Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Tuned liquid damper using heat storage tanks

Y. Kitada, H. Watanabe & K. Shioya
Shimizu Corporation, Koto-ku, Tokyo, Japan
K. Ariizumi, T. Tanaka & H. Matsumoto
Tokyo Electric Power Company, Chofu-shi, Japan

ABSTRACT: The present research is concerned with the vibration control of structures, subjected to moderate earthquakes smaller than VI on the MM scale, by using water oscillation in heat storage tanks, which can effectively equalize the electric power load. A twelve-story steel tower was observed during an earthquake to confirm the effectiveness of a tuned liquid damper using heat storage tanks. The tuned liquid damper (TLD) was installed on the twelfth floor. The responses with and without the tuned liquid damper on the twelfth floor were compared. The results definitely indicated that the responses with the tuned liquid damper were smaller than those without the tuned liquid damper. Simulation analyses were also carried out, and these results satisfactorily matched the observed results.

1 INTRODUCTION

Heat storage tanks and electric calorifiers have the effect of equalizing the electric power load. However, they need a great deal of water compared with other heat sources for air-conditioning or a gas water heaters. This is one of main reasons why heat storage tanks and electric calorifiers are not widely used.

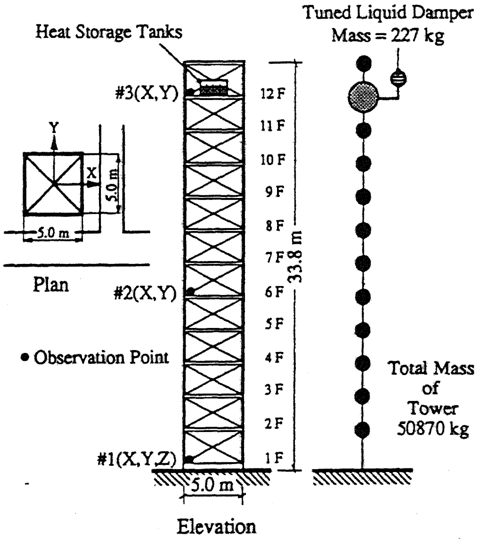
Recently, vibration suppression in tall and narrow buildings has become more important to ensure the comfort of the occupants. Thus, various dynamic absorbers using water tanks or masses have been studied to reduce building movement induced by earthquakes and/or winds (see Wiesner (1986) and Kobori (1990)).

The present research focused on the vibration control of structures, subjected to moderate earthquakes smaller than VI on the MM (Modified Mercalli) scale, by using water oscillation in heat storage tanks. The tuned liquid damper (TLD) is superior to the tuned mass damper given the low cost, easy installation, and fewer maintenance requirements of the former.

The effects of an earthquake on the structure were observed to confirm the effectiveness of a tuned liquid damper, which uses heat storage tanks. Simulation analyses were also carried out using a lumped-mass model to verify the appropriateness of the simulation method.

2 OUTLINE OF THE STRUCTURE AND TUNED LIQUID DAMPER

A twelve-story steel tower was chosen as the object of structural control. The tower was 5.0 meters square, and stood 33.8 meters high. The tuned liquid damper was installed on the



(a) Elevation and plan (b) Simulation model

Figure 1. Twelve-story steel tower

twelfth floor. The elevation and plan of the tower are presented in Figure 1(a). The natural frequencies of the tower after the installation of the tanks were 1.96 Hz horizontally in both directions. The damping ratio of the tower was 1.7 percent in the X direction and 1.6 percent in the Y direction.

The tuned liquid damper consisted of three vertically set heat storage tanks. Each tank measured 2.0 meters by 1.0 meters and had a depth of 0.5 meters. The upper part of each tank was partitioned to synchronize the sloshing frequency of the tank with the natural frequency of the tower. The sloshing frequency was designed to be 1.88 Hz given the increase in the total mass of the tower resulting from the water in the tanks. The elevation and cross section of the tuned liquid damper are shown in Figure 2.

3 SHAKING TABLE TESTS OF THE TUNED LIQUID DAMPER

Experimental parametric studies were conducted using a partial model of the tank in order to evaluate the properties of the tuned liquid damper. The experimental setup is illustrated in Figure 3.

A tuned liquid damper has a theoretically optimal damping ratio to suppress the vibration of a structure. Therefore, floating particles of poly-propylene pellets were used to control the damping ratio.

The partial model was excited sinusoidally with a constant acceleration for frequencies from 1.0 Hz to 3.0 Hz. The experimental results were obtained for four input acceleration levels in five different cases in terms of the quantity of floating particles added.

The equivalent mass and damping ratio of the tuned liquid damper were evaluated by applying a curve-fitting method from the obtained resonance curves of the horizontal force resulting from the liquid motion. Figure 4 presents one of the observed resonance curves. In Figure 4, the solid line represents the experimental results, while the dotted line represents the results calculated by the curve-fitting method.

The relationship between the equivalent mass of the tuned liquid damper and the added quantity of floating particles is shown in Figure 5. In Figure 5, the segmented line represents the value calculated with the equation proposed by Housner (1957). Figure 5 indicates that the equivalent mass is smaller than the theoretical value. The reason for this is that there is no partition in the lower part of the tank.

The effect of the floating particles on the damping ratio of the tuned liquid damper is

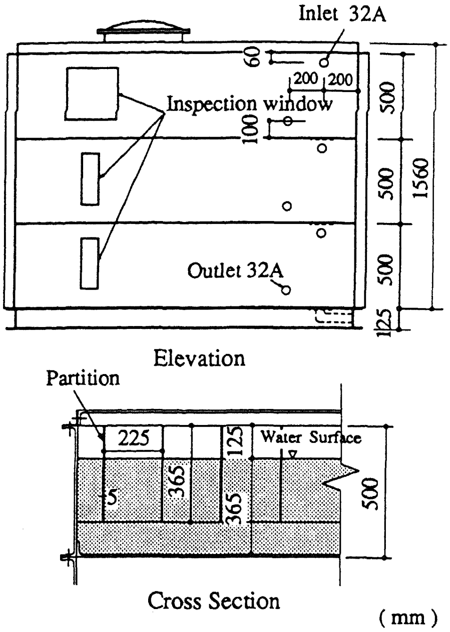


Figure 2. Tuned liquid damper using heat storage tanks

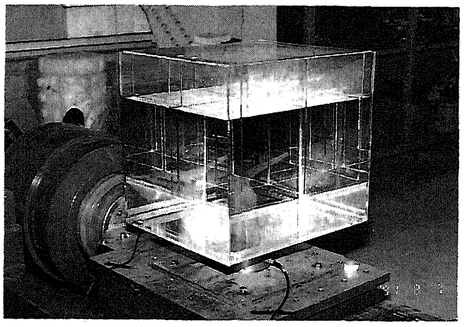


Figure 3. Experimental setup

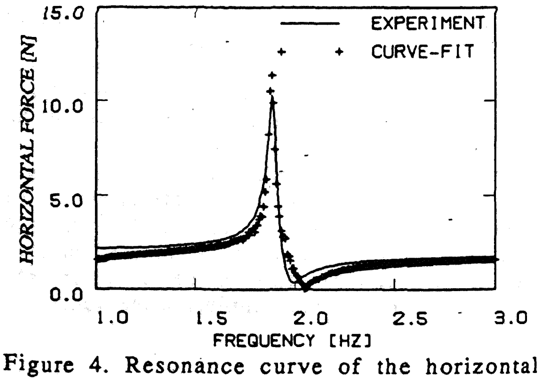


Figure 4. Resonance curve of the horizontal force (Floating particles 0 kg)

demonstrated in Figure 6. The findings revealed that the damping ratio increases proportionally to the added quantity of floating particles in the case of a low excitation amplitude (input acceleration = 0.02 m/s^2). However, this increase in the damping ratio is limited when the input acceleration exceeds 0.05 m/s^2. It, therefore, seems that the damping ratio is affected by the waves breaking in the tank provided that input acceleration is sufficiently large.

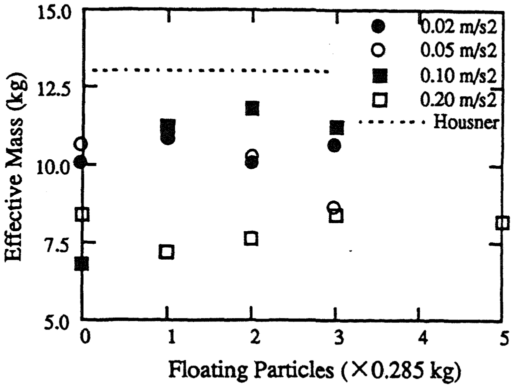


Figure 5. Relationship between the effective mass and the floating particles

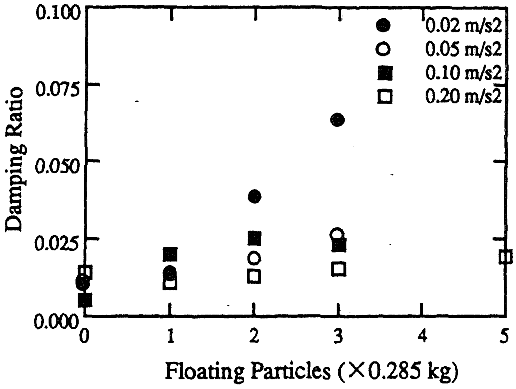


Figure 6. Relationship between the damping ratio and the floating particles

4 EARTHQUAKE OBSERVATION AND NUMERICAL ANALYSIS

4.1 *Earthquake observation*

The accelerometers were installed at three points along the height of the tower. A total of seven earthquake motion components, six horizontal and one vertical, were observed. The setup of the accelerometers is shown in Figure 1(a).

Earthquake observation began in January 1991 when the tanks were empty. This was done because it was deemed necessary to first assess the properties of the tower without the tuned liquid damper. Thereafter, water was injected into the tanks in April 1991. Floating particles were added in October 1991 to increase the damping ratio of the tuned liquid damper.

Eight earthquakes were recorded from January 1991 to December 1991. The maximum acceleration recorded on the ground was 0.098 m/s^2 on July 20, 1991, while the corresponding peak acceleration on the twelfth floor was 0.213 m/s^2.

4.2 *Simulation model*

Dynamic response analyses in the X direction were carried out using a lumped-mass model. The simulation model is shown in Figure 1(b). The mass and damping ratio of the tuned liquid damper were evaluated considering the results of the shaking table tests.

Figure 7 and Figure 8 show the observed and simulated transfer functions, which are expressed as the response on the twelfth floor to the movement on the ground. The transfer functions without the tuned liquid damper are shown in Figure 7, while those with the tuned liquid damper are shown in Figure 8. In those figures, the solid lines and the dotted lines represent the observed and simulated transfer functions, respectively. It can be seen that the simulated transfer functions agree well with the observed functions concerning the first mode.

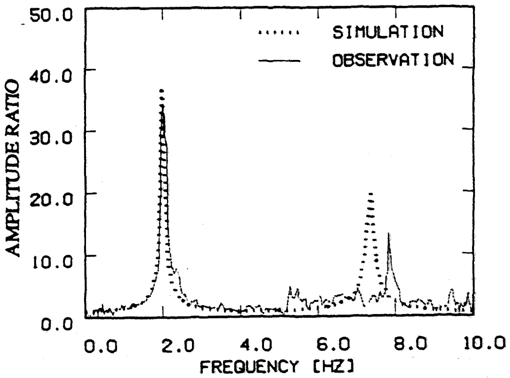


Figure 7. Transfer functions without the tuned liquid damper

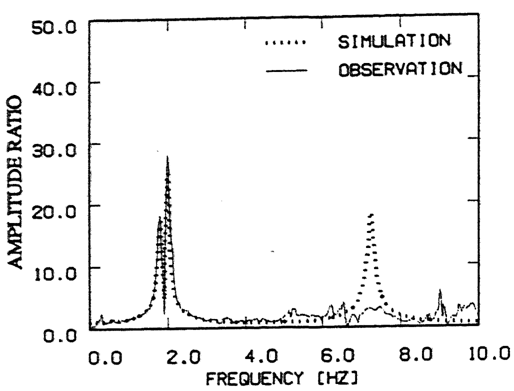


Figure 8. Transfer functions with the tuned liquid damper

4.3 *Simulation results*

Table 1 shows the maximum and root-mean-square (RMS) accelerations on the twelfth floor with and without the tuned liquid damper during five representative earthquakes. Table 2 shows the amplitude ratios of the accelerations on the twelfth floor with the tuned liquid damper to those without the tuned liquid damper. These tables clearly indicate that the responses with the tuned liquid damper are smaller than those without the tuned liquid damper, especially regarding the rms values.

Figure 9 shows the acceleration responses on the twelfth floor with and without the tuned liquid damper during the earthquake of October 19, 1991. In Figure 9, the response with the tuned liquid damper exhibits a phenomenon of beating. This is caused by the interaction of two adjacent peaks in the transfer function (see Figure 8).

Table 1. Comparison of acceleration on the twelfth floor without the tuned liquid damper

($\times 10^{-2}$ m/s^2)

No.	Earthquake	Maximum Value		RMS Value	
		with TLD	without TLD	with TLD	without TLD
1	May 18, 1991	11.20	12.73	2.02	2.73
2	June 28, 1991	4.73	4.89	0.96	1.27
3	July 14, 1991	16.67	16.79	4.31	5.47
*4	Oct. 19, 1991	11.42	13.16	1.72	3.23
*5	Nov. 19, 1991	14.59	15.16	2.46	3.16

* Floating particles were added to the tanks.
TLD : Tuned Liquid Damper

5 CONCLUSIONS

Observations during this confirmed that the tuned liquid damper, which uses heat storage tanks, was effective in reducing the response of a structure. Moreover, these observations also verified the appropriateness of the simulation method.

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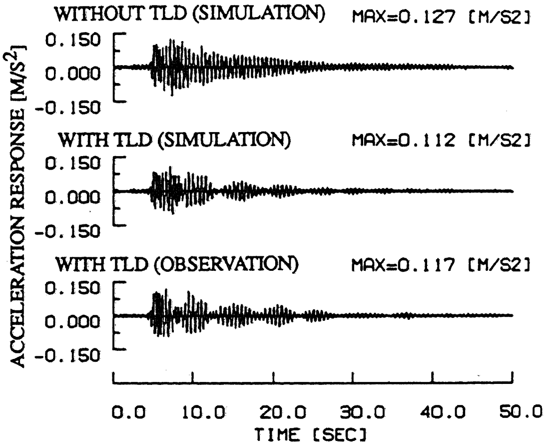

Figure 9. Acceleration response on the twelfth floor to the earthquake record (May 18, 1991)

Table 2. Amplitude ratio of acceleration on the twelfth floor

No.	Earthquake	Maximum Value	RMS Value
1	May 18, 1991	0.88	0.74
2	June 28, 1991	0.97	0.76
3	July 14, 1991	0.99	0.79
*4	Oct. 19, 1991	0.87	0.53
*5	Nov. 19, 1991	0.96	0.78

* Floating particles were added to the tanks.