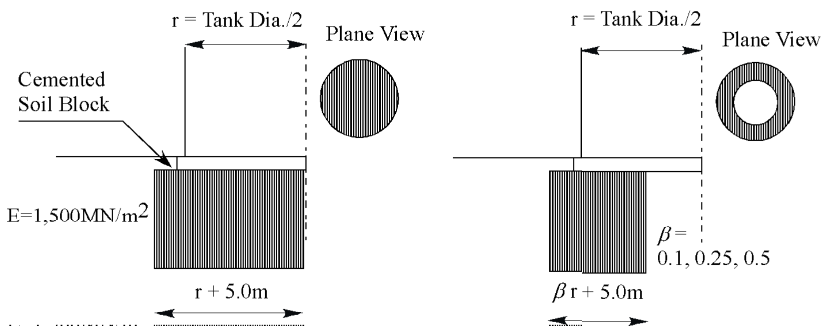
Figure 6 Input Earthquake Motion for the FEM Analysis (Bedrock Motion)

Cases of FEM Analyses and Parameters

Cases of FEM analyses are shown in Table 4. These parameters were chosen to investigate the "Seismic action control" effect in terms of the dimension of the soil block under the tank slab. Figure 7 shows the sketch of improvement area.

Table4 Analyses Conditions

Models /Parameters	Area of the Cemented Soil Block (see Figure 7)				
	0.1r	0.25r	0.5r	1.0r	Conventional
A	R2r01	R2r025	R2r05	R1	D1
B	-	P2r025	P2r05	P1	E1



(a) Whole Improvement (b) Partial Improvement

Figure 7 Area of the Cemented Soil Block

Results and Discussions

Base Shear Coefficient of the Tank

Performances of the "Seismic action control foundation" are evaluated with time histories of the base shear coefficient of the inner tank in this study.

The calculation was carried out using the following equation;

$$k_H(t) = \frac{\sum m_i \cdot \alpha_i(t)}{M} \qquad (2)$$

Where,

$k_H(t)$: Base shear coefficient in time history

m_i : Mass of the section (refer to Figure 8)

$\alpha_i(t)$: Time history of the acceleration of the inner tank member i.

M : Total mass of the inner tank (Steel wall + Liquid + Base plate)

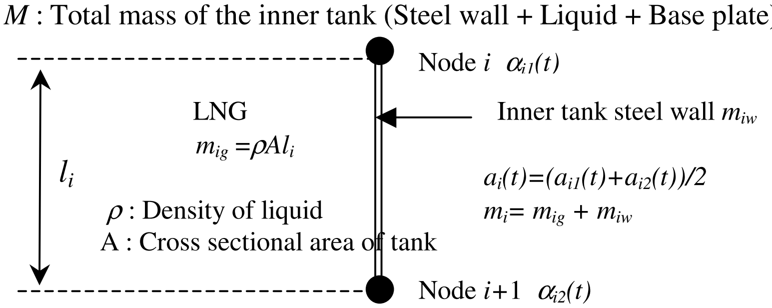


Figure 8 Mass of the Section and the Acceleration Time History of the Member

Response of the Conventional Foundation Tank (Case D1)

Typical dynamic responses (Time histories and transfer functions) of the tank are illustrated in Figure 9.

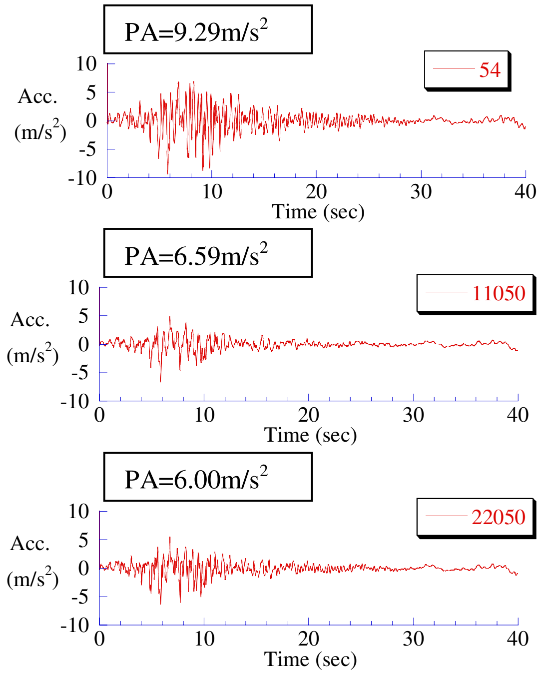
Following characteristics are found from the results.

(1) The first predominant period of the site ground has changed from T_g=0.42 (f_g=2.38Hz) sec to T_{ge}=0.78 (f_{ge}=1.28Hz) sec due to the non-linearity of the ground.

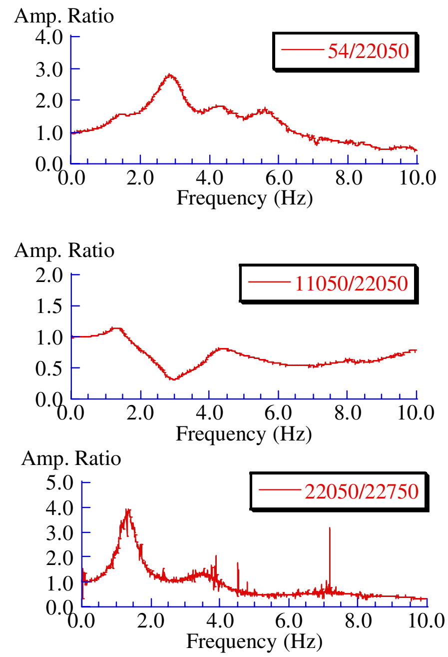
(2) The period of the tank-foundation system, which includes the soil-structure interaction, is about T_{SSI}=0.34sec (f_{SSI}=2.90 Hz).

(3) The maximum acceleration response of the ground under the tank (node 11050) is larger than that of the free field (node 22050). On the other hand, the amplitude of the transfer function between them are smaller than 1.0 throughout almost of the frequency domain.

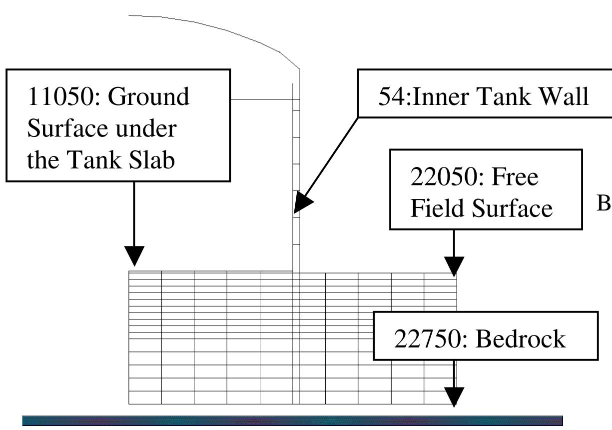
Figure 9(d) shows the time history of the base shear coefficient of the tank calculated utilizing the equation (2) previously defined. The peak amplitude of k_H=0.782 was obtained from the time history. k_H=0.782 will be the reference amplitude in discussing the effect of the SACF later.



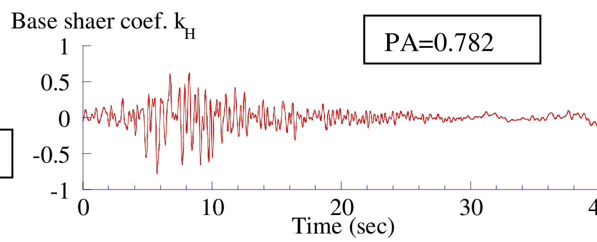
(a) Time Histories



(b) Transfer Functions



(c) FEM Mesh and Node for Plots



(d) Time History of the Base Shear Coefficient of the Tank

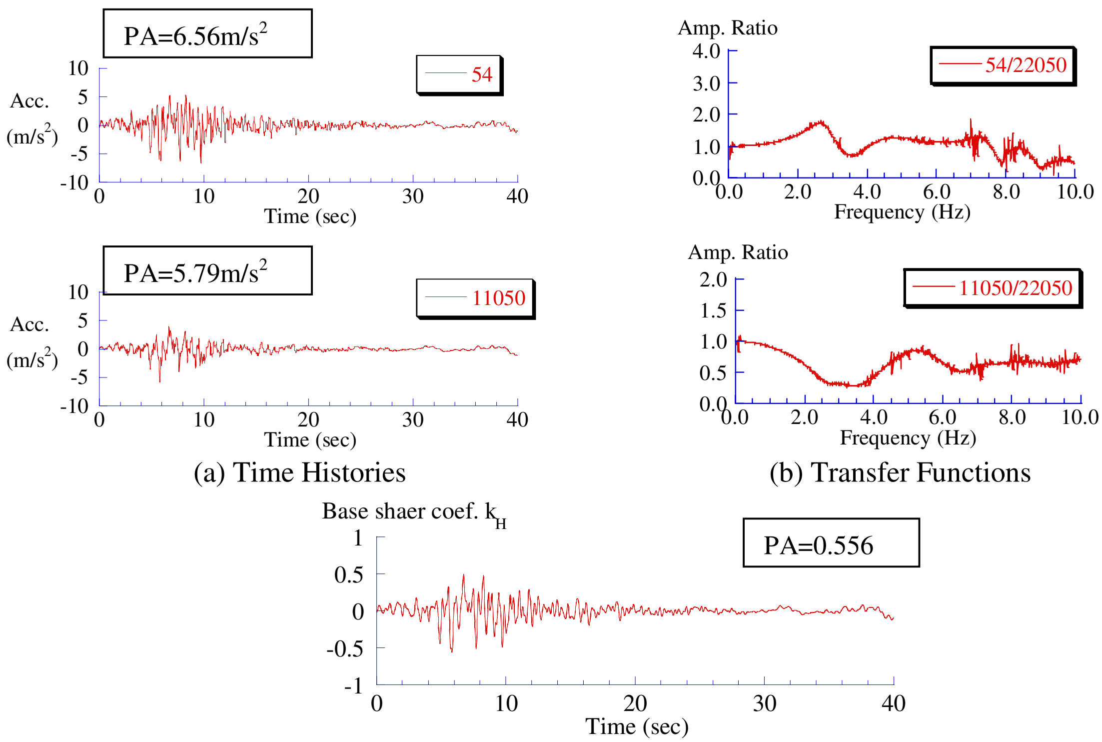
Figure 9 Typical Dynamic Responses of the Conventional Piled Foundation Tank (D1)

Response of the Tank on the "Seismic Action Control Foundation (SACF)" (Case R1)

Typical dynamic responses of the tank with the SACF, case R1, are shown in Figure 10. These time histories and transfer functions are obtained at the same positions as it was shown in Figure 9.

Following characteristics are found from these results.

(1) The period of the tank-foundation system (SSI system) is about T_{SSI}=0.37sec (f_{SSI}=2.67Hz). This is slightly longer than the period of SSI system of the piled foundation tank.
(2) The maximum acceleration response of the ground under the tank (node 11050) is smaller than that of the free field (node 22050 in Figure 9). This can be confirmed from the transfer function between them, in which the amplitude is smaller than 1.0 throughout a wide range of the period.
(3) The maximum acceleration response of the ground under the tank (node 11050) in case R1qu5 is smaller than that of the acceleration observed at the piled foundation case (Figure 9).
Figure 10(c) shows the time history of the base shear coefficient of the tank. The peak amplitude of k_H=0.556 was obtained from the time history, and that is about 30% smaller than the k_H=0.782 obtained from the case of the piled foundation.



(a) Time Histories

(b) Transfer Functions

(c) Time History of the Base Shear Coefficient of the Tank

Figure 10 Typical Dynamic Responses of the Tank on the SACF (R1)

Performance of the SACF under Various Parameters

As it was shown in Table 4, the analyses were performed with different site condition and a variety of parameters to investigate the "Seismic action control" effect. Table 5 summarizes the results of the analyses. Performance of the SACF will be discussed in terms of the reduction factor of the base shear coefficient in this section. Reduction factors were calculated as ratios of the base shear coefficient k_{HSACF} of each case and the k_H of the conventional foundation models. In the case of smaller value of reduction factor indicates that the seismic action control effect becomes large.
According to the Table 5, followings are concluded.

(1) The reduction factor becomes larger in proportion to the strength of the area of the cemented soil block (R1 vs. R2r-xx or P1 vs. P2r-xx).
(2) Higher seismic force reduction effect is observed at the stiffer soil condition (S_D). This suggests performance of the SACF affected by the soil condition.
(3) Area of the SACF can be reduced up to 50% without decreasing the effect of the seismic reduction.

Table 5 Base Shear Coefficient Factor of the Tank

Model /Parameter	Area of the Cemented Soil Block			
	0.1r	0.25r	0.5r	1.0r
A	R2r01	R2r025	R2r05	R1
	0.811	0.717	0.737	0.711
B	-	P2r025	P2r05	P1
	-	0.840	0.830	0.770

EXPERIMENTAL INVESTIGATION

Procedure

To confirm the effect of the SACF, experimental investigation was carried out. In this study, a centrifuge experiment was performed for this purpose.

Centrifuge model setup

Figure 11 shows the centrifuge experiment setup of the SACF. This test was carried out under a 50g centrifugal gravity utilizing the OTRI's geotechnical centrifuge [8], which has the world largest centrifuge earthquake simulator.

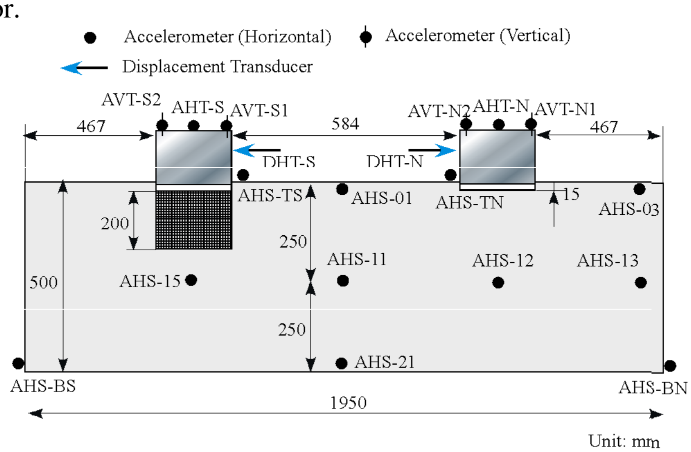


Figure 11 Model Setup for the Centrifuge Shaking Table Test for SACF (under 50g)

The model ground was consisted of dried silica sand. The ground was compacted to obtain the relative density of 90% to simulate the ground type II (S_D). The dimension of the ground is 1950mm long, 800mm wide and 500mm deep, which is equivalent to 95m, 40m and 25m in prototype scale respectively. According to the transfer function of the ground acceleration records (AHS-01/AHS-21) obtained at the white noise shake event, predominant frequency of the ground was detected about F=2.0 Hz (T_g=0.5 sec). Therefore, the average shear wave velocity of the initial ground can be estimated as Vs=200m/s.

Two tank models, which consist of mortal block and steel base plate, were placed on the ground. One of these (the left model) has a cemented soil block underneath, to form the SACF. Design parameters of the tank models are summarized in Table 6.

Table 6 Parameters of the Tank Models

	Diameter (mm)	Height (mm)	Center of the Gravity h_g (mm)	Mass (kg)	Contact Pressure (kN/m^2)
Model	216	150	54	12.2	190 (Under 50g)
Prototype	10,800	7,500	2,700	1,525,000	190

The dimension of the SACF is as same diameter as the tank and 200mm (10m in prototype) thickness. Compression strength of the cemented soil block was q_u=1.5MN/m^2 in this experiment.

Acceleration responses of both ground and tank models were measured at the experiment.

Testing Program

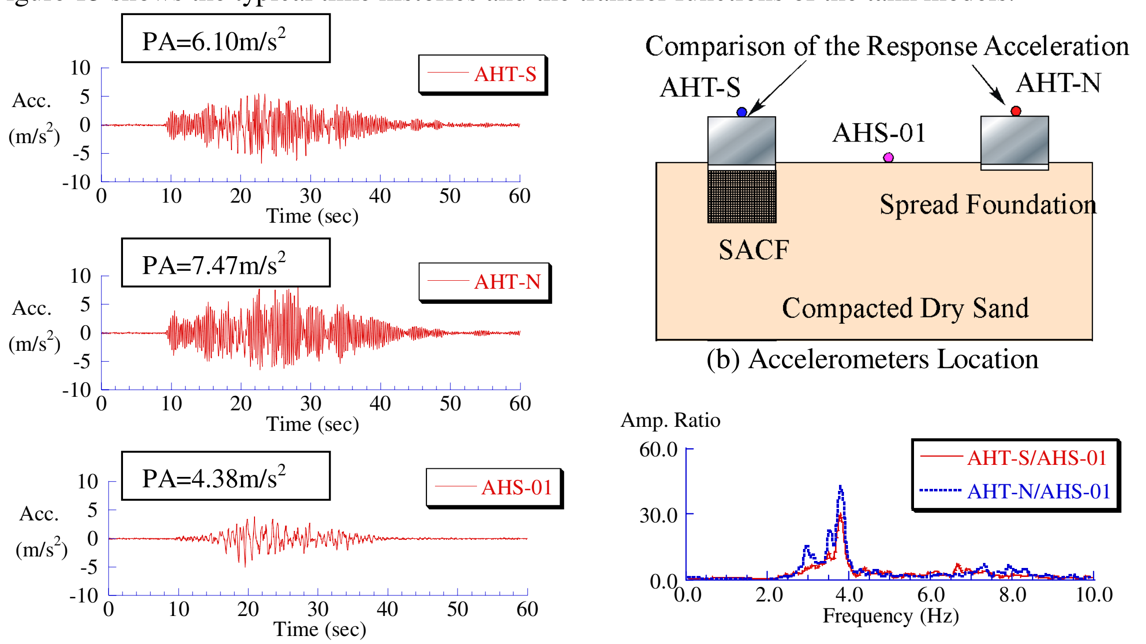
Various shake events were performed under the centrifuge gravity field. Table 7 summarizes the input motions and peak acceleration (observed at the shaking table) of the shake events. Durations of the earthquake motions were converted to 1/50 of the original motion, according to the similitude under the 50g centrifugal gravity. A small white noise shake was performed as well, to get the dynamic characteristics of the model at the beginning of the test.

Table 7 Shake Program for the Centrifuge Shaking Table Tests

Case	Input Motion	PA (m/s^2) (Prototype scale)
r1	White Noise	0.20
d1, d2, d3,d4	Kushiro (Plate Boundary Earthquake)	0.93, 2.10, 3.37, 4.30

Result and Discussions

Figure 13 shows the typical time histories and the transfer functions of the tank models.



(b) Accelerometers Location

(a) Acceleration Time Histories (c) Transfer Functions of the Tank Models

Figure 13 Typical Dynamic Responses of the Centrifuge Shaking Table Test (Case d4)

Figure 13(a) shows the acceleration time histories of the tank models at shake event d4. Acceleration responses of the tank models (AHT-x) seem to contain higher frequency content, comparing with the ground surface response AHS-01. Peak acceleration observed at AHT-S is smaller than that of observed at AHT-N. Peak acceleration ratio of AHT-S/AHT-N is 0.816 in this case. Because of the tank models are the rigid body in this experiment, the acceleration responses of the tank models are equivalent to the base shear.

Figure 13(c) shows the acceleration transfer function between the tank and the ground surface. The peak of the amplitude ratio can be found at f=3.75Hz, which corresponds to the overturning (rocking) mode of the tank, at both tank models. Smaller peak amplitude ratio was achieved at AHT-S, which measured at the response of SACF, than that of the conventional spread foundation, AHT-N. Same phenomena were found at other shake events. This suggests higher damping can be expected on the SACF result from the embedment of the stiff soil block in the soil stratum.

Table 8 summarizes the peak acceleration of the tank and the peak amplitude (PA) ratio between these tank models. 20% to 30% of the peak amplitude reduction of acceleration of the tank are confirmed at the tank model on the SACF.

Table 8 Peak Acceleration of the Tank and the PA Ratio

Shake Event	d1	d2	d3	d4
Spread Foundation (A) (m/s^2)	4.36	5.57	6.54	7.47
SACF (B) (m/s^2)	3.00	3.92	5.05	6.10
PA Ratio (B/A)	0.688	0.704	0.772	0.816

CONCLUSION

A high earthquake proof spread foundation for the tank structures named "Seismic action control foundation" was proposed and performances were investigated with both numerical analyses and experiments. Followings were found from the results.

(1) 20 to 30 % reduction of the base shear of the tank structure was turned out on the "Seismic action control foundation" compared with those of the piled foundation by numerical analyses.

(2) It is able to reduce the area of "Seismic action control foundation" up to 50% without decreasing the effect of the seismic reduction.

(3) 20% to 30% of the peak acceleration reduction of the tank on the SACF were confirmed by the centrifuge experiment. This is due to higher damping of the SACF resulted from the embedment of the stiff soil block in the soil stratum

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1 Deputy Senior Research Engineer, Dept. of Civil Eng., Technical Research Institute of OBAYASHI Corporation, Tokyo, Japan. Email: higuchi.shunichi@obayashi.co.jp

2 Manager, Dept. of Civil Eng., Technical Research Institute of OBAYASHI Corporation, Tokyo, Japan