# SOME CONSIDERATIONS ON SEISMIC DESIGN AND CONTROLS OF SLOSHING IN FLOATING-ROOFED OIL TANKS

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**ABSTRACT :**

During 2003 Tokachi-Oki earthquake (M=8.0) in Japan, many oil storage tanks in Tomakomai were damaged by sloshing due to long-period strong ground motion with high level from 4 to 8 seconds. In this paper, to establish countermeasures against sloshing for floating-roofed oil tanks, the authors investigate sloshing behaviors in consideration of the existence of actual floating-roof, and propose some countermeasures such as an earthquake-resistant structure, an isolation system and a vibration control method for floating-roof sloshing.

**KEYWORDS:** seismic design, vibration control, sloshing, floating-roof, oil tank, long-period motion

## 1. INTRODUCTION

In the 2003 Tokachi-Oki, Japan earthquake (M=8.0), many oil storage tanks were damaged heavily in the Idemitsu Oil Refinery at Tomakomai in Hokkaido. Excessive sloshing was excited in the tanks by the long-period strong ground motion generated from the deep sedimentary basin and having high level of velocity response spectra over Sv=2.0 m/sec between 4 to 8 seconds, and the floating-roofs of the tanks were broken and sunk due to sloshing (The Hazardous Materials Safety Techniques Association, 2004 and Hatayama, K., Zama, S., Nishi, H., Yamada, M., Hirokawa, M., Inoue, R., 2004). Similar examples of damage were seen in 1964 Alaska earthquake (USA) and Niigata earthquake (Japan), 1983 Nihonkai-Chubu earthquake (Japan), 1999 Kocaeli earthquake (Turkey) and Chi-Chi earthquake (Taiwan) and so on.

The floating-roofs can be supposed to have collapsed with buckling of their pontoons, and this damage pattern was already observed in the 1983 Nihonkai-Chubu, Japan earthquake. At that time one of the authors (*Sakai, F., 1985*) discussed the effect by the interactive sloshing behavior between a floating-roof and contained liquid through fluid-structure interactive (FSI) analysis in consideration of flexible floating-roof (Sakai, F., Nishimura, M., Ogawa, H., 1980, 1984), and also he discussed the damages due to the Tokachi-Oki earthquake from the same standpoint (Sakai, F., 2004).

In order to study the cause or mechanism of the collapse of floating-roof, it is necessary to clarify the sloshing behavior taking the existence of floating-roof into consideration, but almost all researches on tank sloshing have treated a free surface state without any floating-roof or assumed a floating-roof as a rigid body (for example, Senda, K., Nakagawa, K., 1954, Housner, G. W., 1957, and Yamamoto, Y., 1965).

As long as the maximum wave height is concerned, either the case of a free surface or the case of a rigid floating-roof does not make much difference, since the first mode response of sloshing is dominant. However, in order to discuss the seismic strength of floating-roof, we need to solve the sloshing behaviors correctly in consideration of actual flexible floating-roof.

Recently in Japan, floating-roof sloshing researches considering the existence of actual floating-roof have been conducted since the Tokachi-Oki earthquake damage (Sakai, F., Inoue, R., Hayashi, S., 2006, Nishiguchi, H., Ito, M., Honobe, H., Kanoh, T., 2005 and Matsui, T. 2006). However, it can be said that the elucidation of floating-roof sloshing behaviors has been still insufficient, and that researches on earthquake-proof countermeasures against floating-roof sloshing have not been promoted so much.

In this paper, the authors first introduce some results of analysis to clarify the floating-roof sloshing behaviors, and secondly, based on the results, propose three new earthquake-proof measures against floating-roof sloshing, those are: an earthquake-resistant structure and an isolation system of floating-roof, and a vibration control method of floating-roof sloshing.

## 2. ANALYZED RESULTS OF FLOATING-ROOF SLOSHING

### *2.1. Method of Analysis*

With respect to the case that an elastic floating-roof exists on the surface of contained liquid in an oil tank, Sakai et al. (Sakai, F., Nishimura, M., Ogawa, H., 1984) developed the boundary element method of analysis, keeping an actual floating-roof in mind to model it as an orthotropic plate, which is based on the assumption of linearized theory, in order to consider simply the interactive sloshing between contained liquid and conventional single- and double-deck type or arbitrary type floating-roof.

### *2.2. Analyzed Model*

A 65,000m$^3$ tank shown in Table 2.1 is used as a model for the above-mentioned analysis, the floating-roof of which is a single-deck type shown in Figure 1. Moreover, considering the case where a double-deck type is used for the same tank, an analyzed model of double-deck floating-roof is shown in Figure 2. In case of double-deck type we need to treat top and bottom plates separately, both of which are stiffened by inside frames such as web plates or trusses, but especially the latter of which is acted upon by liquid pressure. Here it is assume that web plates and trusses are set in the direction of the circumference at r= 5m, 10 m, 15 m, 20 m, 25 m, and 29m and 32.3m respectively.

Table 2.1 Dimensions of analyzed model

| | |
|---|---|
| Tank diameter: 2a=65.000m | Liquid depth: h=20.0m |
| Floating-roof radius: 32.300m | Seal width: 0.200m |
| Floating-roof pontoon<br>Radial bending rigidity:<br>(inside) 37,040kN*m$^2$/m<br>Circumferential bending rigidity:<br>(inside) 200,400kN*m$^2$/m | <br><br>(outside) 63,800kN*m$^2$/m<br><br>(outside) 345,400kN*m$^2$/m |

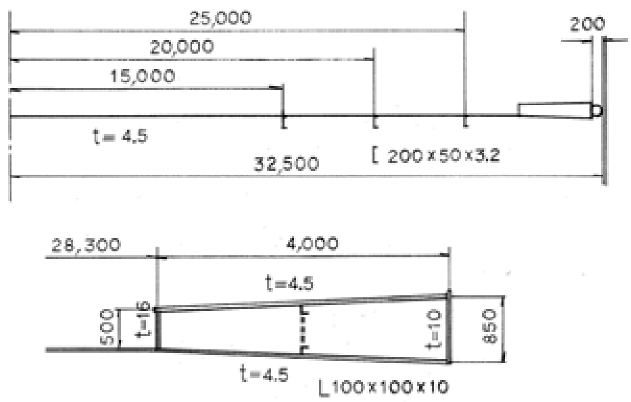



Figure 1 Analyzed model of single-deck floating-roof

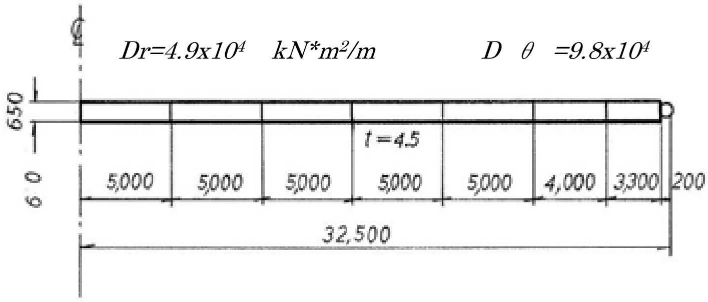



Figure 2 Analyzed model of double-deck floating-roof

### *2.3. Analyzed Results*

Figures 3 and 4 show the analyzed results in the cases of single-deck and double-deck respectively. Those results are the radial distribution of the modal responses of floating-roof vertical displacement and liquid dynamic pressure on $\theta=0$. Here the velocity response spectrum Sv is assumed to be 1.0 m/sec for each mode of the first order to the third order. In the figures the responses in the cases of a free surface and a rigid floating-roof are compared.

*2.3.1. Case of single-deck floating-roof*

Figure 3.(a) shows the radial distribution of floating-roof displacement, in other words the elevation change or the wave shape of liquid. As a whole the elevation change for the single deck differs hardly from the case of a free surface in the first mode to the third mode. This is because the rigidity of single-deck is very small. On the other hand, locally at the pontoon part with high rigidity, it turns out that there is some difference from the case of a free surface.

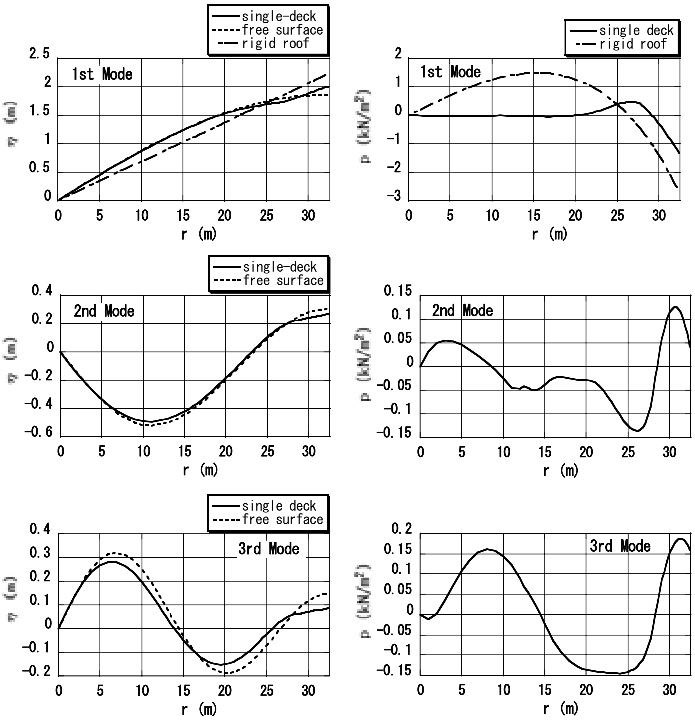
The overall elevation change for the first mode does not make any big difference among the cases of a free surface, a rigid floating-roof and the single-deck floating-roof. Also, in every case the wave height for the first mode, especially at the tank wall is predominant over that for the higher modes. As long as the maximum wave height is concerned, we have only to discuss the sloshing response for the first mode, but have to be careful that the wave height at the central part becomes considerably large, when the response for the second mode becomes significant from the characteristics of ground motion.

Figure 3.(b) shows the radial distribution of liquid dynamic pressure, which is not seen in the case of a free surface. The dynamic pressure for the first mode differs as a whole considerably from the case of a rigid floating-roof, but at the pontoon part with high rigidity negative dynamic pressure is generated similarly to the case of a rigid floating-roof, the order of which is a half of the case. The dynamic pressure for the second mode and the third mode is much smaller than that for the first mode.

*2.3.2. Case of double-deck floating-roof*

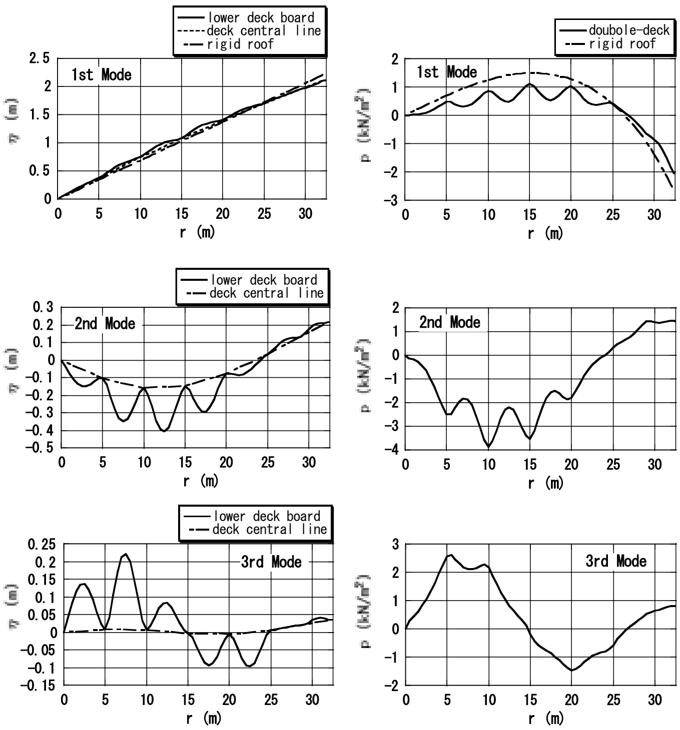
Figure 4.(a) shows the displacement distribution in the case of double-deck floating-roof. With respect to the displacement of double-deck we use two definitions, those are: the displacement along the deck center line between the top and bottom decks which means the overall double-deck displacement and the displacement of the bottom plate which is deformed locally between two stiffeners under the direct action of the liquid pressure. The overall displacement for the first mode agrees well between the cases of double-deck and rigid floating-roof, and the local deformation of the bottom plate is very small. On the other hand, the overall displacement for the higher modes is much smaller than the case of single-deck shown in Figure 3.(a), and this is because the double-deck with high rigidity suppresses the wave height for the higher modes. However, the local deformation of the bottom plate becomes significant and much larger than the overall displacement..

Figure 4.(b) shows the dynamic pressure distribution in the case of double-deck floating-roof. It agrees considerably with the case of a rigid floating-roof for the first mode except at the deck part. It should be noticed that the dynamic pressure for the higher modes becomes large and comparable to that for the first mode. This dynamic pressure, which is generated from suppressing the wave height for the higher modes, induces large bending moment at the central part of the double-deck.




(a) (b)

Figure 3 Modal response in the case of single-deck floating-roof: (a) displacement, (b) dynamic pressure




(a) (b)

Figure 4 Modal response in the case of double-deck floating-roof: (a) displacement, (b) dynamic pressure

Table 2 summarizes the numerical results for the cases of single-deck and double-deck floating-roof. From Figures 3, 4 and Table 2 the following considerations can be done:

- Whatever type of floating-roof is, the natural period for the first mode does not differ from that in the case of a free surface,. The natural period for the higher modes in the case of single-deck is almost the same as that in the case of a free surface, but in the case of double-deck it changes considerably from that in the case of a free surface or single-deck.
- With respect to the floating-roof displacement, that in the case of single-deck is almost equal to that in the case of a free surface, and that for the first mode in the case of double-deck is close to that in the case of a rigid floating-roof. However, the floating-roof displacement for the higher modes, which does not exists in the case of a rigid floating-roof theoretically, differs very much from that in the case of single-deck, in that the overall displacement is suppressed by the floating-roof with high rigidity and that the local deformation becomes predominant.
- In the case of single-deck the circumferential bending moment in the pontoon is generated considerably largely, especially for the first mode. Also, when the response for the second mode is predominant, large displacement is generated at the central part of the deck enough to produce membrane force in the deck part, which raises large compressive stresses in the pontoon. In the case of double-deck the radial and circumferential bending moments become large for the higher modes. These bending moments and the compressive stresses can be supposed to be causes for buckling failure of single-deck and double-deck floating-roof.

Table 2 Numerical results for the cases of single-deck and double-deck floating-roof

(a) Case of single-deck floating-roof

| Mode | Period (sec) | Max. disp. (m) | Max. dyn. pressure (kN/m$^2$) | Pontoon bending moment (kN*m/m) | |
|---|---|---|---|---|---|
| | | | | $M_r$ | $M_\theta$ |
| 1st | 9.369 | 2.017 | 1.385 | 4.002 | 96.13 |
| 2nd | 4.947 | 0.4917 | 0.1360 | 2.978 | 41.20 |
| 3rd | 3.739 | 0.2810 | 0.1867 | 2.724 | 43.10 |

(b) Case of double-deck floating-roof

| Mode | Period (sec) | Max. disp. (m) | Max. dyn. pressure (kN/m$^2$) | Deck bending moment (kN*m/m) | |
|---|---|---|---|---|---|
| | | | | $M_r$ | $M_\theta$ |
| 1st | 9.359 | 2.127 | 2.117 | 50.05 | 45.58 |
| 2nd | 3.524 | 0.4056 | 3.850 | 131.1 | 118.9 |
| 3rd | 2.238 | 0.2218 | 2.602 | 25.19 | 23.51 |

## 3. PROPOSAL OF COUNTERMEASURES

### *3.1. Earthquake Resistant Floating-roof*

When the input level of long-period strong ground motion is high, for example, in the case where the velocity response spectrum Sv is about 2.0 m/sec, the maximum level regulated in the revised Notification on oil storage tanks (The Fire and Disaster Management Agency, 2005) , the wave height of sloshing becomes about 4m at the tank wall for the first mode and about 1m around r=12m for the secondary mode. As mentioned above, such large wave height or in other words such large floating-roof displacement can induce large stresses around the pontoon enough to break the single-deck floating-roof.

The main cause inducing the phenomenon that leads to such buckling failure is in an extreme difference of rigidity between the deck part and the pontoon part of the single-deck floating-roof. It results in that the deck part with too low rigidity invites stress concentration to the pontoon part with high rigidity. Therefore, what is necessary is just to give the deck part appropriate rigidity by setting stiffening members (Sakai, F., Inoue, R., 2005).

In the conventional view, for example even in the Fire and Disaster Management Law, there has been somewhat an inflexible concept for a single deck floating-roof and double-deck floating-roof, and it has been understood that the former has low rigidity and that the latter has high rigidity.

The authors would like to emphasize that their proposal here could be seen to be a new concept of single-deck floating-roof, which can secure enough high rigidity to resist sloshing forces. In order to calculate appropriate rigidity and spacing of stiffening members, for example the above-mentioned method of analysis can be applied.

### *3.2. Isolation of Floating-roof*

In the case of a conventional single-deck type, as mentioned above, the cause of its buckling failure is supposed to be that large stresses are induced locally around the pontoon part with high rigidity. So, if the pontoon has very low rigidity and high capability of deformation, the floating-roof will be able to deform along the wave motion of sloshing, but be free from large stresses, and consequently keep the function.

A way proposed here is to use a kind of isolation system as measures to realize such a concept, that is, to put rubber-like materials intermittently between the pontoon and consequently to reduce its overall rigidity extremely (Sakai, F., Inoue, R., 2005). Also, in the case of a conventional double-deck type or in the case of a new single-deck type mentioned above, similarly we have only to put rubber-like materials in the radial and circumferential direction between double-deck or stiffening members, considering that large bending moment occurs at the central part.

### *3.3. Vibration Control of Floating-roof Sloshing by TLCD*

*3.3.1. Concept of TLCD*

Although the above-mentioned measures of earthquake-resistant and isolation can secure the strength of floating-roof, it cannot reduce the wave height of sloshing response itself. Here, the authors propose a vibration control method to reduce the sloshing wave height by using TLCD (Tuned Liquid Column Damper), a passive damper named and developed previously for suppressing the vibration of bridges and buildings by Sakai et al. (Sakai, F., Takaeda, S., Tamaki, T., 1989).

TLCD is a kind of tuned mass damper, and if we install a TLCD on a floating-roof of tank, tune its natural period with that of the first mode of tank sloshing, and adjust the liquid mass and the orifice damping appropriately, we could suppress the floating-roof sloshing. When the notations are defined as follows: $\rho_1$=liquid density, L=liquid length, A=cross-sectional area of liquid column, and B=width of liquid column, the natural period and the damping coefficient of TLCD are obtained from the following equations, in which g is the gravity acceleration, $\kappa$ the loss coefficient of orifice and $\xi$ the elevation change:

$$T = 2\pi\sqrt{\frac{L}{2g}} \qquad C_{eq} = \frac{1}{2}\rho_1 A\kappa|\dot{\xi}| \qquad (3.1.\ a, b)$$

*3.3.2. Fundamental Equations of TLCD-Floating-roof Sloshing*

Since a general theory of TLCD with respect to arbitrary parallel and rotational movement is given (Sakai, F., Takaeda, S., Tamaki, T., 1989), the fundamental equations for the system of a tank and a rectangular TLCD shown in Figure 5 can be derived as follows (Sakai. F., Inoue, R., 2007).

Here it is assumed that the floating-roof is rigid, because as long as the maximum wave height is concerned, whether rigid or flexible a floating-roof is does not make much difference. We define the horizontal ground motion as X, the floating-roof displacement or the wave height at the tank wall as $\eta_0$, and the liquid height of TLCD as H. Also, in Equation (3.2) $I_R$, $I_T$ are the moments of inertia of the floating-roof and the TLCD container respectively, and $Z_\xi$, $Z_\eta$ are the participation factors for $\xi$ and $\eta_0$ respectively. Also, $I_\eta$, $C_\eta$ and $K_\eta$ represent respectively the moment of inertia, the damping coefficient and the generalized stiffness corresponding to the sloshing motion of the tank liquid.

$$\begin{bmatrix} \rho_1 AL & \rho_1 ABH/a \\ \rho_1 ABH/a & \dfrac{1}{a^2}\left[I_\eta + I_R + I_T + \rho_1 A\left\{\dfrac{1}{2}B^2\left(H+\dfrac{B}{6}\right)\right\} + \dfrac{2}{3}H^3\right] \end{bmatrix} \begin{Bmatrix} \ddot{\xi} \\ \ddot{\eta}_0 \end{Bmatrix} + \begin{bmatrix} \dfrac{1}{2}\rho_1 A\kappa|\dot{\xi}| & 0 \\ 0 & C_\eta \end{bmatrix} \begin{Bmatrix} \dot{\xi} \\ \dot{\eta}_0 \end{Bmatrix} + \begin{bmatrix} 2\rho_1 Ag & 0 \\ 0 & K_\eta \end{bmatrix} \begin{Bmatrix} \xi \\ \eta_0 \end{Bmatrix} = -\begin{Bmatrix} Z_\xi \\ Z_\eta \end{Bmatrix} \ddot{X} \qquad (3.2)$$

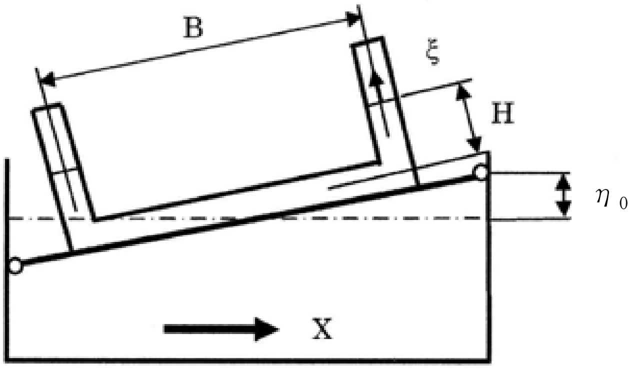
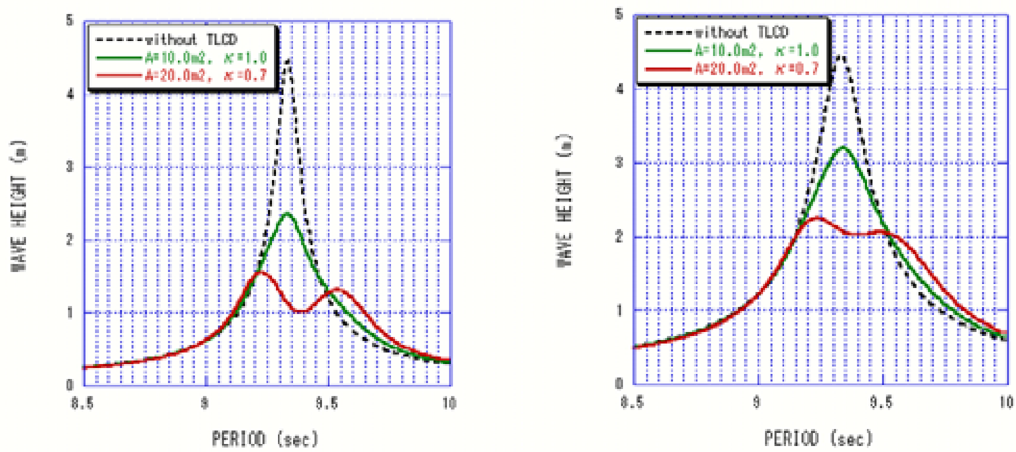



Figure 5 TLCD set on floating-roof of oil tank

*3.3.3. Example*

Let us analyze an application of TLCD shown in Figure 5 to the above-mentioned model tank. The dimensions of TLCD are given as $\rho_1$=1,000kg/m$^3$, B=30.0m, H=7.0m, A=10.0m$^2$ and 20.0m$^2$. Also, the damping ratio of the first mode sloshing for the tank is 0.5% and 1.0%.

The results of steady state vibration analysis are shown in Figure 6. The response is dependent of $\kappa$, and the values of $\kappa$ shown in the figure are corresponding to the cases in which the effect of TLCD is considerably high. It can be seen that the TLCD with A=20.0m$^2$ reduces the peak response to 1/3-1/2 for the damping ratio 0.5%-1.0% of the first mode sloshing. This indicates that the equivalent damping ratio of the first mode sloshing in the case with TLCD becomes twice to three times larger than in the case without TLCD.




(a) sloshing damping ratio 0.5% (b) sloshing damping ratio 1.0%

Figure 6 Comparison between the cases without and with TLCD (Sv=2.0m/sec)

## 4. CONCLUSIONS

The authors first introduced the results of fluid-elastic sloshing analysis with respect to a model tank with single-deck and double-deck floating-roofs to clarify the floating-roof sloshing behaviors, which so far have not been discussed sufficiently. Next, based on the results they proposed three new countermeasures of an earthquake-resistant structure and an isolation system of floating-roof, and a vibration control of floating-roof sloshing by using TLCD. Lastly, they derived the fundamental equations of TLCD-floating-roof sloshing and discussed the effect for reduction of the maximum wave height through some numerical analysis. Further study to actualize these measures will be needed hereafter.

## ACKNOWLEDGEMENTS

This research was in part supported by the Grant-in-Aid for Scientific Research (C) 17560420 from the Japan Society for the Promotion of Science. The authors would like to express our sincere gratitude to the society.

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