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Vibration Response Suppression of Space Structure using Two U-Shaped Water Container

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***Abstract*— Nowadays, a passive vibration control technique using dynamic vibration absorbers (DVA) has drawn many researchers' attention in the structural dynamic field. The reason is that this technique is simple and it can work effectively in reducing the vibration response when its parameters are optimally designed. The DVA fundamental concept is the addition of a new vibration system to the primary system. This new system addition causes reduction of the vibration response of the primary system during excited by a dynamic load. One simple technique to realize the DVA for structural application is by using water vibration. This research is aimed to develop one type of dynamic vibration absorber using the water vibration system in a U-shaped container for a two-story building structure model. Besides being used as the dynamic absorber, this U-shaped container is also functioned as the water storage tank in the building. Regarding reduce the first bending mode response of the structure in x-z and y-z plane, two U-shaped water storage tanks are placed on the upper floor of the building. The dimensions of the water storage tanks are designed so that the natural frequency of moving water in the tank is the same as the natural frequency of the first bending mode of the structure in x-z and y-z plane. The performance of dynamic absorber is evaluated by applying the impulsive and seismic loads on the building. The simulation results show that the U-shaped water storage tank placed on the upper floor of the building can reduce the response amplitude of the structure under impulsive loads. Meanwhile, for the seismic load case, the performance of dynamic absorber is clearly seen when the excitation frequency is close to the natural frequency of the building structure.**

***Keywords*— building; water tank; vibration; seismic; absorber.**

I. INTRODUCTION

In general, there are two main approaches that can be used to improve the structural resistance against the dynamic load. The most popular method is by using the flexible foundation or vibration isolator [1]. This vibration attenuation device was successfully applied to several types of structures such as bridges and buildings in many countries. Another method is by increasing the structural stiffness and damping using passive damper elements [2].

The requirement of the vibration isolation method is that the isolator should be installed on the structure foundation before the structure is built. The difference with the first method, the second method can be applied to the structure even though the structure had been built. Several techniques have been proposed by many researchers to increase the structural stiffness and damping. Satria, et al.[3] uses friction damper elements to increase the structural stiffness and damping. Saloma et al. propose a technique for structural strengthening using bracing system [4]. Yeghnem, et al.[5] investigate reinforced concrete (RC) coupled shear wall structures strengthened by composite plates.

The dynamic vibration absorber (DVA) is a technique used to increase the damping factor of the vibration system. DVA is a vibration system which is added to the primary structure for reducing the vibration response of the system at a predetermined frequency range. This method usually used to suppress the excessive vibration response of the structure near its natural frequency [6], [7], [8], [9]. The DVA can effectively reduce the vibration response of the main system when its parameters are optimally designed. Some techniques have been proposed by researchers to optimally select the DVA parameters [10],[11],[12].

In this research, the damping factor of a two-storey building model is increased by using the DVA. A concept of DVA using u-shaped water storage tank is proposed in this study. The water motion inside the tank results in a reverse force against the inertia force of the building during seismic excitation. Two u-shape water tanks are used to reduce the vibration response of the building in *x* and *y*-direction. These two absorbers are designed that its frequency is tuned to the first bending mode frequency in *x-z* and *y-z* plane. A model of the two-storey building with a u-shape water tank as the dynamic vibration absorber is shown in Fig.1.

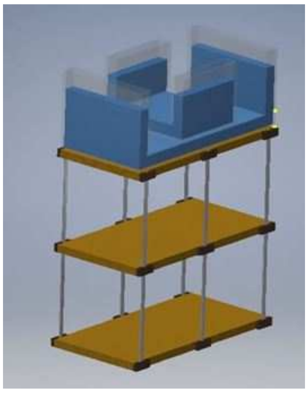


Fig. 1 A two-storey building model with u-shape water tank

II. MATERIAL AND METHOD

The governing equations of the two-storey building are modeled and analyzed using the Finite Elements Method (FEM)[13]. Each floor of the building is modeled using plate elements. The number of plate elements for the first and the second floor is 192 elements. The columns of the building are modeled using 3D frame elements. The elements numbers of all columns are 24. The scheme of building model and u-shape water tank are shown in Fig. 2. The governing equations of the building structural model with the water tank are written as follows:

$$\mathbf{Mu} + \mathbf{Cu} + \mathbf{Ku} = \mathbf{B_x} f_p + \mathbf{B_y} f_q \quad (1)$$

u denotes the displacement of the structure with DVA; **M**, **C,** and **K** are the structural mass, damping and stiffness matrix, respectively. f_p, f_q and **u** are the excitation force acting on p and q coordinate and the displacement vector of the structure, respectively. $\mathbf{B_x}$ and **By** are vectors that depend on the position of the external forces. These vectors can be written by,

$$\mathbf{B_x} = \left\{ \delta_{p,1} \quad \cdots \quad \delta_{p,j} \quad \cdots \quad \delta_{p,NDOF} \right\}^T \quad (2)$$

$$\mathbf{B_y} = \left\{ \delta_{q,1} \quad \cdots \quad \delta_{q,j} \quad \cdots \quad \delta_{q,NDOF} \right\}^T \quad (3)$$

p and q denote the position of the external forces f_p and f_q, respectively. NDOF is the number of degree of freedom and $\delta_{i,j}$ is delta function which is given by

$$\delta_{i,j} = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases} \quad (4)$$

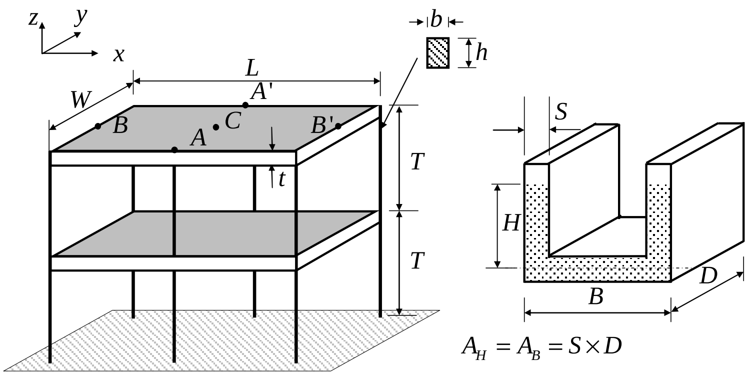


Fig. 2 Scheme of the two-storey building and water tank

The system mass, damping and stiffness matrix are calculated as follows [14]:

$$\mathbf{M} = \begin{bmatrix} m_{11} & \cdots & m_{1p} & \cdots & m_{1q} & \cdots & m_{1n} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_{p1} & \cdots & m_{pp} + m_{f1} & \cdots & m_{pq} & \cdots & m_{pn} & mf_1\bar{\kappa}_1 & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ m_{q1} & \cdots & m_{qp} & \cdots & m_{qq} + m_{f2} & \cdots & m_{qn} & 0 & mf_1\bar{\kappa}_2 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots & \vdots \\ m_{n1} & \cdots & m_{np} & \cdots & m_{nq} & \cdots & m_{nn} & 0 & 0 \\ 0 & \cdots & \kappa_1 & \cdots & 0 & \cdots & 0 & 1 & 0 \\ 0 & \cdots & 0 & \cdots & \kappa_2 & \cdots & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$\mathbf{C} = \begin{bmatrix} c_{11} & \cdots & c_{1p} & \cdots & c_{1q} & \cdots & c_{1n} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{p1} & \cdots & c_{pp} & \cdots & c_{pq} & \cdots & c_{pn} & 0 & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{q1} & \cdots & c_{qp} & \cdots & c_{qq} & \cdots & c_{qn} & 0 & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots & \vdots \\ c_{n1} & \cdots & c_{np} & \cdots & c_{nq} & \cdots & c_{nn} & 0 & 0 \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 & 2\zeta_{A1}\omega_{A1} & 0 \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 & 0 & 2\zeta_{A2}\omega_{A2} \end{bmatrix} \quad (6)$$

and

$$\mathbf{K}=\begin{bmatrix} k_{11} & \cdots & k_{1p} & \cdots & k_{1q} & \cdots & k_{1n} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ k_{p1} & \cdots & k_{pp} & \cdots & k_{pq} & \cdots & k_{pn} & 0 & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ k_{q1} & \cdots & k_{qp} & \cdots & k_{qq} & \cdots & k_{qn} & 0 & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots & \vdots \\ k_{n1} & \cdots & k_{np} & \cdots & k_{nq} & \cdots & k_{nn} & 0 & 0 \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 & \omega_{A1}^2 & 0 \\ 0 & \cdots & 0 & \cdots & 0 & \cdots & 0 & 0 & \omega_{A2}^2 \end{bmatrix} \quad (7)$$

The DVA damping ratios ζ_{A1} and ζ_{A2} in equation (6) are influenced by the characteristic of the orifice inside the water tank column [15]. The vibration parameters of the water inside the storage tank can be calculated as follows [16]:

$$\bar{\kappa}_i=\frac{B_i}{L_{1i}},\ m_{fi}=\rho\left(2H_iA_{H_i}+B_iA_{B_i}\right)=\rho A_{H_i}L_{1i}\ ,\ i=1,2 \quad (8)$$

$$\kappa_i=\frac{B_i}{L_{eff_i}},\ L_{eff_i}=2H_i+\frac{A_{H_i}}{A_{B_i}}B_i\ ,\ \omega_{Ai}=\sqrt{\frac{2g}{L_{eff_i}}}\ ,\ i=1,2 \quad (9)$$

The governing equation (1) is written in the modal coordinate as follows:

$$\ddot{q}+2\zeta_i\omega_i\dot{q}_i+\omega_i^2q_i=\mathbf{\Psi}_i\left[\mathbf{B}_\mathbf{x}f_p+\mathbf{B}_\mathbf{y}f_q\right], i=1,2,\cdots NDOF \quad (10)$$

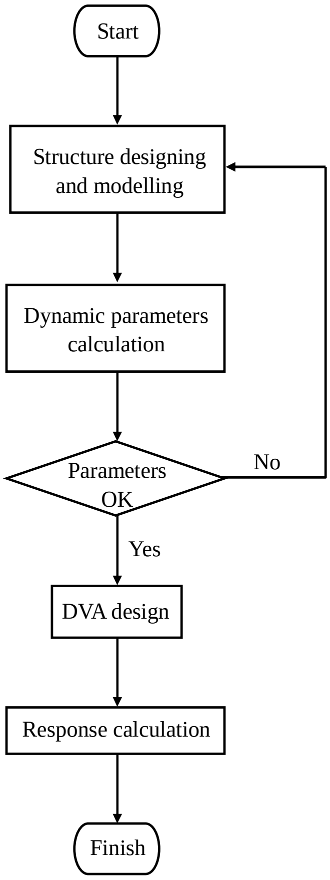


Fig. 3 Flowchart of the research

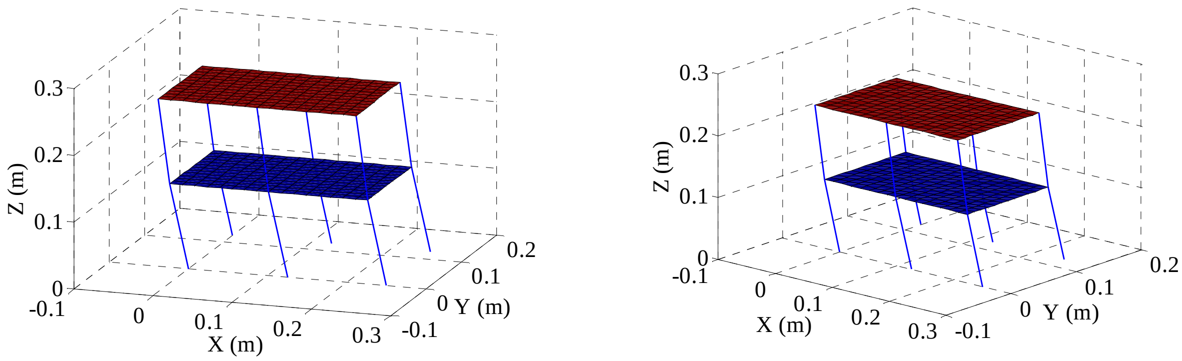
Fig. 3 shows a flowchart of the research work. First, the building structure is designed and modeled using the Finite Element Method (FEM). The numerical simulation using MATLAB software is performed to calculate the structural dynamic parameters, i.e., natural frequency and mode shape. In this case, the structure is designed that two lowest mode shapes are relating to the first bending mode on *x*-*z* and *y*-*z* plane. Next, the DVA system using two u-shape water tanks are designed by considering the two lowest mode shapes of the structure. Last, the structure responses are calculated in the case of without and with DVA. The parameters of the building structure are depicted in Table 1. The materials for floor and column are steel and aluminum.

TABLE I
STRUCTURAL PARAMETERS

No	Components		
	Name	**Material**	**Dimension**
1	Floors	Steel	Length (*L*) = 250 mm Width (*W*) = 125 mm Thickness (*t*) = 20 mm
2	Column	Aluminium	Length (*T*) = 125 mm Width (*b*)= 2 mm Thickness (*h*) = 3 mm

III. RESULTS AND DISCUSSION

Two lowest mode shapes of the structure are shown in Fig.4. It is shown from Fig.4 that the 1st and the 2nd mode shape relating to the first bending mode on *x-z* and *y-z* plane, respectively. The natural frequencies of the 1st and 2nd mode shapes are 1.12 Hz and 1.68 Hz, respectively.



a. f_1 =1.12 Hz f_2 =1.68 Hz

Fig. 4 Two lowest modes of the structure

The water tank dimensions are designed that the water natural frequency is tuned to the 1st and the 2nd natural frequency of the structure. The first water tank is designed to attenuate the vibration response of the structure at the first bending mode on the *x-z* plane, and another water tank is used to reduce the first bending mode vibration on the *y-z* plane. Table 2 shows the calculation results of the tank dimension and the fluid height for each DVA.

TABLE II
DVA PARAMETERS

No	Components		
	Name	**Material**	**Dimension**
1	DVA 1 (water tank 1)	Acrylic	Length (B_1) = 250 mm Height (H_1) = 75 mm Width (D_1) = 180 mm Thickness (S_1) = 20 mm
2	DVA 2 (water tank 2)	Acrylic	Length (B_2) = 125 mm Height (H_2) = 50 mm Width (D_2) = 180 mm Thickness (S_2) = 20 mm

The simulation study is conducted using MATLAB software. The structural damping ratios are assumed the same for each structure's mode shape. The structural damping and the water damping ratios used in the simulation are 1% and 5%, respectively. Frequency response functions (FRF) of the system without and with DVA are calculated for two conditions. First, the excitation is applied at point B on *x*-direction, and the response measured at point B' on *x*-direction. Next, the excitation and measurement points are A and A' at *y*-direction.

Fig. 5 shows the system FRF when the structure is excited at point B and the response measured at point B'. It is shown from Fig.5 that the natural frequency relating to the first bending mode on the *x-z* plane at 1.12 Hz is clearly detected. Furthermore, a significant reduction of the FRF peak near 1.12 Hz can be observed for the structure with a water tank.

Fig. 6 shows FRF of the system without and with a water tank in the case of the excitation and measurement points are A and A'. It is shown in Fig. 6, the addition of the DVA not only changes the location of the resonance frequency of the structure but also reduce the level of the resonance peak. Furthermore, it is shown from Fig.6 that the significant reduction of the FRF peak near 1.68 Hz is detected.

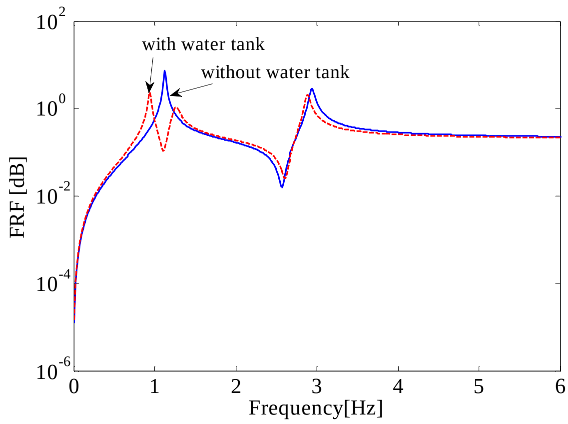


Fig. 5 FRF B-B'

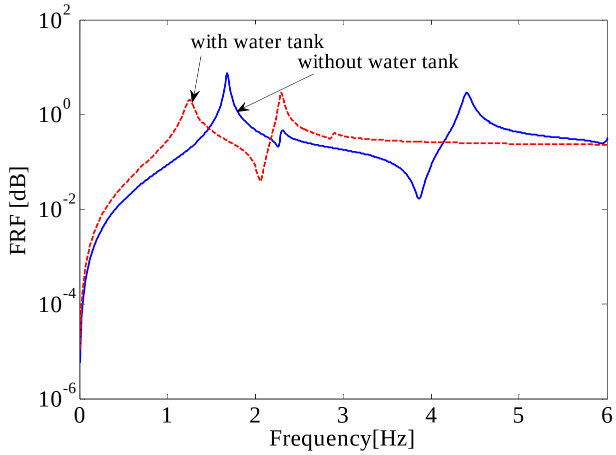


Fig. 6 FRF A-A'

In order to investigate the performance of the water tank DVA under transient load excitation, the structure is excited by impulsive force. Two conditions of the impulsive force are investigated in this study, i.e., excitation by an impulsive force in *x* and *y*-direction.

A. Excitation by impulsive force in the x-direction

In this condition, the impulsive force acts in the *x*-direction at point *B*. The measurement point is *B*,' and the response is measured in the *x*-direction. Fig. 7 shows the measured acceleration response in the *x*-direction. It can be shown from Fig.7 that the water tank effectively reduces the transient response of the structure.

B. Excitation by impulsive force in the y-direction

The impulsive force in the *y*-direction is applied at point *A*. The measurement point is *A*,' and the response is measured in the *y*-direction. The measured acceleration response in the *y*-direction is shown in Fig.8. It is shown from Fig.8 that the water tank can reduce the transient response amplitude of the structure.

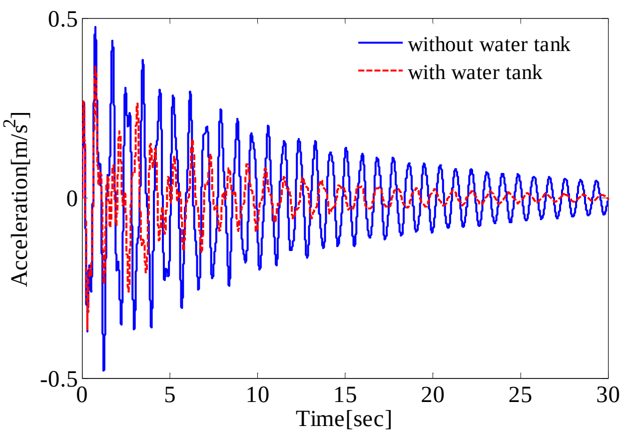


Fig. 7 Acceleration response at point B' under impulsive excitation

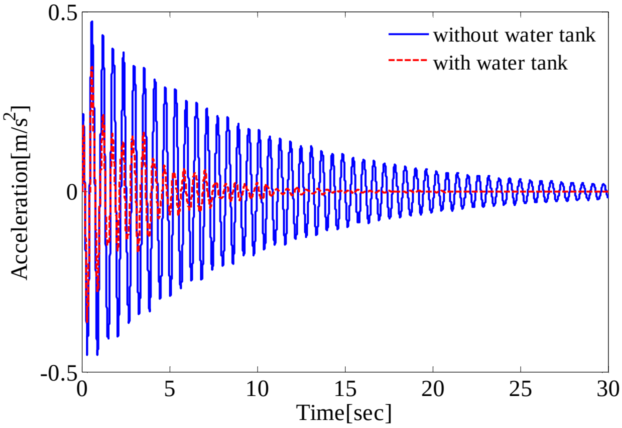


Fig. 8 Acceleration response at point A' under impulsive excitation

Evaluation of DVA performance under seismic load is investigated using three types of seismic load, i.e., El-Centro, Hachinohe and Kobe earthquake. The excitation forces act on point A and B, and the measurement points are point A' and B' as depicted in Fig.2. Excitation at point A and B are applied at *x* and *y*-direction, respectively. The excitation amplitude on *x* and *y*-direction is assumed the same.

C. Excitation by El-Centro Earthquake

Fig. 9 shows the acceleration response of the structure in *x*-direction measured at point B' meanwhile Fig.10 shows the acceleration response in *y*-direction measured at point A'. It is shown from Fig.9 that the reduction of acceleration amplitude in *x*-direction using water tank is clearly detected. The attenuation of acceleration response in the *y*-direction is not as large as shown in Fig. 10.

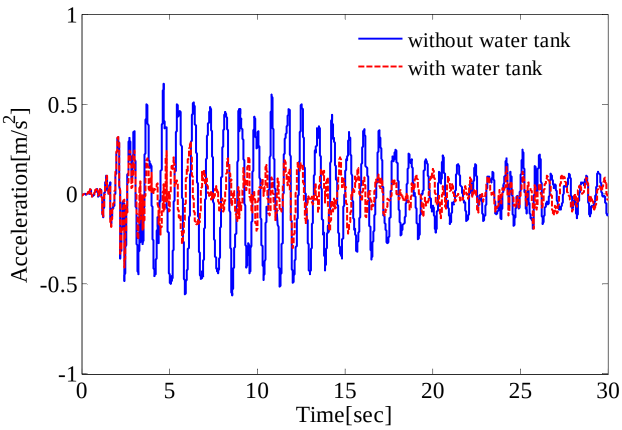


Fig. 9 Acceleration response at point B' under El-Centro earthquake

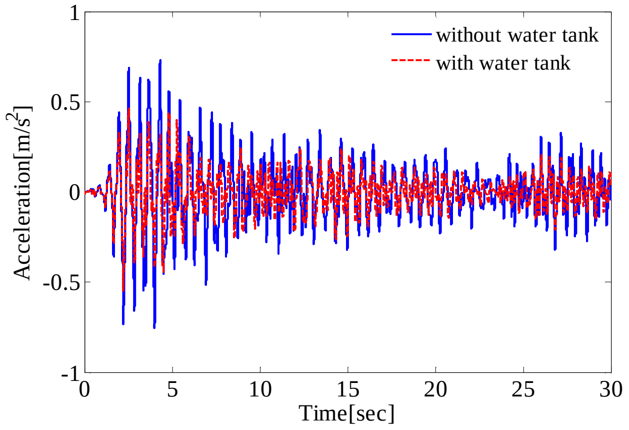


Fig. 10 Acceleration response at point A' under El-Centro earthquake

D. *Excitation by Hachinohe Earthquake*

The acceleration response measured in *x* and *y*-direction at points B' and A,' under Hachinohe earthquake is shown in Fig. 11 and 12, respectively. It can be shown in Fig. 11 that a significant reduction of acceleration amplitude in *x*-direction appears in the response. For the response in the *y*-direction as shown in Fig. 12, the damper works effectively after 13 seconds. At this time, the system response reduces significantly using DVA. This is due to the better performance of DVA occurs when the excitation signal closest to the natural frequency of the structure.

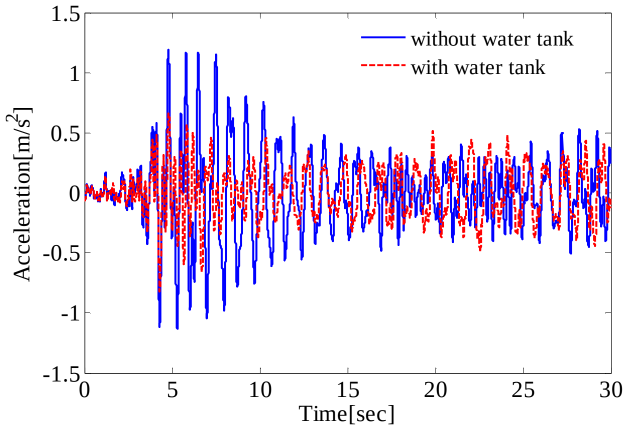


Fig. 11 Acceleration response at point B' under Hachinohe earthquake

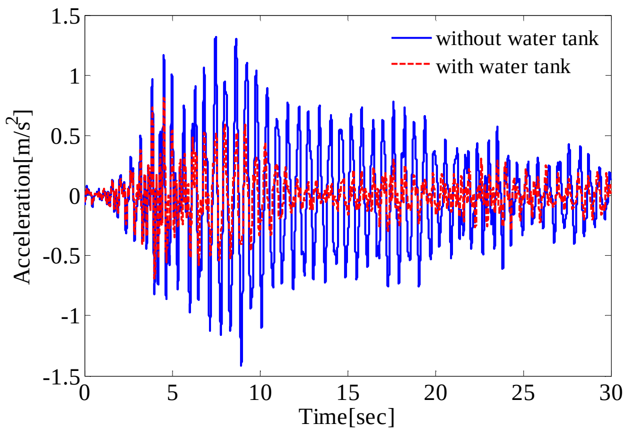


Fig. 12 Acceleration response at point A' under Hachinohe earthquake

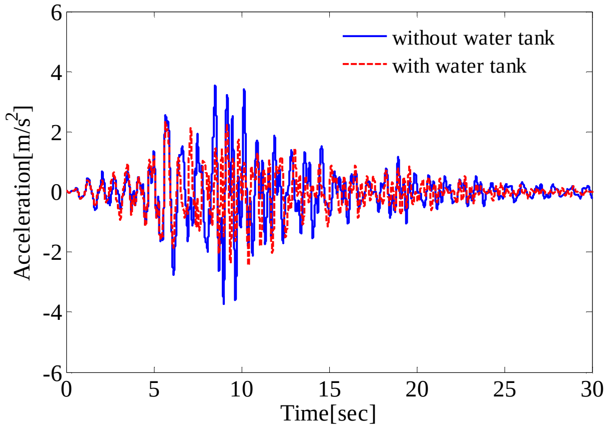


Fig. 13 Acceleration response at point B' under Kobe earthquake

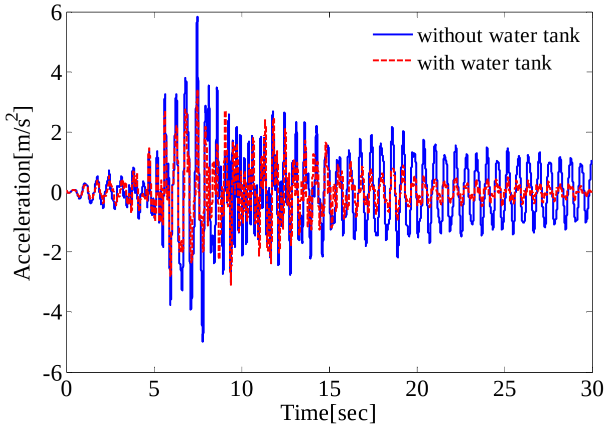


Fig. 14 Acceleration response at point A' under Kobe earthquake

E. *Excitation by Kobe Earthquake*

Fig. 13 and 14 show the acceleration response of building structure model under the Kobe earthquake. The acceleration response in *x*-direction measured at point B' is shown in Fig.13. It can be observed from Fig.13 that the acceleration response is not much reducing when using DVA. This phenomenon is also detected in the *y*-direction. However, after 15 seconds, the absorbers effectively reduce the acceleration response in the *y*-direction as shown in Fig. 14. This condition due to the frequency content of the Kobe earthquake excitation signal is much larger than the 1st and the 2nd natural frequency of the structure.

Comparison of the structure response measured at point *B* and *A* using water tank with different values of DVA damping ratio(ζ) are shown in Fig.15 and Fig.16. In this simulation study, the excitation signal is the Kobe Earthquake. It can be observed from Fig.15 and Fig.16 that the water tank performance using ζ = 0.05 and 0.1 are better than that obtained using ζ = 0. Furthermore, the structural response using water tank with ζ = 0.05 and 0.1 are almost similar as shown in Fig.15 and 16.

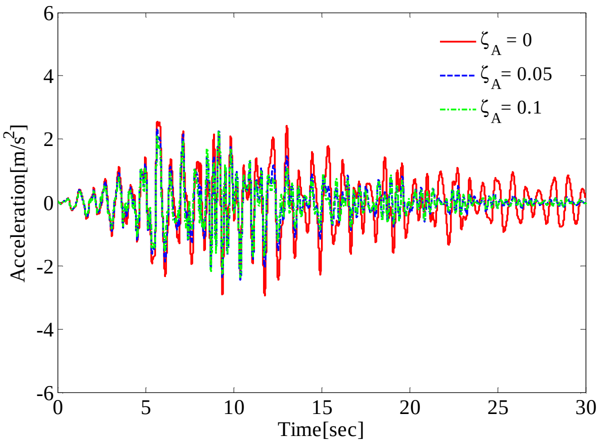


Fig. 15 Acceleration response at point B' with a variation of ζ

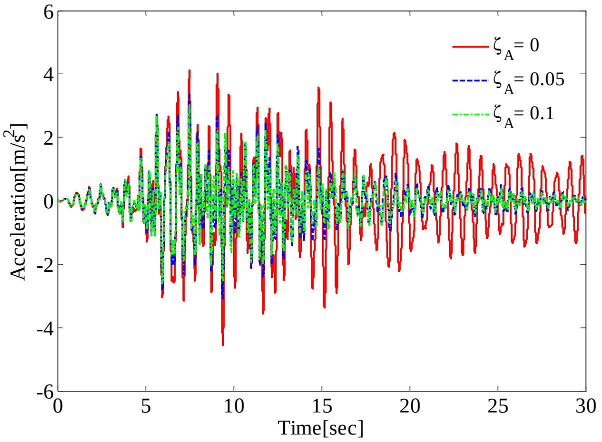


Fig. 16 Acceleration response at point A' with variation of ζ

IV. CONCLUSIONS

Application of u-shape water storage tank as the dynamic vibration absorber (DVA) for a two storey building model has been investigated. The simulation study shows that the water storage tank can improve the structural resistance under the seismic load. Furthermore, the water tank dynamic vibration absorber can effectively reduce the structural response when the excitation frequency closest to the natural frequency of the structure.

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