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Development of Seismic Device for Stainless Steel Rectangular Water Tank at Short Period Earthquake

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ABSTRACT

The seismic device effective for an existing stainless steel rectangular water tank was developed to prevent the damage of tank by earthquake, especially focusing on the short period earthquake where the impulsive pressure acts on the side wall of tank. The seismic device consisted of a thin high damping rubber plate, sandwiched with two metal plates, which were attached on both the surfaces of the rubber plate. These seismic devices were expected to be set between the base frame of tank and the anchor block.

First, a shaking table test of a small water tank (1,000 mm×1,000 mm×1,000 mm) made of stainless steel panels was performed under the several conditions of the number, shape and rubber thickness of the seismic devices. Then, eight seismic devices were set to a large water tank (3,000 mm×3,000 mm×3,000 mm) constructed from nine stainless steel panels for each side wall. These tanks were put on the shaking tables and dynamic shaking tests were performed. The shaking frequency was varied from DC to 12 Hz with a given interval step and the water pressure on the side wall of tank was measured.

In this study, by setting the seismic devices to both the small and large water tanks, the natural impulsive frequencies of tanks became a little lower, and the impulsive pressure at the natural frequency became smaller with increasing rubber thickness and with increasing surface pressure. When the HYOGOKEN-NANBU earthquake waves were given to the large water tank with the seismic devices, the impulsive pressure at the short period oscillation was largely suppressed but the sloshing pressure at the long period oscillation was scarcely enhanced.

Keywords: earthquake, seismic device, water tank, impulsive pressure

1 INTRODUCTION

Some water tanks made of stainless steel and FRP were damaged by the big earthquake at Kumamoto (M 7.3), 2016 in Japan (1). In the case of long period earthquake the convective pressure occurs at the upper side wall of tank by sloshing, and in the case of short period earthquake, on the other hand, the impulsive pressure does at the lower side wall of tank. Many studies have been performed on the former, but few ones have been found on the latter.

In Japan, the water tanks have been designed to resist the earthquake oscillation without the consideration of absorption and isolation of oscillation. In the other countries, the concrete tanks with isolation laminated rubber bearing and/or sliding bearings have been analytically and experimentally studied (2-9). However, these seismic devices are set at the construction of new tank, and are very difficult to be set to the existing tanks. Furthermore, these devices are considered to enhance sloshing.

In this study, the seismic device for an existing stainless steel rectangular water tank was developed to prevent the damage of tank by the earthquake, especially focusing on the short period earthquake where the impulsive pressure acts on the side wall of tank. The seismic device consisted of a thin high damping rubber plate sandwiched with two metal plates.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Shaking table test for small water tank

Figure 1 shows the photo and outline of the experimental apparatus for the small water tank. The tank was made of stainless steel panel with 1.5 mm in thickness. The dimensions were 1,000 mm in width, 1,000 mm in length and 1,000 mm in height. The panels with pressed hemispherical surface were used for the side walls of tank. This tank was put on a small shaking table. The water level was 900 mm. Several seismic devices were set between the base frame of tank and the anchor block. Four pressure sensors were installed at the center of side wall of tank. The shaking frequency was varied from 1 to 12 Hz with a given interval step and the water pressure on the side wall was measured.

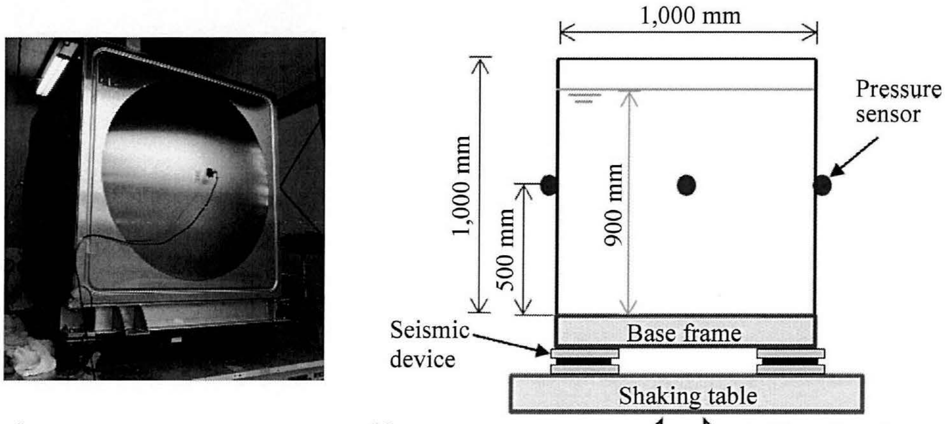
The present seismic device consisted of a thin high damping rubber plate sandwiched with two metal plates, which were attached on both the surfaces of the rubber plate. As *Table 1* shows, the dimensions, thickness and shape of rubber plate, and the number and placement of seismic devices were combined. Surface pressure, W means the total weight of water tank divided by the surface area of rubber plates. The allowable surface pressure, W_A is calculated from the size of rubber plate and the static shear elasticity of rubber used. The pressure ratio, W / W_A is the ratio of the former to the latter. For Cases 1 to 11, the high damping rubber was used, and for Case 12, used was the natural rubber (NR) with the similar hardness to that of high damping rubber.

2.2 Shaking table test for large water tank

Figure 2 shows the photo and outline of the experimental apparatus for the large water tank. The tank was made of stainless steel panels of thickness 1.5, 2.0 and 2.5 mm for the upper, middle and lower side walls, respectively, and the dimensions were 3,000 mm in width, 3,000 mm in length and 3,000 mm in height. The side wall of tank was constructed from nine panels with pressed hemispherical surface, and the stainless steel reinforcements were installed in the inside of tank. This tank was put on a large shaking table. The water level was 2,700 mm. Six pressure sensors were installed vertically at the center of side wall of tank. The shaking frequency was varied from 1.5 to 6 Hz with a given interval step and the water pressure on the side wall was measured.

Eight seismic devices were installed to the large water tank at the placement D, and the dimensions and thickness of rubber plate were combined as *Table 2* shows.

As a typical earthquake with short period oscillation, HYOGOKEN-NANBU earthquake waves were given to the large water tank without and with seismic device (Case 13).



a) b)

Fig. 1. a) Photo; b) Outline of experimental apparatus for small water tank

Table 1. Experimental conditions of seismic device for small water tank

Case	Dimensions of rubber plate [mm]	Thickness of rubber plate [mm]	Shape of rubber plate	Number of seismic device	Placement of seismic device	Surface pressure W [N/mm^2]	Allowable surface pressure W_A [N/mm^2]	Pressure ratio W/W_A [-]
1	62×62	10	Square	4	A	0.65	0.85	0.76
2	62×62	10	Square	6	B	0.43	0.85	0.51
3	62×62	10	Square	6	C	0.43	0.85	0.51
4	62×62	10	Square	8	D	0.33	0.85	0.38
5	75×75	10	Square	4	A	0.43	1.18	0.36
6	108×54	10	Rectangle	4	E	0.43	1.10	0.39
7	54×108	10	Rectangle	4	F	0.43	1.10	0.39
8	ϕ85	10	Circle	4	A	0.44	1.14	0.39
9	90×90	10	Square	4	A	0.31	1.64	0.19
10	75×75	5	Square	4	A	0.43	4.31	0.10
11	75×75	15	Square	4	A	0.43	0.60	0.72
12	75×75 (NR)	10	Square	4	A	0.43	1.18	0.36

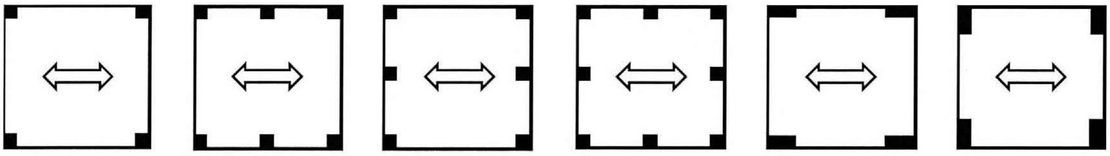
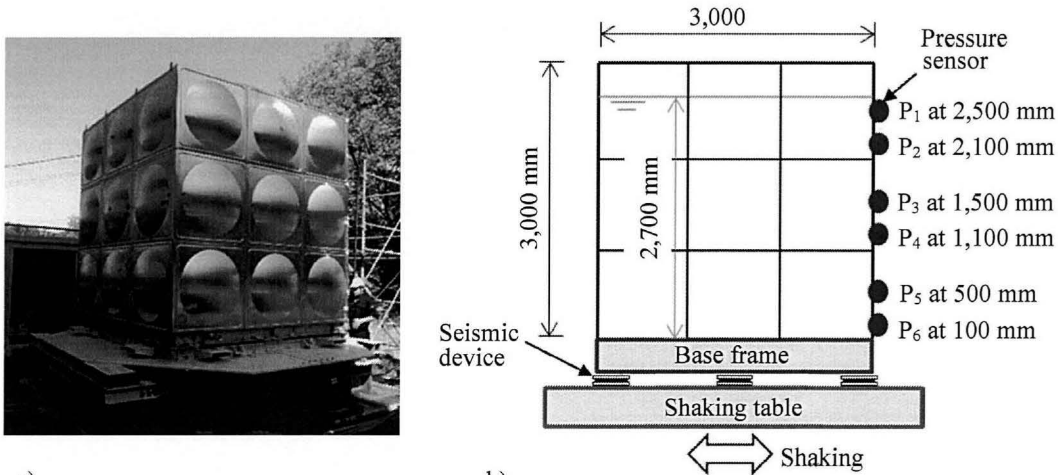


Table 2. Experimental conditions of seismic device for large water tank

Case	Dimensions of rubber plate [mm]	Thickness of rubber plate [mm]	Shape of rubber plate	Number of seismic device	Placement of seismic device	Surface pressure W [N/mm^2]	Allowable surface pressure W_A [N/mm^2]	Pressure ratio W/W_A [-]
13	150×150	10	Square	8	D	1.43	4.31	0.33
14	120×120	10	Square	8	D	2.24	2.81	0.80
15	180×180	10	Square	8	D	0.99	6.15	0.16
16	150×150	5	Square	8	D	1.43	16.8	0.08
17	150×150	15	Square	8	D	1.43	1.99	0.72



a) b)

Fig. 2. a) Photo; b) Outline of experimental apparatus for large water tank

3 RESULTS AND DISCUSSION

3.1 Effect of seismic device on water pressure in small water tank

Figure 3 shows the change in corresponding water pressure with the frequency for different seismic devices set to the small water tank. The force exciting to the tank increases with the frequency, and is calculated from the frequency. The corresponding water pressure is obtained by dividing the water pressure by the exciting force, and represents the water pressure normalized by the exciting force. Since the water pressure on the side wall perpendicular to the shaking direction was high, the highest water pressure among the four sensors was adopted.

In the tank without seismic device, the peak of corresponding water pressure appears near the frequency of 8.8 Hz. This frequency is the natural impulsive one of the small tank, where the impulsive pressure occurs. In the tank with seismic device, the natural impulsive frequencies are 6.0 - 8.0 Hz, and are slightly lower than that of tank without it. In the tanks with seismic device using high damping rubber (Cases 1 to 11), the peak of corresponding water pressure (impulsive one) is much lower than that of the tank without it. This is because the high damping rubber absorbs the oscillation energy as the thermal one. While the peak of the tank with the seismic device using natural rubber (Case 12) is lower than that of the tank without seismic device, it is higher than that of the tank with the seismic device using high damping rubber at the same condition (Case 5).

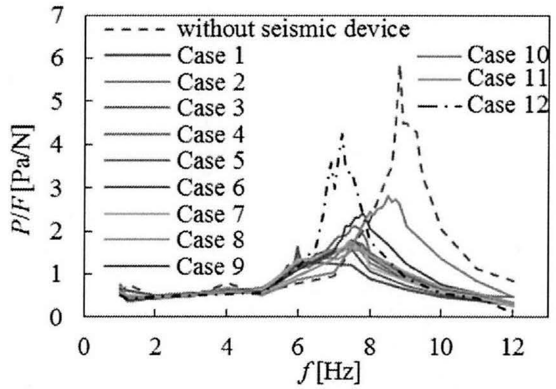


Fig. 3. Change in corresponding water pressure with frequency for different seismic devices set to small water tank

3.2 Effect of seismic device on water pressure in large water tank

Figure 4 shows the change in corresponding water pressure with the frequency for different seismic devices set to the large water tank. Since the water pressures at the relatively low positions (P_3 - P_6) were higher in the vertical distribution of water pressure, the maximum was adopted in calculating the corresponding water pressure. In the tank without seismic device, the peak of corresponding water pressure appears near the frequency of 4.5 Hz, which is the natural impulsive frequency of the large water tank. In the tanks with seismic device, the natural impulsive frequencies become to 3.5 to 4.0 Hz, and the peak of corresponding water pressure (impulsive one) is much lower than that of tank without it. These tendencies are the same as those in the small tank.

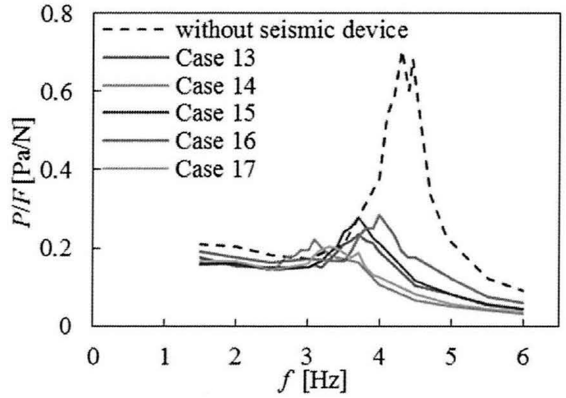


Fig. 4. Change in corresponding water pressure with frequency for different seismic devices set to large water tank

3.3 Effect of seismic device property on decrement of water pressure in water tank

To quantify the decrement of corresponding water pressure, the following index, D_{WP} is defined;

$$D_{WP} = \{1-(P/F)_{MAX}/(P/F)_{MAX,0}\} \times 100 \quad [\%] \qquad (1)$$

where $(P/F)_{MAX}$ and $(P/F)_{MAX,0}$ are the maximums of corresponding water pressure in the tanks with and without seismic device, respectively. The decrement of corresponding water pressure increased with increasing thickness of rubber plate and with increasing surface pressure, but it was not clearly correlated by these properties. So, it was plotted against the ratio of surface pressure on rubber plate to permissible value of it, W/W_A, as shown in *Fig. 5*. The decrement of corresponding water pressure of Case 12 (NR) was 28%, and it was excluded in this plot. When the seismic device using the high damping rubber is set to the water tank, the decrement of corresponding water pressure ranges in 60-70 %, and becomes higher as this ratio of surface pressure increases. Since the data of two different size tanks are on a line, the water pressure decrement due to the present seismic device is considered to depend strongly on the ratio of surface pressure. The decrement of corresponding water pressure is approximated by the following equation;

$$D_{WP} = 76(W/W_A)^{0.12} \quad [\%] \qquad (0.1 \leqq W/W_A \leqq 0.8) \qquad (2)$$

Equation (2) reproduces the measured data of decrement of corresponding water pressure within the errors of ± 10%. So, by using *Eq. (2)*, the ratio of surface pressure on rubber plate to permissible value of it can be estimated for a desirable decrement of corresponding water pressure.

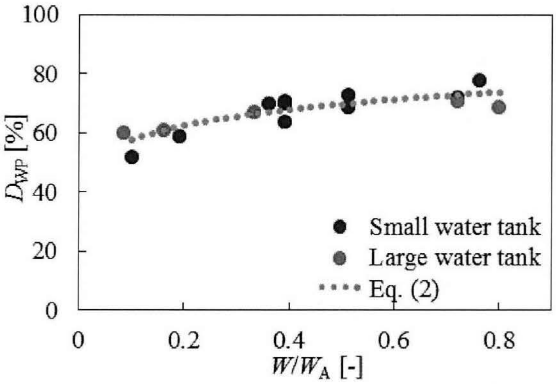


Fig. 5. Plot of decrement of corresponding water pressure against ratio of surface pressure on rubber plate to permissible value

3.4 In case of earthquake waves

Figure 6 shows the power spectrum of water pressure at P_5 in the large water tank without and with seismic device at the HYOGOKEN-NANBU earthquake waves.

By setting the seismic device to the large tank, the maximum power spectrum without seismic device around the frequency of 4.5 Hz, which corresponds to the natural impulsive frequency at the short period oscillation, is largely suppressed, but the spectra at the lower frequencies, which

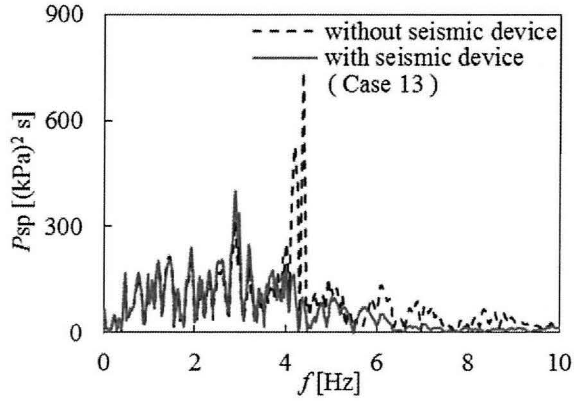


Fig. 6. Power spectrum of water pressure in large water tank at HYOGOKEN-NANBU earthquake waves

include the natural sloshing frequency at the long period oscillation, are scarcely enhanced. From these, it is recognized that the present seismic device is effective for the short period earthquake.

4 CONCLUSIONS

In this study, the seismic device effective for an existing stainless steel rectangular water tank was developed, especially focusing on the short period earthquake where the impulsive pressure acts on the side wall of water tank. The proposed seismic devices were set to the small and large tanks, which were put on the shaking tables. Under the various conditions of seismic device, the shaking table test was performed and the water pressure on the side wall of tank was measured. The following conclusions were obtained;

1) By setting the seismic devices to both the small and large water tanks, the natural impulsive frequencies of tanks becomes a little lower, and the impulsive pressure at the natural frequency becomes much smaller with increasing rubber thickness and with increasing surface pressure.
2) The effect of seismic device on the decrement of corresponding water pressure is the same for the small and large tanks, and the decrement ranges in 60-70 %. The decrement increases with increasing ratio of surface pressure on rubber plate to permissible value of it, and is approximated by *Eq.* (2).
3) When the HYOGOKEN-NANBU earthquake waves are given to the large water tank with seismic device, the impulsive pressure at the short period oscillation is largely suppressed but the sloshing pressure at the long period oscillation is scarcely enhanced.

REFERENCES

1. **Inoue, R., F. Sakai and S. Omine**. Damage of water tanks and its relationship with strong ground motion in Kumamoto area during the 2016 Kumamoto earthquake. *Journal of Japan Society of Civil Engineering A1*. 2017, vol. 73, no. 4, pp. I_711-I_720.
2. **Liang, B and J.-X. Tang**. Vibration studies of base-isolated liquid storage tanks. *Computers Structures,* 1994, vol. 52, no. 5, pp. 1051-1059.
3. **Kim, N.-S. and D.-G. Lee**. Pseudodynamic test for evaluation of seismic performance of baseisolated liquid storage tanks. *Engineering Structures*, 1995, vol. 17, no. 3, pp. 198-208.
4. **Park, J.-H., H. M. Koh and J. K. Kim**. Seismic isolation of pool-type tanks for the storage of nuclear spent fuel assemblies. *Nuclear Engineering and Design*, 2000, vol. 199, pp. 143–154.
5. **Shrimali, M. K. and R. S. Jangid**. "Non-linear seismic response of base-isolated liquid storage tanks to bi-directional excitation. *Nuclear Engineering and Design*, 2002, vol. 217, pp. 1–20.
6. **Shrimali, M. K. and R. S. Jangid**. Seismic of liquid storage tanks isolated by sliding bearings. *Engineering Structures*, 2002, vol. 24, pp. 909-921.
7. **Shekari, M. R., N. Khaji and M. T. Ahmadi**. On the seismic behavior of cylindrical base-isolated liquid storage tanks excited by long-period ground motions. *Soil Dynamics and Earthquake Engineering*, 2010, vol. 30, pp. 968–980.
8. **Vosoughifar, H. R. and M. A. Naderi**. Numerical analysis of the base-Isolated rectangular storage tanks under bi-directional seismic excitation. *British Journal of Mathematics and Computer Science*, 2014, vol. 4, no. 21, pp. 3054-3067.
9. **Hashemia, S. and M. H. Aghashirib**. Seismic responses of base-isolated flexible rectangular fluid containers under horizontal ground motion. *Soil Dynamics and Earthquake Engineering*, 2017, vol. 100, pp. 159-168.