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# SLOSHING CONTROL OF A LIQUID STORAGE TANK UNDER LONG PERIOD GROUND EXCITATION

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## *Abstract*

The isolation technology is often employed to reduce the base shear of the liquid storage tank, but consequently causing the increase of the sloshing response, which may result in the damage of tanks, especially for those tanks excited by the long-period ground motions. In this study, a kind of rotatory damper, called viscous mass damper (VMD), is used with isolation bearings to control the sloshing response of the liquid storage tank excited by long-period ground motions. A two-lumped-mass model is used to represent the liquid storage tank, and a large number of time history analyses are conducted to investigate and compare the seismic responses of the non-isolated tank, the isolated tank without a VMD, and the one with a VMD. Three natural earthquake records are chosen for the seismic analysis, including the 1940 Imperial Valley earthquake, the 1999 Chi-Chi earthquake and the 2003 Tokachi-oki earthquake, and the last two are considered to be long period earthquakes. The analysis results show that the wave heights of the storage tank under the Chi-Chi and Tokachi-oki earthquake are much higher than that under the Imperial Valley earthquake, even though the PGAs of the former two earthquake records are much lower than that of the Imperial Valley record. In the long period earthquake cases, the base shear and wave height of the liquid storage tank are even found to be higher than those of the non-isolated tank. Therefore, the seismic response of liquid storage tank under the long period ground motion cannot be effectively controlled by only subjoining the isolating bearings. However, under both the Imperial Valley and the long period ground motions, the wave heights of the isolated tank with a VMD are found to be lower than those of the non-isolated tank, which implies that the sloshing response of the liquid storage tank can be reduced by using the isolation bearing and VMD. Also, the base shears of the isolated tank with a VMD are found to be much lower than those of the non-isolated tank. What’s more, compared with the isolated tank, the base displacement of the isolated liquid storage tank with a VMD is much lower. Therefore, the VMD can be used with isolation bearings to effectively control the sloshing response, as well as the base shear, of the liquid storage tank under the long period ground motion.

*Keywords: liquid storage tank; viscous mass damper; sloshing response; long period ground motion*

## 1. Introduction

Liquid storage tanks are often used in water supply systems, chemical industries, and nuclear plants and are therefore very important facilities for public life and safety. In previous decades, failures of liquid storage tanks were observed during strong earthquakes, like the 1999 kocaeli earthquake, the 1999 Chi-Chi earthquake, the 2003 Tokachi-oki earthquake and 2011 East Japanese earthquake [1-4]. Studies have used base isolation techniques to reduce the seismic response of the liquid storage tank [5-7]. It has been proved that the base shear of the tank can be reduced by subjoining the isolation bearings. However, in the long period earthquake case, the sloshing response of the liquid storage tank may be destructive and cause damages of the tank, like the rupture of the joint, buckling of the top shell, or damage of floating roofs [8, 9]. Several authors have observed that using the traditional isolation methods cannot help to control the sloshing of the liquid storage tank [10,11]. Therefore, it is essential to find new methods to reduce the sloshing of the liquid storage tank, especially under the long period ground motions.

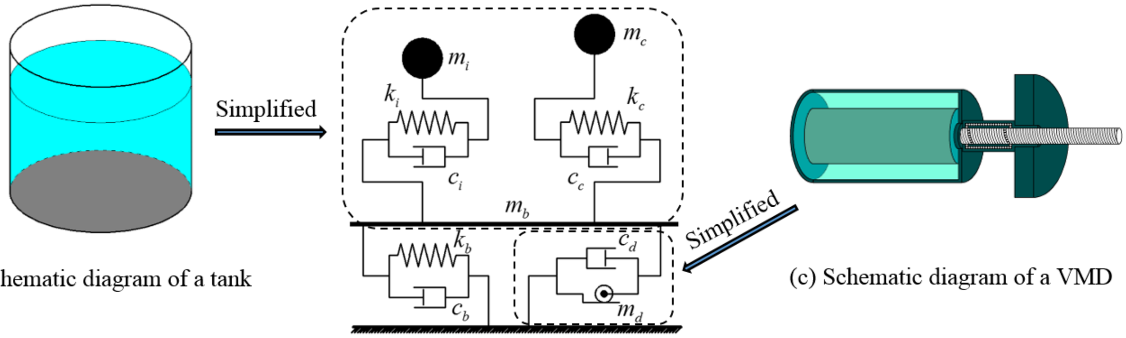
In this study, a new method, in which a rotatory mass damper called viscous mass damper (VMD) is used with isolation bearings, is proposed to control the sloshing responses of the liquid storage tank under the long period ground motions. For the liquid storage tank with isolation bearings and VMD, the input energy due to the earthquake is partly transferred and dissipated by the VMD, so the seismic response of the main structure may be suppressed. To the best of our knowledge, the application of the VMD to reducing the sloshing of the liquid storage tank under the long period ground motion has not been researched. Thus, under the long period earthquake, the seismic response of the liquid storage tank with isolation bearings and VMD is investigated and the effectiveness of the new control method is verified in this study.

This paper mainly includes: the mechanical models of the liquid storage tank and VMD in Chapter 2; the governing motion equations of the isolated tank with a VMD and their solutions in Chapter 3; and the investigation of the seismic response of the isolated tank with a VMD, and comparisons with those of the non-isolated tank and the isolated tank without a VMD, under the 1940 Imperial Valley earthquake and two long period earthquakes in Chapter 4.

## 2. Mechanical models

### 2.1 Simplified model of tanks

In this study, Malhotra's model [12] is employed to analyze the seismic response of the liquid storage tank. As shown in Fig. 1, the liquid storage tank can be simply represented by a two-lumped-mass model. The storage liquid is divided into two parts: convective component and impulsive component.



(a) Schematic diagram of a tank

(b) Simplified model of the controlled system

(c) Schematic diagram of a VMD

Fig.1 – Mechanical model of the isolated liquid storage tank with a VMD

In Fig.1, $m$, $k$ and $c$ are the equivalent mass, equivalent stiffness and equivalent damping coefficient, respectively. The subscripts $i$ and $c$ denote the impulsive and convective components, respectively, and the subscripts $b$ and $d$ denote the isolation system and the VMD system, respectively. By using Malhotra's method, the structural parameters of the liquid storage tank are obtained according to the following equations and Table 1.

$$m_l = \pi\rho_l HR^2 \tag{1}$$

$$T_i = C_i \frac{H\sqrt{\rho_l}}{\sqrt{t/R}\times\sqrt{E_s}} \tag{2}$$

$$T_c = C_c\sqrt{R} \tag{3}$$

$$k_i = m_i\left(\frac{2\pi}{T_i}\right)^2 \tag{4}$$

$$k_c = m_c (\frac{2\pi}{T_c})^2 \tag{5}$$

$$c_i = 2\xi_i \sqrt{k_i m_i} \tag{6}$$

$$c_c = 2\xi_c \sqrt{k_c m_c} \tag{7}$$

where $m_l$ is the total mass of the storage liquid in the tank; $H$ and $R$ are the height of the storage liquid and the radius of the tank, respectively; $\rho_l$ is the physical density of the storage liquid; $t$ and $E_s$ are the thickness and Young's modulus of the tank wall, respectively; $T$ , $C$ and $\xi$ denote the equivalent period, the period coefficient from Table 1 and the equivalent damping ratio, and the $i$ and $c$ denote the impulsive and convective components, respectively.

Table 1 – Parameters for simplified model [12]

| $r = H / R$ | $C_i$ | $C_c$ | $m_i / m_l$ | $m_c / m_l$ | $h_i / H$ | $h_c / H$ |
|---|---|---|---|---|---|---|
| 0.3 | 9.28 | 2.09 | 0.176 | 0.824 | 0.400 | 0.521 |
| 0.5 | 7.74 | 1.74 | 0.300 | 0.700 | 0.400 | 0.543 |
| 0.7 | 6.97 | 1.60 | 0.414 | 0.586 | 0.401 | 0.571 |
| 1.0 | 6.36 | 1.52 | 0.548 | 0.452 | 0.419 | 0.616 |
| 1.5 | 6.06 | 1.48 | 0.686 | 0.314 | 0.439 | 0.690 |
| 2.0 | 6.21 | 1.48 | 0.763 | 0.237 | 0.448 | 0.751 |
| 2.5 | 6.56 | 1.48 | 0.810 | 0.190 | 0.452 | 0.794 |
| 3.0 | 7.03 | 1.48 | 0.842 | 0.158 | 0.453 | 0.825 |

## 2.2 Simplified model of a rotatory damper

The VMD mainly consists of two parts, a flywheel and an inner tube coated with viscous fluid, both of which are mounted with a ball screw, as shown in Fig.1. Through the ball screw and ball nut, longitudinal motion such as inter-story drift of a building can be transferred into the high-speed rotational motion of the flywheel and internal tube. Consequently, both the equivalent inertial mass of the flywheel and the viscous effect of the viscous fluid can be amplified significantly.

To derive a mathematical model, the rotary flywheel can be simplified as a mass element, and the viscous fluid around the rotatory internal tube can be idealized as a viscous damping element. The physical characters of this system are that the two elements share the same displacement while having dependent forces, which can be modeled by the parallel connection between the mass element and the viscous element. Therefore, the mechanical model for a VMD can be represented as shown in Fig. 1, where $c_d$ denotes the equivalent damping coefficient of the viscous damping element and $m_d$ , the equivalent mass of the rotary mass element.

## 2.3 Mechanism for enhancing rotatory dampers

In the VMD, the linear inter-story drift can be transferred into the high-speed rotary motion of the flywheel and viscous fluid. Because the inertial mass element and viscous element are mounted in parallel, they share the same displacements, and the damping force of this damper can be calculated by the following equation:

$$p_d = c_d \dot{x}_d + m_d \ddot{x}_d \tag{8}$$

where $p_d$ is the longitudinal damping force of the VMD; $\dot{x}_d$ and $\ddot{x}_d$ are the velocity and acceleration of the VMD, respectively. The equivalent inertial mass and equivalent damping coefficient can be respectively written as follows [13]:

$$m_d = 0.5 S_i^2 (r_o^2 + r_i^2) m_0 \tag{9}$$

$$c_d = S_v^2 \upsilon A / d_y \tag{10}$$

where $S_i$ denotes the ratio of the angular acceleration at the internal wall of the housing to the linear relative acceleration; $r_o$ and $r_i$ are the outer and inner radius of the flywheel, respectively; $m_0$ is the original mass of the flywheel; $S_v$ denotes the ratio of the angular velocity at the internal wall of the housing to the linear relative velocity; $\upsilon$ is the kinematic viscosity of the viscous material; $A$ is the lateral area of the internal tube; and $d_y$ is the gap between the internal and the external tubes. From Eq.(9), it is found that the mass of the flywheel can be amplified by $0.5 S_i^2 (r_o^2 + r_i^2)$ times, which can exceed several thousands [13].

## 3. Governing motion equations

It shows in Fig.1 that both the isolation bearings and the VMD are installed between the base of the tank and the ground. Assuming that the controlled tank is excited by ground motion $\ddot{x}_0$, the governing motion equations can be expressed as follows:

$$\begin{cases} m_c \ddot{x}_c + c_c(\dot{x}_c - \dot{x}_b) + k_c(x_c - x_b) = -m_c \ddot{x}_0 \\ m_i \ddot{x}_i + c_i(\dot{x}_i - \dot{x}_b) + k_i(x_i - x_b) = -m_i \ddot{x}_0 \\ m_b \ddot{x}_b + k_b x_b + c_b \dot{x}_b + p_d - c_i(\dot{x}_i - \dot{x}_b) - k_i(x_i - x_b) - c_c(\dot{x}_c - \dot{x}_b) - k_c(x_c - x_b) = -m_b \ddot{x}_0 \\ p_d = m_d \ddot{x}_b + c_d \dot{x}_b \end{cases} \tag{11}$$

where $x$, $\dot{x}$ and $\ddot{x}$ denote the relative displacement, velocity and acceleration, respectively; and the subscripts $c$, $i$ and $b$ denote the convective component, impulsive component and the tank base, respectively. The above equations can be expressed in metric form as follows:

$$(\mathbf{M_s} + \mathbf{M_a})\ddot{\mathbf{x}} + \mathbf{K_s}\dot{\mathbf{x}} + (\mathbf{C_s} + \mathbf{C_a})\mathbf{x} = -\mathbf{M_s}\mathbf{I}\ddot{x}_0 \tag{12}$$

where $\mathbf{M_s}$, $\mathbf{K_s}$, and $\mathbf{C_s}$ are the mass matrix, stiffness matrix, and damping matrix of the main structure, respectively; $\mathbf{M_a}$ and $\mathbf{C_a}$ are the additional mass matrix and additional damping matrix provided by the VMD, respectively; $\mathbf{x}$ is the displacement vector of the controlled tank; and $\mathbf{I}$ is the unit vector. The above matrixes and vectors are respectively expressed as follows:

$$\begin{gathered} \mathbf{M_s} = \begin{bmatrix} m_c & & \\ & m_i & \\ & & m_b \end{bmatrix}, \quad \mathbf{M_a} = \begin{bmatrix} 0 & & \\ & 0 & \\ & & m_d \end{bmatrix}, \quad \mathbf{K_s} = \begin{bmatrix} k_c & 0 & -k_c \\ 0 & k_i & -k_i \\ -k_c & -k_i & k_c + k_i + k_b \end{bmatrix} \\ \mathbf{C_s} = \begin{bmatrix} c_c & 0 & -c_c \\ 0 & c_i & -c_i \\ -c_c & -c_i & c_c + c_i + c_b \end{bmatrix}, \quad \mathbf{C_a} = \begin{bmatrix} 0 & & \\ & 0 & \\ & & c_d \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} x_c \\ x_i \\ x_b \end{bmatrix}, \quad \mathbf{I} = \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} \end{gathered} \tag{13}$$

Using the Newmark's algorithm, these equations can be easily solved to obtain numerical solutions for the controlled tank and to thus obtain the seismic response of the system.

## 4. Numerical examples and seismic analysis

### 4.1 Parameters of the tank and VMD

To evaluate the control effect on the vibration of the isolated tank with a VMD, a benchmark model [11] is employed in this analysis, the physical parameters of which are listed in Table 2.

Table 2 – Parameters of tank used in this study

| Liquid | Radius | Height | Aspect ratio | Physical density | Wall thickness | Young's modulus |
|---|---|---|---|---|---|---|
| Water | 7.32 m | 10.98 m | 1.5 | 1000 kg/m$^3$ | 0.0254 m | $2.06\times10^{11}$ N/m$^2$ |

Using Malhotra's above-described procedure, the structural parameters of this tank can be obtained, as shown in Table 3.

Table 3 – Structural parameters of tank used in this study

| Parameter | Impulsive component | Convective component |
|---|---|---|
| Equivalent mass | $1.268\times10^6$ kg | $5.804\times10^5$ kg |
| Equivalent period | 0.079 s | 4.004 s |
| Equivalent stiffness | $8.082\times10^9$ N/m | $1.429\times10^6$ N/m |
| Damping ratio | 0.02 | 0.005 |
| Damping coefficient | $4.049\times10^6$ N·s/m | $9.107\times10^3$ N·s/m |

The base of the tank is designed such that its mass is $1.848\times10^5$ kg, and the laminated rubber bearings are used with a stiffness of $1.24\times10^7$ N/m and an additional damping ratio of 0.10. Modal analysis of the isolated tank is conducted, and the modal periods are obtained as 4.301 s, 2.004 s, and 0.028 s. By installing isolation bearings, both the first and the second modal periods of the liquid storage tank are enlarged. In this analysis, the first modal period is enlarged by 8%, whereas the second modal period is amplified by around 25 times.

Because the damping force provided by the VMD is closely related to the responses of the tank base, which are mainly influenced by the impulsive component of the liquid stored in the tank, the equivalent mass $m_d$ can be adjusted as per the impulsive mass, and the equivalent viscous damping coefficient $c_d$ can be adjusted as per the impulsive damping coefficient as follows:

$$m_d = \mu m_i \tag{14}$$

$$c_d = \eta c_i \tag{15}$$

where $\mu$ and $\eta$ denote the adjustment factors of the equivalent mass and equivalent viscous damping coefficient of the VMD, respectively. In this study, they are both considered to be 0.6.

### 4.2 ground motions

Time history analysis method is employed to conduct the seismic analysis of the isolated tank with a VMD. For this purpose, three natural earthquake records are chosen: the 1940 Imperial Valley earthquake, the 1999 Chi-Chi earthquake, and the 2003 Tokachi-oki earthquake. The last two earthquakes are considered to be long-period earthquakes [14]. The PGAs of the Imperial Valley, Chi-Chi, Tokachi-oki earthquake records are 3.417m/s$^2$, 1.152m/s$^2$ and 0.729m/s$^2$. The acceleration time histories and acceleration spectra of these records are plotted in Fig.2.

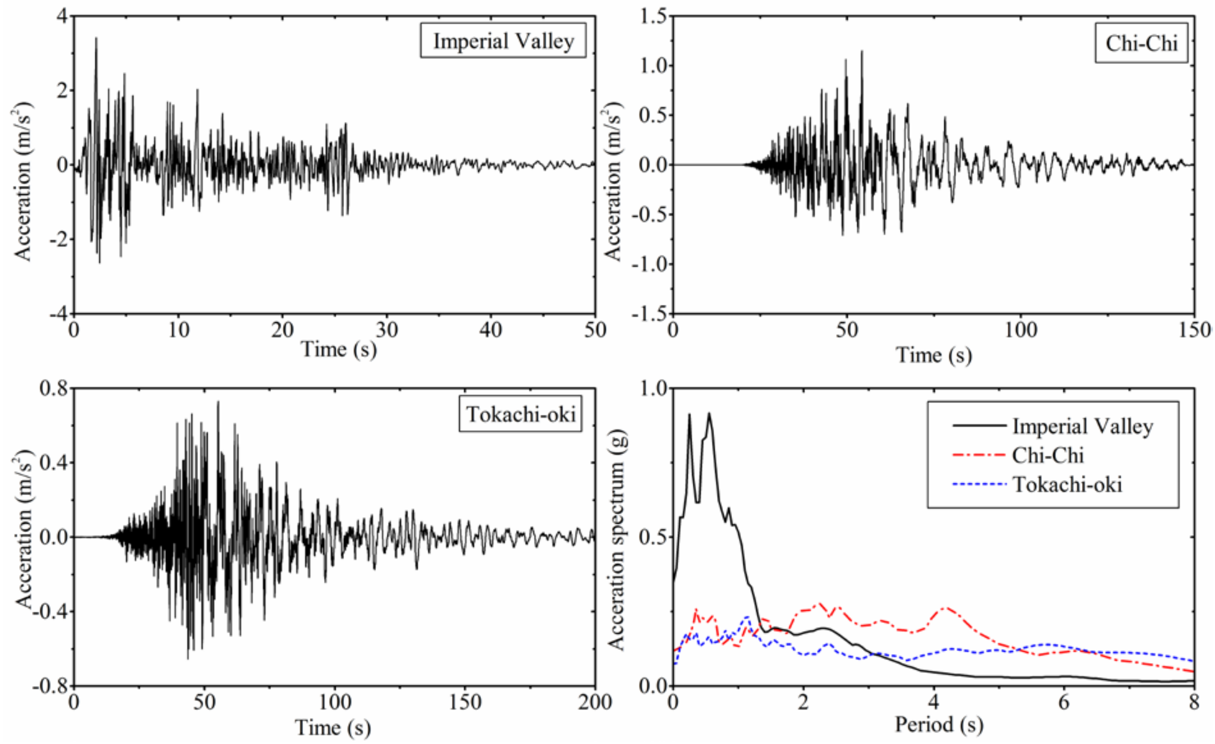


Fig.2 – Ground acceleration time histories and the corresponding acceleration spectra considered in this study.

## 4.3 Seisimc analysis of the isolated tank with a VMD

To verify the effectiveness of controlling the vibration of the isolated tank with a VMD, the seismic responses of the non-isolated tank and the isolated tank without VMD are also analyzed for comparison. The relative displacement of the basement $x_b$, the normalized base shear $\tilde{F}_b$, and the wave height $H_w$ for the three tanks are compared to assess the control effect of the VMD used with isolated bearings on the seismic response of the liquid storage tank. The normalized base shear $\tilde{F}_b$ is defined as the ratio of the base shear to the total gravity, $\tilde{F}_b = F_b / W$, and $F_b$ and $W$ are the base shear and total weight of the tank structure, respectively, which are expressed as follows:

$$F_b = m_c(\ddot{x}_c + \ddot{x}_0) + m_i(\ddot{x}_i + \ddot{x}_0) + m_b(\ddot{x}_b + \ddot{x}_0) \tag{16}$$

$$W = (m_c + m_i + m_b)g \tag{17}$$

where $g$ is the acceleration due to gravity. The wave height $H_w$ is calculated based on the absolute convective acceleration as follows [15]:

$$H_w = 0.84R(\ddot{x}_c + \ddot{x}_0) / g \tag{18}$$

The proceeding three natural earthquake records are employed to conduct time history analyses for the non-isolated tank, the isolated tank without VMD and the isolated tank with VMD. Time histories of the base displacement, normalized base shear and wave height of the three tanks are presented in Fig.3~Fig.5, and the according maximum results are listed in Table 4.

It can be observed from Table 4 that, under the Imperial Valley earthquake, the base shear of the isolated tank is far lower than that of the non-isolated tank, which implies that using the isolation method may help to reduce the base shear of the liquid storage tank. However, the wave height of the isolated tank is somewhat higher than that of the non-isolated one, which agrees with the conclusions made by several researchers [10,11]. In this case, the wave height of liquid storage tank is amplified by about 5.8% by using the isolation method.

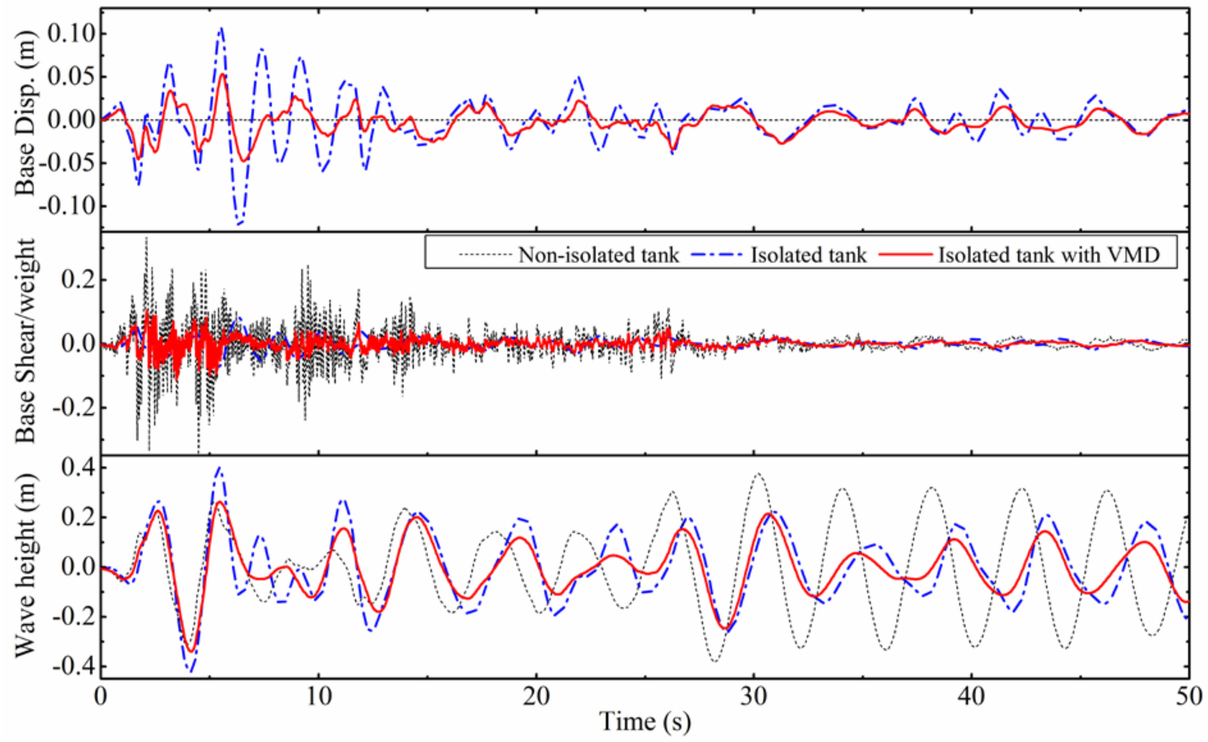


Fig.3 – Time history variations of the base displacements, normalized base shears and wave heights of the three tanks under the 1940 Imperial Valley earthquake.

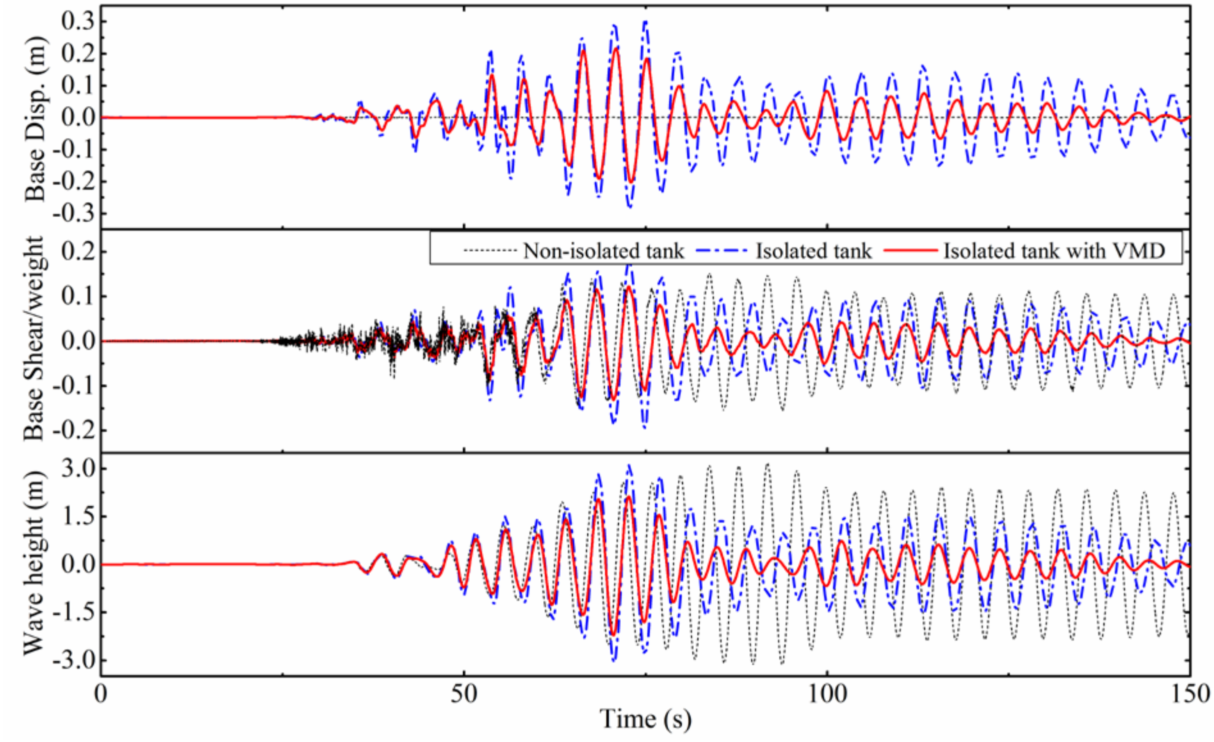


Fig.4 – Time history variations of the base displacements, normalized base shears and wave heights of the three tanks under the 1999 Chi-Chi earthquake.

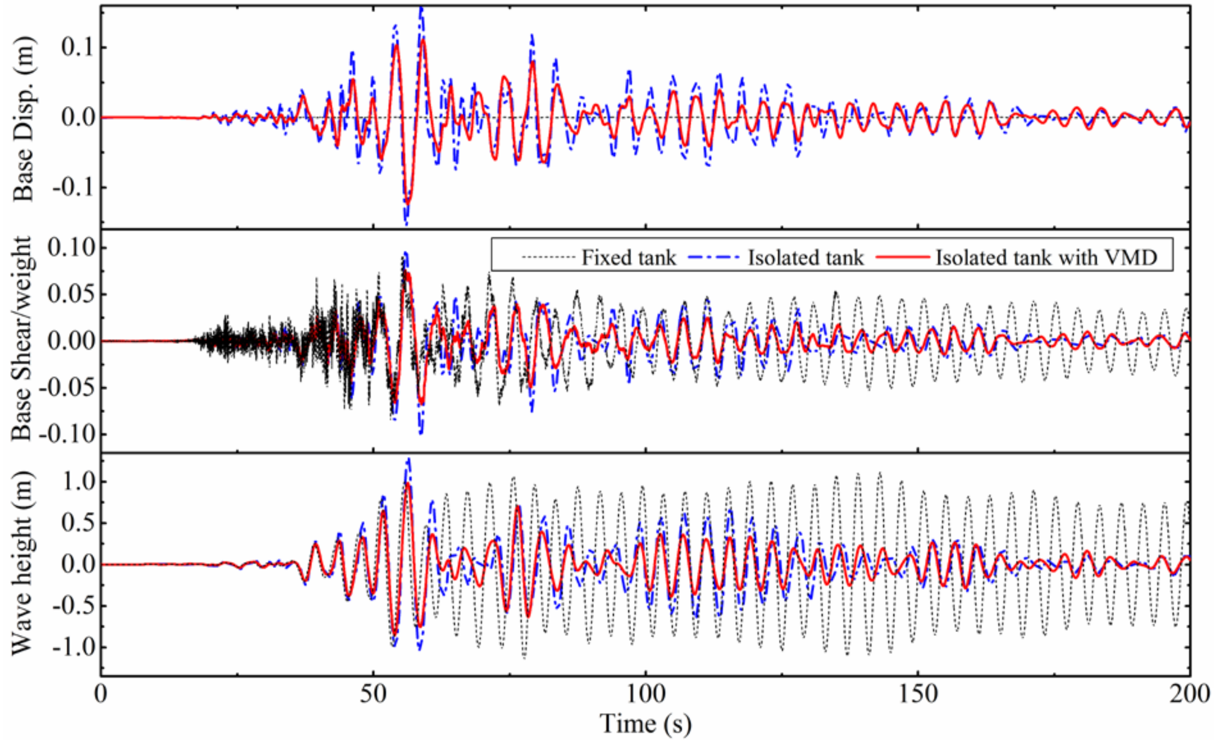


Fig.5 – Time history variations of the base displacements, normalized base shears and wave heights of the three tanks under the 2003 Tokachi-oki earthquake.

Table 4 Maximum seismic responses of the three tanks under various ground motions

| Earthquake | Type of tank | Base disp. (m) | Base shear/Weight | Wave height (m) |
|---|---|---|---|---|
| Imperial Valley,1940 | Non-isolated tank | 0.000 | 0.334 | 0.377 |
| | Isolated tank | 0.107 | 0.081 | 0.399 |
| | Isolated tank with VMD | 0.054 | 0.104 | 0.262 |
| Chi-Chi, 1999 | Non-isolated tank | 0.000 | 0.092 | 1.110 |
| | Isolated tank | 0.161 | 0.097 | 1.293 |
| | Isolated tank with VMD | 0.111 | 0.076 | 0.982 |
| Tokachi-oki, 2003 | Non-isolated tank | 0.000 | 0.151 | 3.175 |
| | Isolated tank | 0.308 | 0.178 | 3.124 |
| | Isolated tank with VMD | 0.216 | 0.122 | 2.125 |

For the isolated tank with VMD, both the base shear and the wave height are lower than those of the non-isolated tank, and the reduction ratios on the base shear and wave height are about 68.9% and 34.1%. Therefore, the VMD can be used with the isolation bearings to reduce the wave height of the liquid storage tank. Although the base shear of the isolated tank with VMD, in this case, is little larger than that of the isolated tank, it is still much lower than that of the non-isolated tank.

Under the Chi-Chi and Tokachi-oki ground motions, it is found that the base shears of the isolated tank are larger by about 6.4% and 17.9% than those of the non-isolated tank, respectively. In these case, the isolation bearings fail to reduce the base shear of the liquid storage tank because the isolation period is closed to the characteristic periods of the Chi-Chi and Tokachi-oki ground motions. The wave heights of the tanks in these case are much higher than those of the tanks under the Imperial Valley earthquake. It has been observed by several authors [8, 9] that the large sloshing response of the liquid storage tank may result in the damage of the floating roof, failure of the link element or spillover of the storage liquid. So in the long-period earthquake case, it becomes of great significance to control the sloshing of the liquid storage tank. In Table 4, it is found that the wave height of the isolated tank under the Tokachi-oki ground motion is larger by about 16.5% than that of the non-isolated tank. Therefore, using the isolation bearings cannot reduce base shear of liquid storage tank under long period ground motions, and even amplify the destructive sloshing response.

However, in Table 4, it can be found that, under the Chi-Chi earthquake, the base shear and wave height of the isolated tank with VMD are lower by about 19.1% and 33.1% than those of the non-isolated tank, respectively; and in the case of the Tokachi-oki earthquake, they are lower by about 16.7% and 11.5% than those of the non-isolated tank, respectively. So a VMD used with isolation bearings can help to reduce both the base shear and the wave height of the liquid storage tank.

What’s more, it is observed in Table 4 that the base displacement and wave height of the isolated tank can be largely reduced by appending a VMD. Under the Imperial Valley, Chi-Chi and Tokachi-oki earthquakes, the base displacements of the isolated tank with VMD are lower by about 50.1%, 30.9% and 30.0% than that of the isolated tank, respectively, which is very beneficial to those tanks where the pipelines are serious restricted. And the wave heights of the isolated tank with VMD are lower by about 34.4%, 24.0% and 32.0% than that of the isolated tank.

## 5. Conclusions

In this study, a VMD is used with the isolated bearings to control the sloshing response of the liquid storage tank under the long period ground motion. A two lumped mass simplified model is used to represent the liquid storage tank and the time history analyses method is employed. Three natural earthquake records, including the 1940 Imperial Valley earthquake record and two long period earthquake records are selected to conduct the seismic analysis. Three types of tanks are taken into consideration: non-isolated tank, isolated tank without VMD and isolated tank with VND. The base displacements, base shears and wave heights of the three tanks are analysed and compared. The main conclusions can be drawn as follows.

(i) the base displacement and wave height of the isolated liquid storage tank can be largely reduced by appending a VMD; Under the Imperial Valley, Chi-Chi and Tokachi-oki earthquakes, the base displacements of the isolated tank with VMD are found to be lower by about 50.1%, 30.9% and 30.0% than that of the isolated tank, respectively; and the wave heights are lower by about 34.4%, 24.0% and 32.0% than that of the isolated tank.

(ii) under the long period earthquake, using the isolation bearings fails to reduce the base shear of the liquid storage tank, and may even amplify the wave height; a VMD used with isolation bearings can help to reduce both the base shear and the wave height of the liquid storage tank. Under the Imperial Valley, Chi-Chi and Tokachi-oki earthquakes, the wave heights are lower by about 30.4%, 11.5% and 33.1% than that of the non-isolated tank, respectively; and the base shears of the isolated tank with VMD are found to be lower by about 68.9%, 16.7% and 19.1% than that of the non-isolated tank, respectively.

## 6. Acknowledgments

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## 7. Copyrights

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