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OPTIMAL DESIGN METHOD OF BASE-ISOLATED LIQUID STORAGE TANK USING TUNED VISCOUS MASS DAMPER BASED ON GENETIC ALGORITHM

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Abstract

Liquid storage tank is a kind of important infrastructure and it should not be damaged in seismic event. Conventional base-isolated technique can effectively reduce the base shear of the liquid storage tank, but usually cause the base displacement and the sloshing wave height amplified. In order to improve the seismic performance, a tuned viscous mass damper (TVMD) is applied to the base-isolated liquid storage tank in this study. For determining the optimal parameter values of TVMD, an optimal design method based on genetic algorithm (GA) is proposed and the corresponding flow chart is given. In the optimal process, the stiffness ratio, mass ratio and damping ratio are selected as decision variables of GA in the mathematical optimization model of the base-isolated tank with a TVMD. Considering the normal working and safety of the base-isolated tank with a TVMD under seismic event, the base displacement is taken as the optimal object in GA. The result shows that the proposed optimal procedure possesses high efficiency to obtain optimal solutions, with the advantage of parallel computation, global searching and strong robustness of GA. By performance analysis based on the optimal results, it is proved that base-isolated liquid storage tank by using a TVMD can not only reduce the base displacement and base shear significantly, but also decrease the sloshing wave height which is difficult to control using conventional base-isolated technology. At last, parametric studies are conducted by using the time history analysis method and the effects of parameters (the stiffness ratio, the mass ratio and damping ratio) on seismic response are investigated. Because the proposed optimal design method is general, it can also be used to solve other optimal questions of isolated structure.

Keywords: tuned viscous mass damper; genetic algorithm; optimum design; liquid storage tank; vibration control

1. Introduction

Liquid storage tanks are vital structures of lifeline, which are widely used in urban resource water, nuclear power plants and petroleum industry in the world. The destruction of liquid storage tanks will not only cause large direct loss, but also result serious secondary disaster such as fire, environmental pollution, nuclear radiation and so on. In recent seismic events [1] [2], it is reported that many liquid storage tanks are damaged, thus to improve the seismic performance of liquid storage tank is important and urgent. In the past decades, the base isolation technology, equipping isolated devices between the tank base and ground, is widely applied to improve the seismic performance of liquid storage tanks. The primary function of isolated device is to change the natural period of main structure away from the characteristic period of seismic ground motion, then the seismic response such as the base shear of tank is reduced effectively. At present, the isolated devices mainly have rubber bearings, lead rubber bearings [3], high damping rubber bearing [4], sliding bearings [5], friction pendulum [6] and multiple friction pendulum systems [7]. The base-isolated liquid storage tank has lower base shear, but larger base displacement that may affect the tank's normal working and even damage the connecting system of tank during seismic event. Moreover, the sloshing wave height also may be increased due to the increasing of the second natural period of base-isolated liquid storage tank and the large wave height may also cause the spillover of storage liquid or the damage of tank roof. Therefore, it is worthy to find a method to improve the seismic performance of base-isolated liquid storage tank.

In this study, a new vibration control method is proposed to improve the seismic performance of base-isolated liquid storage tank by affiliating TVMD system between the tank base and ground. Firstly, the analytical models of tank and TVMD are illustrated, and the dynamic equations of base-isolated tank with a TVMD are derived. Secondly, the optimal model of TVMD based on GA is given. Thirdly, according to the result of optimal parameters, the time history analysis method is used to compare the seismic responses of base-fixed tank, base-isolated tank and base-isolated tank with TVMD. Lastly, the parametric studies are conducted to investigate the effects of seismic response for the stiffness ratio, mass ratio and damping ratio.

2. Analytical models

2.1 Two-lumped-mass model of tank

A cylindrical liquid storage tank is shown in Fig. 1(a); H and R are the height and the radius of the tank respectively. Malhotra et al. [8] proposed a simple two-lumped-mass model of liquid storage tank as shown in Fig. 1(b). The simple model consists of two parts: the convective component and the impulsive component. m_i and m_c are the equivalent impulsive mass and the equivalent convective mass, respectively; k_i and k_c are the equivalent stiffness of springs which connect the impulsive and convective parts to the tank wall, repectively; c_i and c_c are the equivalent viscous damping coefficients of impulsive and convective parts, respectively. Those parameters mentioned above can be calculated by the following formulas and Table 1.

(a) Schematic diagram (b) Two-lumped-mass model

Fig.1 — Diagrams for a cylindrical liquid storage tank

$$m = \pi \rho_l H R^2 \tag{1}$$

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

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

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

$$k_c = m_c \left(2\pi / T_c\right)^2 \tag{5}$$

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

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

where m is the total mass of the storage liquid in the tank; T_i and T_c are the natural periods of the impulsive and convective responses, respectively; C_i and C_c are the natural period coefficients of the impulsive and convective parts, respectively, which can be gotten from Table 1; ξ_i and ξ_c are the equivalent damping ratios of the impulsive and convective parts which values usually are 0.02 and 0.005 for steel tank, respectively; ρ_l is the mass density of liquid in tank; t is the thickness of the tank wall and E_s is the Young's modulus of the liquid storage tank wall, respectively.

Table1 — Parameters for the simplified tank model [8]

H/R	C_i	C_c [$s\sqrt{m}$]	m_i/m	m_c/m
0.3	9.28	2.09	0.176	0.824
0.5	7.74	1.74	0.300	0.700
0.7	6.97	1.60	0.414	0.586
1.0	6.36	1.52	0.548	0.452
1.5	6.06	1.48	0.686	0.314
2.0	6.21	1.48	0.763	0.237
2.5	6.56	1.48	0.810	0.190
3.0	7.03	1.48	0.842	0.158

2.2 Analytical model of TVMD

Hwang et al. improved rotational viscous damper by adding a flywheel, and then proposed a viscous mass damper (VMD) shown in Fig.2 [9]. The VMD system mainly includes two parts: a flywheel and an internal tube covered with viscous material, both of them are equipped with a ball screw. Through the ball screw mechanism, the small linear motion can be translated to high-speed rotation. The equivalent inertial mass of flywheel and rotational viscous damping are amplified significantly by the amplifying mechanism. By conducting an initial design of full-scale device, the equivalent inertial mass can exceed several thousand times of the actual mass [10]

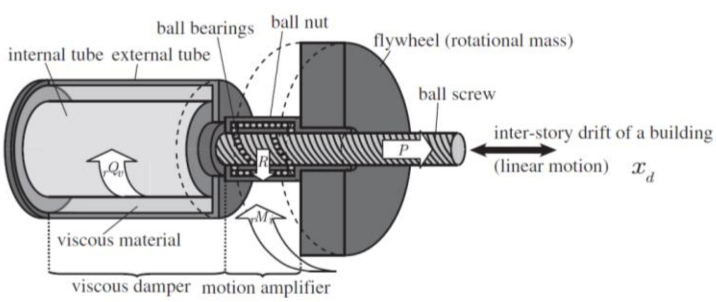


Fig.2 — Schematic representation of VMD [10]

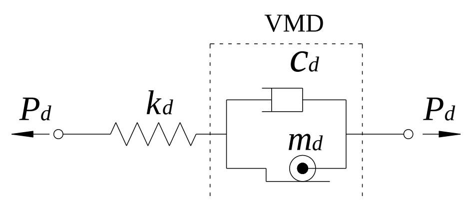


Fig.3 — Analytical model of TVMD

Satio et al. proposed an improved VMD, called tuned viscous mass damper (TVMD) [10], in which the VMD is connected in series with an elastic spring. The total displacement of TVMD is summation of VMD and spring, while the axial force of spring is equal to the VMD. The fundamental period of TVMD is expected to be tuned close to that of the primary system, therefore mitigate its vibration significantly. In order to obtain the analytical model, the rotary flywheel and rotatory internal tube covered viscous material in VMD are simplified as a mass element and a viscous damping element, respectively. Hence the analytical model of TVMD can be represented in Fig.3, where P_d represent the axial force, k_d is the stiffness of tuned spring element, c_d and m_d are the equivalent viscous damping coefficient and the equivalent inertial mass, respectively.

3. Dynamic equations of base-isolated tank with TVMD

Based on the two-lumped-mass model of tank, the base-isolated tank with TVMD can be simplified as shown in Fig.4. k_b and c_b are denoted as the stiffness and the damping coefficient of rubber bearing, respectively. m_b is the mass of tank base. Assuming the base-isolate tank with TVMD is excited by a ground motion $\ddot{x}_g$, the dynamic equations can be writen as:

$$\begin{cases} m_c\ddot{x}_c + c_c\left(\dot{x}_c - \dot{x}_b\right) + k_c\left(x_c - x_b\right) = -m_c\ddot{x}_g \\ m_i\ddot{x}_i + c_i\left(\dot{x}_i - \dot{x}_b\right) + k_i\left(x_i - x_b\right) = -m_i\ddot{x}_g \\ m_b\ddot{x}_b + c_b\dot{x}_b + k_b x_b + P_d - c_c\left(\dot{x}_c - \dot{x}_b\right) - k_c\left(x_c - x_b\right) - c_i\left(\dot{x}_i - \dot{x}_b\right) - k_i\left(x_i - x_b\right) = -m_b\ddot{x}_g \\ P_d = c_d\dot{x}_d + m_d\ddot{x}_d = k_d\left(x_b - x_d\right) \end{cases} \quad (8)$$

where x_c, x_i, x_b and x_d are the relative displacements of the convective mass, the impulsive mass, the tank base and the deformation of spring element in the TVMD system.

Using the state-space representation, the Eq. (8) can be solved easily with Runge-Kutta algorithm to obtain numerical solution for the base-isolate tank with TVMD under ground motion excitation.

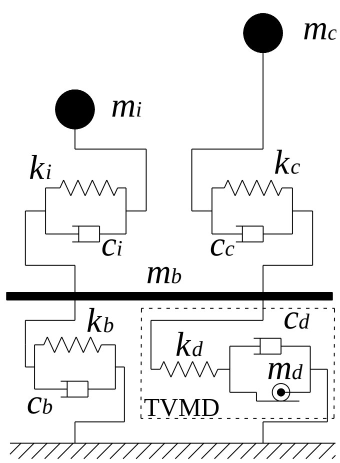


Fig.4 — Base-isolated tank with a TVMD

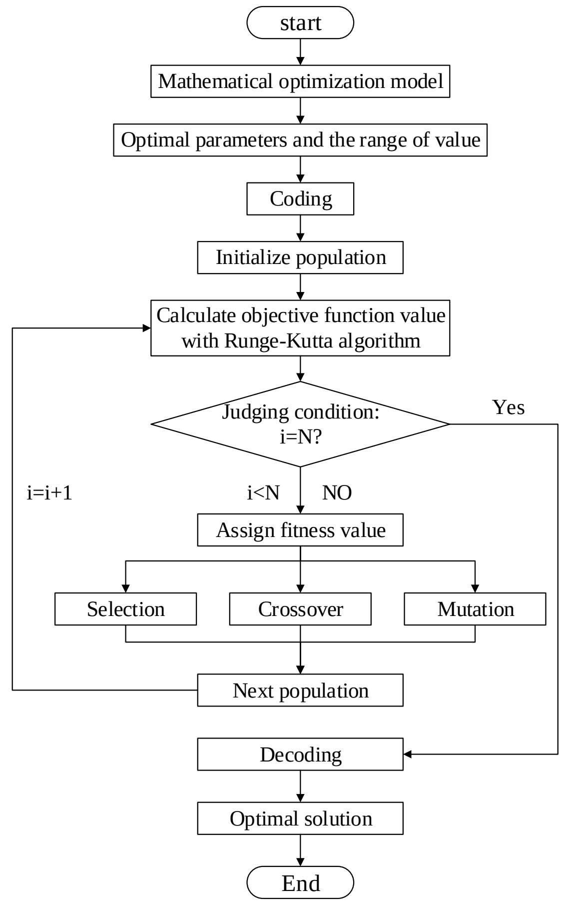


Fig.5 — Flow chart of optimal procedure based on GA

4. Optimal procedure of TVMD based on GA

In order to achieve good effect of vibration control, the optimal parameters of TVMD should be estimated primarily. Because of the randomness of seismic ground motion and the multi-parameters optimization of TVMD, the GA is proposed to be used in this study. The GA is a kind of adaptive optimum algorithms with the advantages of high efficiency, parallel computing, global searching and strong robustness [11]. Based on GA, a optimal procedure on special object is built and the flow chart is shown in Fig.5.

4.1 Mathematical optimization model

It is well know that the base shear can be reduced effectively using base-isolated technology, but the base displacement is amplified meanwhile. Larger base displacement is not only harmful to the normal working of tank, but also damages the pipeline of connection. Hence, the base displacement is an important optimal object of vibration control for base-isolate tanks. In this study, the minimum base displacement, denoted by X , is used as the optimal object to calculate the optimal parameters of TVMD system.

The dynamic characteristics of TVMD are determined by k_d, m_d and c_d, those parameters are non-dimensionalized as the stiffness ratio ρ_d, the mass ratio μ_d and the damping ratio ζ_d:

$$\rho_d = k_d / k_i \tag{9}$$

$$\mu_d = m_d / m_i \tag{10}$$

$$\zeta_d = c_d / c_i \tag{11}$$

Therefore, the mathematical optimization model can be expressed as:

$$\begin{cases} min\, X = f(\rho_d, \mu_d, \zeta_d) \\ \text{s. t.} \quad \rho_d, \mu_d, \zeta_d \end{cases} \tag{12}$$

4.2 Parameters optimal Procedure of GA

Based on mathematical optimization model, the bridge between the solution space of question and searching space of GA is established by coding and decoding. Then GA imitates the evolution of living individuals in nature to get optimal solution of question by selection, crossover and mutation operation.

4.2.1 Coding and decoding

Coding is the key process of GA, which realizes the transformation from the solution space of question to the searching space of GA, so its performance will directly affect the efficiency of computation. The binary coding, which only consists of binary symbols "0" and "1" in the assembly of codes, is one of the common and important methods in GA , so is is used in this study.The individual genotype constructed from binary coding is a string of characters, therefore, the pricision of the solution is depended on the length of binary codes.

For example, the length of binary codes of the stiffness ratio ρ_d in this study is 7, therefore, there are 2^7 different codes to represent the parameter and the corresponding relationships are shown as follows:

0 000 000=0 $\rightarrow U_1$

0 000 001=1 $\rightarrow U_1+\delta$

0 000 010=2 $\rightarrow U_1+2\delta$

……

1 111 111=2^7-1 $\rightarrow U_2$

where the interval $[U_1, U_2]$ is the value range of optimal parameter ρ_d , the δ represents the computational precision and can be calculated as:

$$\delta = \frac{U_2 - U_1}{2^7 - 1} \tag{13}$$

The inverse process of coding is called decoding. The binary decoding process is reciprocal to the coding and transformational relation is expressed as following:

$$X = U_1 + \left(\sum_{i=1}^{k} b_i \cdot 2^{i-1} \right) \cdot \frac{U_2 - U_1}{2^k - 1} \tag{14}$$

where X represents the value range of optimal parameter, the b_i and k are the place value and the length of binary codes, respectively.

4.2.2 Selection, Crossover and Mutation

There are three basic operations: selection, crossover and mutation in GA.

Selection is a procedure that good individuals can be selected from present group and give them the chance to breed next generation. According to the fitness of individuals and the rule of roulette wheel, some good individuals are selected to be fathers and keep their genetic information from previous generation to the next.

Crossover is the main operation of inheritance in GA and it determines the performance of global searching. By the crossover operation, all new individuals of next generation will be produced and combined with the characteristics of their fathers. In this study, the random pairing is firstly adopted, and then the one-point crossover method is used to produce new generation.

Mutation is an assistant method to generate new individuals, but it determines the capability of local searching, and it is also an indispensable step in GA. During the operation of mutation, some values of genes in some locus are substituted by other alleles in the same locus to produce new individuals with very low probability of occurrence.

5. Numerical study

5.1 Structural parameters of tank

A numerical model of liquid storage tank is considered [12] and its basic information are listed in Table 2. The structural parameters of two-lumped-mass tank model are given in Table 3.

Table 2 — Basic information of base-isolated tank with VD model

Parameter	Radio (m)	Height (m)	Thickness (m)	Aspect ratio	Physical density (kg/m^3)	Young's modulus (N/m^2)
Value	7.32	10.98	0.0245	1.5	1000	2.06×10^{11}

Table 3 — Structural parameters of the used tank model

Parameters	Impulsive component	Convective component
Equivalent mass (kg)	1.268×10^{6}	5.804×10^{5}
Equivalent period (s)	0.079	4.004
Equivalent stiffness (N/m)	8.109×10^{9}	1.429×10^{6}
Equivalent damping ratio	0.020	0.005
Equivalent damping (N s/m)	4.056×10^{6}	9.107×10^{3}

5.2 Ground motions

Seven seismic ground motions are selected to conduct the time history analysis, in which AW1, AW2 are artificial waves and NW1-NW5 are natural waves. The five natural waves are chosen from the strong motion database of the Pacific Earthquake Research Center (PEER) [13]. All the waves are in according with a characteristic period of 0.4s used in Chinese code [14] and the design spectrum in Chinese code is defined as follows:

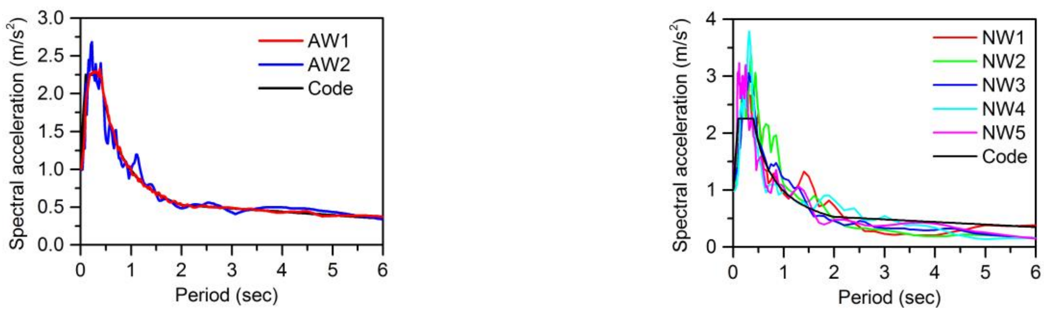
$$\beta=\begin{cases}1+10(\beta_{max}-1)T & (T\le 0.1s)\\ \beta_{max} & (0.1s<T\le 0.4s)\\ (T_g/T)^{0.9}\beta_{max} & (0.4s<T\le 2s)\\ [0.2^{0.9}-0.02(T-5T_g)]\beta_{max} & (2s<T\le 6s)\end{cases}\tag{15}$$

where, β_{max} is the maximum of the normalized acceleration spectrum, set as 2.25; T_g is the site predominant period, assumed as 0.4s in this study; T is the structure fundamental period.

The details of the five natural waves are listed in Table 4. The response spectra including code spectrum are shown in Fig.6 and the normalized acceleration time history of the AW1 is shown in Fig.7. Before using the seven seismic waves in time history analysis, the peak of ground acceleration (PGA) are set to 0.2g.

Table 4 — Details of natural waves

No.	RSN	Year	Magnitude	Event	Station
1	9	1942	6.5	Borrego	El Centro Array #9
2	15	1952	7.36	Kern County	Taft Lincoln School
3	40	1968	6.63	Borrego Mtn	San Onofre- So Cal Edison
4	55	1971	6.61	San Fernando	Buena Vista- Taft
5	68	1971	6.61	San Fernando	LA-Hollywood Stor FF



(a) Artificial wave AW1 and AW2 (b) Natural waves NW1-NW5

Fig.6 — Normalized response spectrum

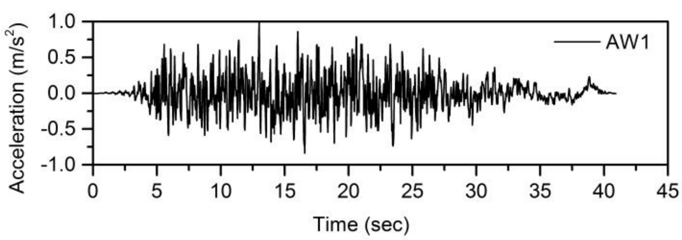


Fig. 7 — Acceleration time history of artificial wave AW1

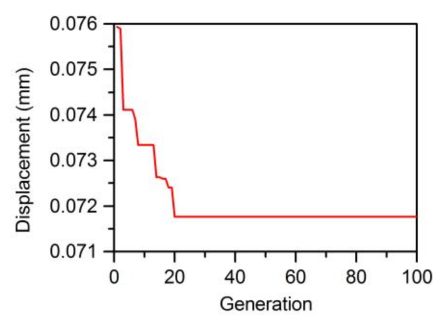


Fig.8 — Displacement and generation curve

5.3 Optimal results and numerical models

In this study, the stiffness ratio ρ_d , the mass ratio μ_d and the damping ratio ζ_d are used as the optimal parameters and the optimal object is the base displacement of tank, X , as mentioned in the previous section. Because the artificial wave AX-1 is well fitted fir the code response spectrum and is most representative of those ground motions, this wave is selected as acceleration excitation for the mathematical optimization model. Considering the above factors, the mathematical optimization model Eq. (12) is rewritten as:

$$\begin{cases} \quad min\, X = f(\rho_d, \mu_d, \zeta_d) \\ \text{s.t.} \quad 0 < \rho_d < 1,\ 0 < \mu_d < 1,\ 0 < \zeta_d < 1 \end{cases} \tag{16}$$

Solving the above optimization model based on GA, the results of ρ_d, μ_d and ζ_d corresponding to the minimum X are determined and listed in Table 5. The curve of displacement X and generation is shown in Fig.8, which illustrates a good convergence after generation 20.

Table 5 — Optimum design result of TVMD

Stiffness ratio ρ_d	Mass ratio μ_d	Damping ratio ζ_d
0.0233	0.9612	0.9922

In order to evaluate the effectiveness of the TVMD system, three types of tanks are considered: the base-fixed tank (ST0), the base-isolated tank (ST1) and the base-isolated tank with TVMD (ST2). The size and structural parameters of three tanks are same, and other design parameters are listed in Table 6.

Table 6 — Design parameters of the three tanks

Parameters	ST0	ST1	ST1
Base mass (kg)	1.848×10^5	1.848×10^5	1.848×10^5
Stiffness of bearing (N/m)	$+\infty$	1.247×10^7	1.247×10^7
Damping of bearing (N s/m)	0	3.965×10^5	3.965×10^5
Equivalent stiffness of TVMD (N/m)	0	0	1.889×10^8
Equivalent mass of TVMD (kg)	0	0	1.219×10^6
Equivalent damping of TVMD (N s/m)	0	0	4.024×10^6

5.4 Performance analysis

After the choice of compressive indices, the time history analysis is conducted by using all seven seismic ground motions to verify the optimal result and analyze the control effect on the seismic responses of the base isolated tank with a TVMD.

5.4.1 Comparision indices

Three parameters are chosen as comparison indices, including the base displacement, the ratio of base-shear to weight and the sloshing wave height. The mass of impulsive component, m_i, the mass of convective component, m_c , and the mass of tank base, m_b, are considered for the ratio of base-shear to weight.

The ratio of base-shear to weight of the tank is calculated as following:

$$R_{sw} = [m_i(\ddot{x}_i + \ddot{x}_g) + m_c(\ddot{x}_c + \ddot{x}_g) + m_b(\ddot{x}_b + \ddot{x}_g)]/(mg) \tag{17}$$

where $m = m_i + m_c + m_b$ is the total mass of the storage liquid and g is the acceleration of gravity.

The sloshing wave height of the tank is calculated according to the following formula [15]:

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

5.4.2 Time history analysis

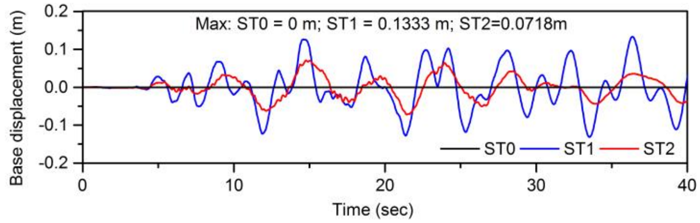
The time history variances of the base displacement, the ratio of base-shear to weight and the sloshing wave height of the three tanks under artificial wave AX-1, are plotted in Fig.9. The maximum response results of all seven waves and the corresponding averages are listed in Table.7. To obtain the quantitative comparison results among the seimsic responses of the three tanks, three comparisive indices Γ_1, Γ_2 and Γ_3, are defined as:

$$\Gamma_1 = (R_{ST1} - R_{ST0}) / R_{ST0} \tag{19}$$

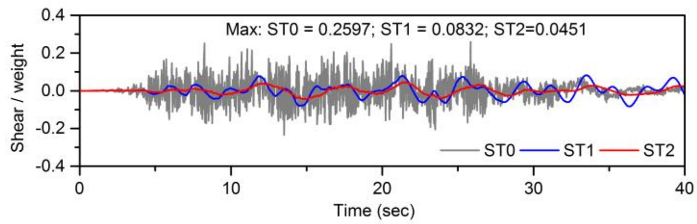
$$\Gamma_2 = (R_{ST2} - R_{ST0}) / R_{ST0} \tag{20}$$

$$\Gamma_3 = (R_{ST2} - R_{ST1}) / R_{ST1} \tag{21}$$

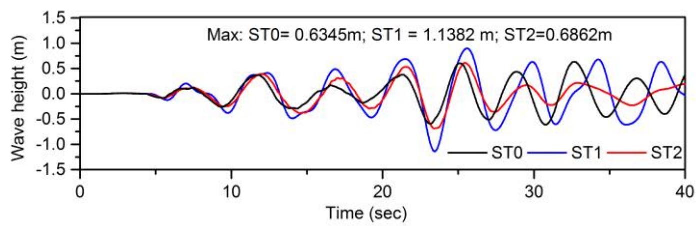
where R_{ST0}, R_{ST1} and R_{ST2} denote the maximum seismic responses of the tank ST0, ST1 and ST2.



(a) the base displacement



(b) the ratio of base-shear to weight



(a) the sloshing wave height

Fig. 9 — Time history of seismic responses under AW-1

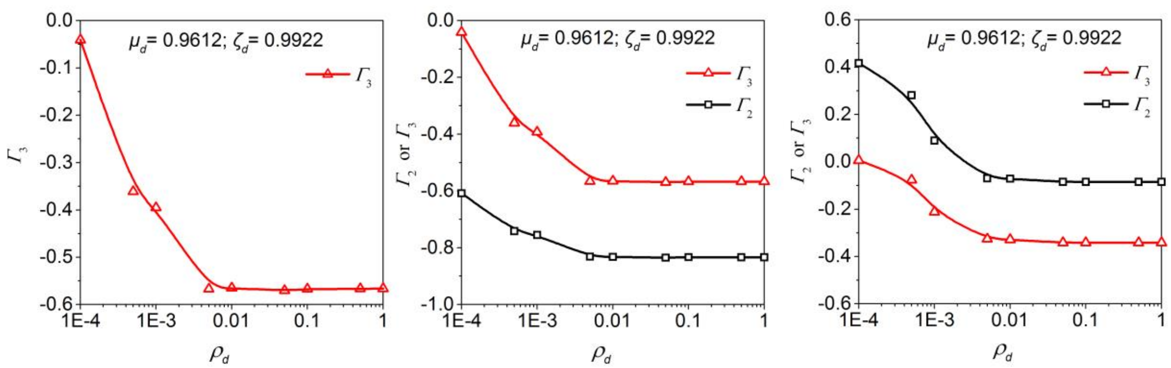
Table 7 — Seismic responses of three tanks ST0, ST1 and ST2

Maximum Response		AW1	AW2	NW1	NW2	NW3	NW4	NW5	Average
Base Disp. (m)	ST0	0	0	0	0	0	0	0	0
	ST1	0.1333	0.1524	0.1493	0.1534	0.0924	0.1533	0.1429	0.1396
	ST2	0.0718	0.0876	0.0543	0.0460	0.0409	0.0460	0.0667	0.0590
	Γ_3	-46.15%	-42.52%	-63.65%	-70.03%	-55.73%	-70.03%	-53.31%	-57.35%
Base Shear/ Weight	ST0	0.2597	0.2713	0.2046	0.1708	0.1756	0.1708	0.3334	0.2266
	ST1	0.0832	0.0951	0.0933	0.0961	0.0578	0.0961	0.0892	0.0872
	ST2	0.0451	0.0548	0.0339	0.0288	0.0255	0.0288	0.0416	0.0369
	Γ_1	-67.95%	-64.96%	-54.41%	-43.75%	-67.12%	-43.76%	-73.26%	-59.32%
	Γ_2	-82.63%	-79.82%	-83.44%	-83.17%	-85.49%	-83.17%	-87.51%	-83.60%
	Γ_3	-45.80%	-42.40%	-63.68%	-70.07%	-55.87%	-70.07%	-53.31%	-57.31%
Wave height (m)	ST0	0.6345	0.8209	0.2562	0.3792	0.5593	0.3791	0.8129	0.5489
	ST1	1.1382	0.9944	0.5235	0.4772	0.6311	0.4772	0.9568	0.7426
	ST2	0.6862	0.7751	0.3026	0.3103	0.4077	0.3105	0.6779	0.4958
	Γ_1	79.40%	21.13%	104.30%	25.84%	12.83%	25.88%	17.71%	41.01%
	Γ_2	8.15%	-5.58%	18.11%	-18.16%	-27.12%	-18.10%	-16.60%	-8.47%
	Γ_3	-39.72%	-22.05%	-42.19%	-34.97%	-35.40%	-34.94%	-29.15%	-34.06%

Table.7 shows that the average base displacement of ST2 is 0.059m , which is much lower than 0.1396m of ST1 and Γ_3=-57.35%, so it is proved that the base displacement of base-isolated tank can be effectively reduced by using the TVMD system. The average ratio of base shear to weight is further reduced from 0.0872 of ST1 to 0.0389 of ST2 and Γ_3=-57.31%, it is implied that the TVMD system can significantly control the implusive response of base-isolated tank. The average results of sloshing wave height shown in Table.7 illustrate that the base-isolated technolgy can not mitigate the convective response, whearas amplify the sloshing wave height from 0.5489m to 0.7426m and Γ_1=41%. However, the average sloshing wave height of ST2 is 0.4958m, which is obviously lower than 0.7426m of ST1 and 0.5489m of ST0, and the corresponding Γ_3=-34% and Γ_2=-8%, respectively. Therefore, it is indicated that the TVMD system can effectively control the sloshing wave height of the based isolated tank.

5.5 Parametric study

In order to investigate the effects of characteristic parameters on the seismic response of the base-isolated liquid storage tank with a TVMD, in this section, a parametric study is conducted by using the time history analysis method. Keeping the two of three optimal parameters as contants, another parameter is continuously changing in the range of 0 to 1 in this optimal study. Considering the computational efficiency and representativeness, these discrete value 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, 10^{-2}, 5×10^{-2}, 10^{-1}, 5×10^{-1} and 10^{0} are selected as the value of parameter in the numerical computation. Seven seismic waves mentioned in previous section are used to conduct the time history analysis, and the average results of base displacement, ratio of base-shear to weight and sloshing wave height are calculated, with the corresponding comparisive indices Γ_2 and Γ_3 shown in Fig.10-12.

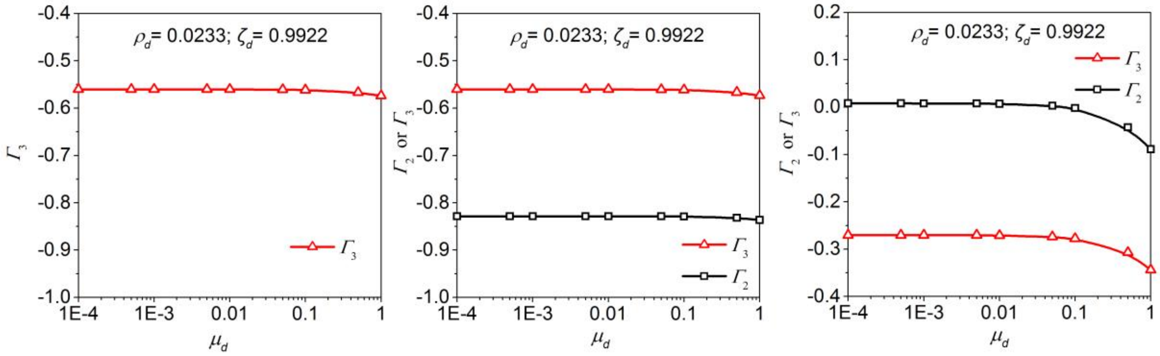


(a) base displacement (b) ratio of base-shear to weight (c) sloshing wave height

Fig.10 —The stiffness ratio ρ_d

Fig.10 indicates that with the increasing of the stiffness ratio ρ_d, all comparision indices are decreasing at first. When ρ_d exceeds the optimal value, all comparison indices will keep constant. This fact indicates that the system of TVMD should have appropriate stiffness value, and too large stiffness is not necessary. Whereas, the Γ_2 of sloshing wave height shows that small stiffness ratio ρ_d may amplify the sloshing wave height relative to ST0.

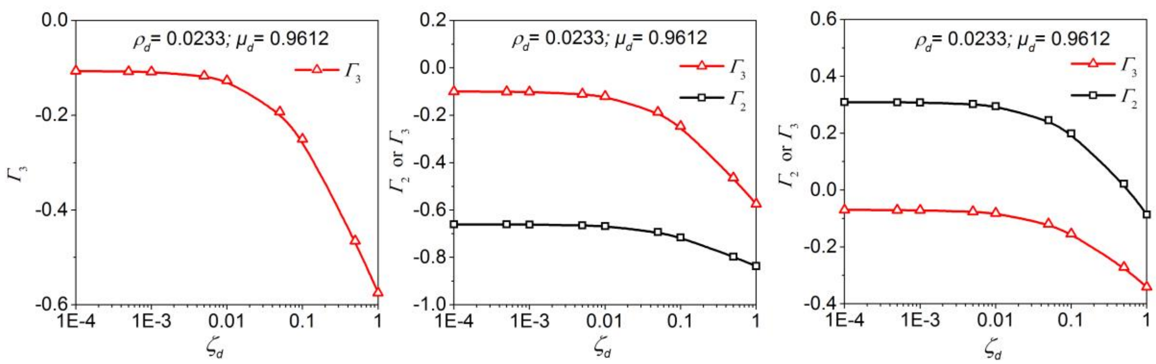
Fig.11 shows that the comparison indinces Γ_2 and Γ_3 of the base displacement and ratio of base-shear remain stable with the increasing of the mass ratio μ_d. For the sloshing wave height, Γ_2 and Γ_3 keep constant before μ_d=0.1, then Γ_2 and Γ_3 decrease from 0 to -9% and -27% to -34% with the μ_d increasing. Therefore, it can be inferred that increasing the mass ratio can not reduce the base displacement and base shear almost, but can decrease the sloshing wave height.



(a) base displacement (b) ratio of base-shear to weight (c) sloshing wave height

Fig. 11 — The mass ratio μ_d

From Fig.12, it is shown that with the increasing of damping ratio ζ_d , all comparison indices are reduced rapidly: the base displacement from Γ_2=-11% to -57%; the ratio of base-shear to weight from Γ_2= -12% to -57% and Γ_3= -67% to -84%; the sloshing wave height from Γ_2= 31% to -9% and Γ_3= -8% to -34%. It may be noticed that the small ζ_d cannot reduce the sloshing wave height relative to ST0, but amplify the value. However, with respect to ST1, the sloshing wave height is always reduced.



(a) base displacement (b) ratio of base-shear to weight (c) sloshing wave height

Fig. 12 — The damping ratio ζ_d

6. Conclusions

In this study, based on GA, an optimal design method of TVMD is proposed to enhance the seismic performance of base-isolated tank. Three tanks, including base-fixed tank, base-isolated tank and base-isolated tank with a TVMD, are taken into cosideration, and the seismic responses of these tanks are analyzed and compared by using time history analysis method. At last, parametric studies are conducted to investigate the effect of optimal parameter value. The main conclusions can be drawn as follows:

(1) GA is a high efficient algorithm to obtain the optimal solutions of parameters for the TVMD installed in base-isolated tank, with the advantages of parallel computaion, global searching and strong robustness.

(2) The base-isolated tank by using a TVMD under optimal parameters can effectively reduce the seismic responses, not only the base displacement and the base shear, but also the sloshing wave height.

(3) Parametric studies indicate that proper stiffness ratio of TVMD is necessary to control the seismic responses; and increasing the mass ratio alone cannot reduce the base displacement and the base shear, but can decrease the sloshing wave heigh; and the base displacement, the base shear and the sloshing wave height are reduced significantly by increasing the damping ratio.

7. Acknowledgements

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8. Copyrights

9. References

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Dear Editor,

RE: Manuscript ID: 1214

We would like to thank you for giving us an opportunity to revise our manuscript.

We thank the reviewer for their careful reading and thoughtful comments on previous draft. We have carefully taken their comments into consideration in preparing our revision, which has resulted in a paper that is clearer, more compelling, and broader. Below is our response to their comments.

Thanks for all the help.

Best wishes,

Hua Shen

(1) On page 1: "with advantage of high efficiency"--> should add with THE advantage of...

Reply: We have added "the" in the modified manuscript and checked the subsequent manuscript. Thank you.

(2) On page 1: this reviewer suggests rephrasing the following statement, because its meaning is not clear --> "Because the optimal design method of TVMD is of generality, it can be referenced to similar isolated structure design or relative optimal question."

Reply: Due to ambiguousness, we have changed the sentence to "Because the proposed optimal design method is general, it can also be used to solve other optimal questions of isolated structure." Thank you.

(3) This reviewer considers that adding a brief explanation of the motivation behind this study (as expressed in the Introductory section) to the Abstract would increase the impact of the article.

Reply: It is a very good advice. We have changed the beginning of abstract to "Liquid storage tank is a kind of important infrastructure and it should not be damaged in seismic event. Conventional base-isolated technique can effectively reduce the base shear of the liquid storage tank, but usually cause the base displacement and the sloshing wave height amplified. In order to improve the seismic performance, a tuned viscous mass damper (TVMD) is applied to the base-isolated liquid storage tank in this study." Thank you.

(4) On page 2: "The destroy of liquid storage tanks not only will cause large direct loss," --> The word "destroy" is used as a noun but it is actually a verb...please rephrase this sentence.

Reply: This is a mistake which we should not have made. We have changed the verb "destroy" to the noun "destruction" and the new sentence is "The destruction of liquid storage tanks will not only cause large direct loss, but also result serious secondary disaster such as fire, environmental pollution, nuclear radiation and so on." Thank you.

(5) On page 2: Not all parameters shown in Equations 1 to 7 were defined in the text. Also, the symbol for mass density should not be inserted as a picture/image in the text.

Reply: Please forgive our carelessness. We have checked all parameters shown in Equations (1) to (7). There two mistakes: the parameter ρ_1 should be ρ_l in Eq. (2) and the parameter ζ_1 should be ζ_i in Eq. (6). The symbol for mass density have been changed to formula format ρ_l. Thank you.

(6) On page 3: the caption of Table 1 should provide a description of the nomenclature used to facilitate the interpretation of the data.

Reply: Because the two parameters h_i and h_c are not used in this manucript, we have deleted the last two columns of Table1 for simplicity. Then all the interpretations of data in Table 1 have been defined in the modified manuscript. Thank you.

(7) On page 3: "The VMD system mainly includeS two parts:..." --> add an "s" to include

Reply: Thank you. We have added an “s” to include and checked the tenses of other sentences in the modified manuscript.

(8) On page 3: a space should be provided between the captions of Figures 2 and 3 and the subsequent text.

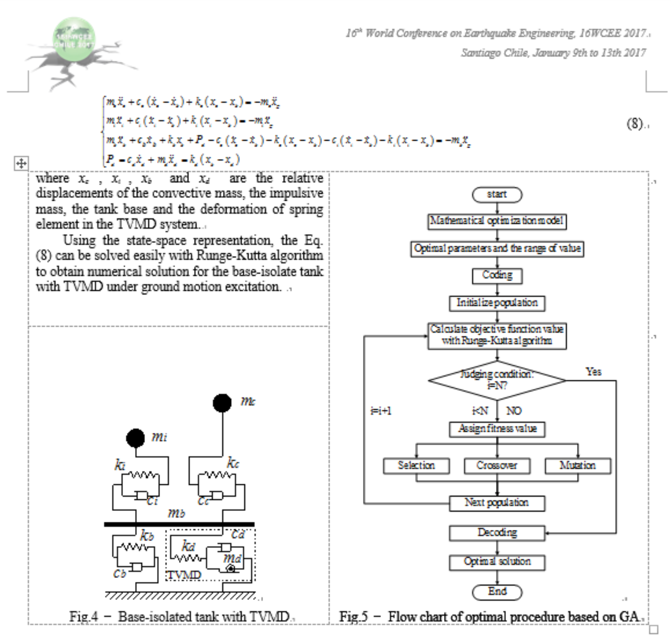
Reply: We have adjusted the space between the captions of Figures 2 and 3 and the subsequent text according to the requested format for submission to this conference, and have checked all other spaces between the caption of figure or table and subsequent text. Thank you.

(9) On page 3: "Satio et al. proposed a improved VMD,"--> The citation has not been done according to the requested format for submissions to this conference.

Reply: We have rearranged the citation and conference, and the modified sentence is “Satio et al. proposed an improved VMD, called tuned viscous mass damper (TVMD)[10], in which the VMD is connected in series with an elastic spring.” Thank you.

(10) A better utilization of the provided space for figures and text should be done. Specially for figures 4 and 5 on page 4.

Reply: Due to the difference sizes of figures 4 and 5, a relative blank space was formed. We have utilized this space for some text as the following figure. Thank you.


16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017

[illegible] (8)

where x_c, x_i, x_b and x_d are the relative displacements of the convective mass, the impulsive mass, the tank base and the deformation of spring element in the TVMD system.

Using the state-space representation, the Eq. (8) can be solved easily with Runge-Kutta algorithm to obtain numerical solution for the base-isolate tank with TVMD under ground motion excitation.

Fig.4 – Base-isolated tank with TVMD.

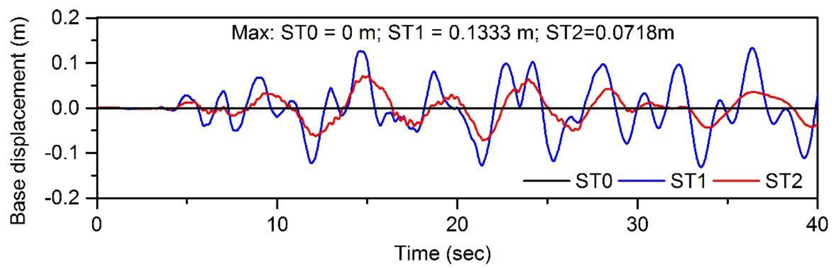
Fig.5 – Flow chart of optimal procedure based on GA.

(11) On page 5: A brief description of section "4.2 Parameters optimal Procedure of GA" should be provided instead of going directly to items 4.2.1 and 4.2.2

Reply: We have added a brief description "Based on mathematical optimization model, the bridge between the solution space of question and searching space of GA is established by coding and decoding. Then GA imitates the evolution of living individuals in nature to get optimal solution of question by selection, crossover and mutation operation." Thank you.

(12) On page 7, Figures 6, 7 and 8: the axis labels are rather small. The overall quality of the figures should be improved.

Reply: We have adjusted the size of the axis labels and increased the resolution of these figures. These improved figures are exampled as the following figure. Thank you.



(13) On page 8: A brief description of section "Performance analysis" should be provided instead of going directly to items 5.4.1 and 5.4.2

Reply: We have added a brief description "After the choice of compressive indices, the time history analysis is conducted by using all seven seismic ground motions to verify the optimal result and analyze the control effect on the seismic responses of the base isolated tank with a TVMD." Thank you.

MANDATORY CHANGES:

(1) The overall quality of the grammar used in this paper is not good. A careful editorial revision by the authors must be conducted.

Reply: After receiving the email, we have made a careful revision and try our best to improve the quality of the grammar used in this manuscript. Because of many modifications including the grammar, vocabulary and structure of sentence, please forgive us for not exampling all the changes one by one. If you have any question about this paper, please don't hesitate to let us know. Thank you.

(2) The overall quality of the figures must be improved.

Reply: According to the format requirement of this conference, we have adjusted the font size and resolution of figures to improve the quality. Thank you.