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Effect of the limiting-device type on the dynamic responses of sliding isolation in a CRLSS

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Abstract. To study the effectiveness of sliding isolation in a CRLSS (concrete rectangular liquid-storage structure) and develop a reasonable limiting-device method, dynamic responses of non-isolation, sliding isolation with spring limiting-devices and sliding isolation with steel bar limiting-devices are comparatively studied by shaking table test. The seismic response reduction advantage of sliding isolation for concrete liquid-storage structures is discussed, and the effect of the limiting-device type on system dynamic responses is analyzed. The results show that the dynamic responses of sliding isolation CRLSS with steel bar-limiting devices are significantly smaller than that of sliding isolation CRLSS with spring-limiting devices. The structure acceleration and liquid sloshing wave height are greatly influenced by spring-limiting devices. The acceleration of the structure in this case is close to or greater than that of a non-isolated structure. Liquid sloshing shows stronger nonlinear characteristics. On the other hand, sliding isolation with steel bar-limiting devices has a good control effect on the structural dynamic response and the liquid sloshing height simultaneously. Thus, a limiting device is an important factor affecting the seismic response reduction effect of sliding isolation. To take full advantage of sliding isolation in a concrete liquid-storage structure, a reasonable design of the limiting device is particularly important.

Keywords: sliding isolation; concrete rectangular liquid-storage structure; limiting device; shaking table test; dynamic response

1. Introduction

An earthquake can cause not only the destruction of a concrete liquid-storage structure itself but also some special liquid leakage, resulting in secondary disasters, such as environmental pollution, fire, and, most seriously, the deaths of people. In all previous earthquakes, many cases of the destruction of concrete liquid-storage structures have been reported; some examples of seismic destruction cases are shown in Fig. 1.

The improvement of concrete liquid-storage structure safety or reduction of the structure damage probability during an earthquake has importance for material reserves, disaster prevention, rescue and relief work and post-disaster reconstruction. Isolation, as an effective measure, can improve the seismic capacity of the structure comprehensively and reduce the failure probability of the structure under earthquake action. Fortunately, a large number of theoretical studies regarding seismic reduction of liquid-storage structure have been conducted, most of which considering rubber isolation (Malhotra 1997, Shekari *et al*. 2010, Saha *et al*. 2013, Cheng *et al*. 2015, Saha *et al*. 2016). Some researchers also explored other methods for seismic response reduction of liquid-storage structure, mainly including single friction pendulum isolation, multiple friction pendulum isolation, variable frequency pendulum isolation, and sliding friction isolation (Saha *et al*. 2016, Abalı and Uçkan 2010, Zhang *et al*. 2011, Panchal and Jangid 2011). At present, research studies on the seismic response reduction of a liquid-storage structure based on the shaking table test are very limited. Chalhoub and Kelly (1990) conducted shaking table tests of non-isolation and isolation steel liquid-storage tanks and found that isolation decreased the dynamic excitation of the steel liquid-storage tank but amplified the liquid sloshing height. Kim and Lee (1995) conducted a shaking table test of LRB isolation on a steel liquid-storage tank under bidirectional earthquake action and found that the seismic performance of the steel liquid-storage tank was effectively improved by the isolation. Angelis *et al*. (2010) comparatively studied the dynamic responses of scale models of non-isolation, high-damping rubber isolation and sliding isolation with elastic-plastic dampers on steel liquid-storage tanks using a shaking table; the results showed that two types of isolation methods can effectively reduce the hydrodynamic pressure acting on the wall. Zhang *et al*. (2014) used a shaking table

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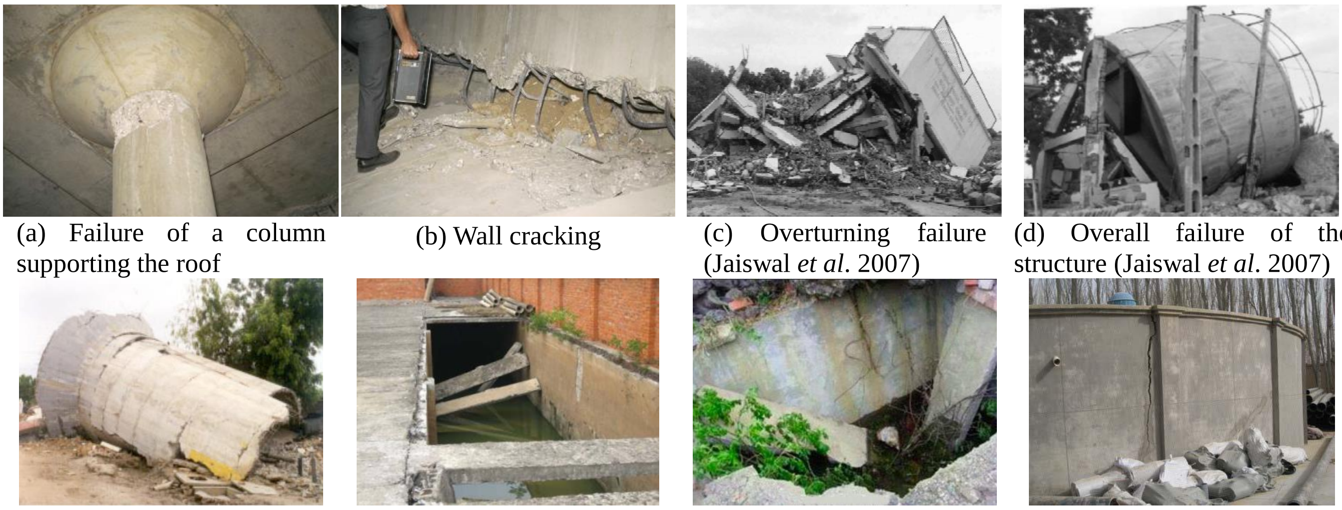


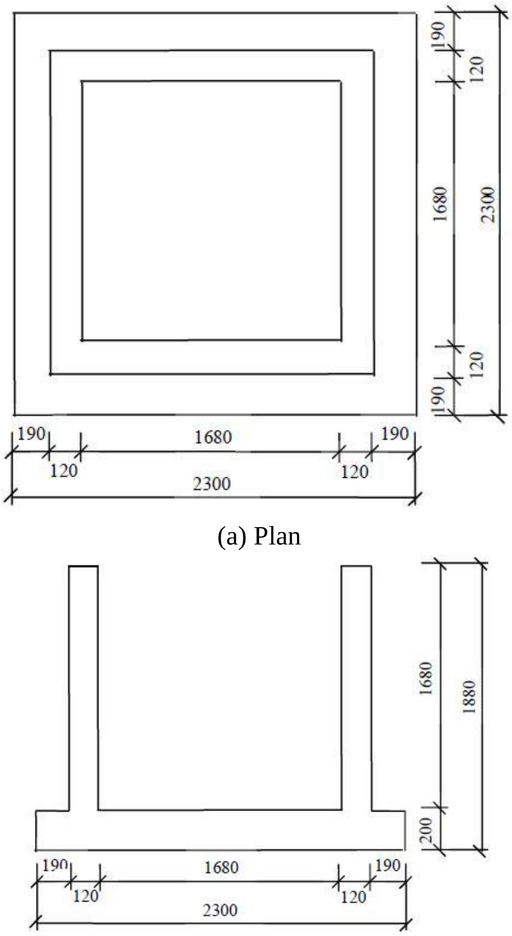
(a) Failure of a column supporting the roof
(b) Wall cracking
(c) Overturning failure (Jaiswal *et al*. 2007)
(d) Overall failure of the structure (Jaiswal *et al*. 2007)
(e) Collapse failure of a water tower (Rai 2002)
(f) Cover collapse (Gao *et al*. 2012)
(g) Wall cracking (Gao *et al.* 2012)
(h) Wall cracking (Gao *et al.* 2012)

Fig. 1 Seismic damage cases of concrete liquid-storage structures

test to study the seismic response of a multiple friction pendulum isolation steel liquid-storage tank and found that multiple friction pendulum isolation was very beneficial for liquid-storage tank overall, but its control effect on liquid sloshing wave height was not obvious.

A large number of studies regarding the isolation steel liquid-storage tank and the isolation CRLSS showed that although rubber isolation can significantly reduce the dynamic responses of the structure itself, such as base shear force and wall stress, it does not obviously control liquid sloshing wave height and even increases the liquid sloshing wave height. In contrast, some studies on the seismic response reduction of steel liquid-storage tanks showed that friction sliding isolation can realize the independence of the structure and the liquid sloshing periods; thus, the structure resonance can be avoided, and better seismic response reduction advantages for liquid-storage structure can be achieved. Although the sliding isolation control effect is good, a pure sliding isolation structure will suffer large horizontal displacement and residual displacement under earthquake action; as a result, a displacement-limiting measure is necessary. Many types of sliding isolation with limiting-device systems have been proposed over years of research. Fan and Tang (2001) proposed a sliding isolation system with limiting devices and obtained the corresponding response spectrum curve; they found that the maximum inter-story shear force and the maximum absolute acceleration distribution of a sliding isolation structure under seismic action are different from those of the non-isolation structure. Madden *et al*. (2002) formed an adaptive isolation system by combining sliding isolation and an adaptive hydraulic damper, proposed the corresponding analysis model and verified the model via experiment. Li and Deng (2008) used fuzzy control and sliding mode control to design a sliding mode controller and added the controller to the sliding isolation layer to form a hybrid control system; the numerical simulation results showed that the hybrid control method could not only effectively reduce the peak response of the upper structure but also effectively control the displacement of the isolation layer and allow the isolation layer to have a good reset ability. Jalali *et al*. (2001) combined shape memory alloy (SMA) with sliding bearings to form a type of intelligent recovery sliding isolation system: the sliding bearings could support the weight of the upper structure and allow the structure to produce large horizontal displacement, and SMA could provide a certain amount of lateral stiffness to the sliding isolation layer and make structure have appropriate reset ability. Lu *et al*. (2013) studied the influence of the additional damping of viscous dampers on the sliding isolation system under the action of pulse-like earthquake by using the shaking table test and found that the pulse-like earthquake was likely to cause a resonance phenomenon in the bearings displacement of the sliding isolation system and that adding the viscous damper could effectively reduce the resonance response of the sliding isolation system. Zou *et al.* (2016) used a friction damper to overcome the imperfection of a sliding isolation wood structure caused by large displacement under large earthquake actions and found that the friction damper could reduce the displacement of the isolation layer but cause the structural acceleration response to increase. Chakraborty *et al.* (2016) used a nonlinear spring as a reset device for the sliding isolation system and found that the control system could minimize the bearing displacement and make the residual displacement of the bearing be close to zero at the same time.

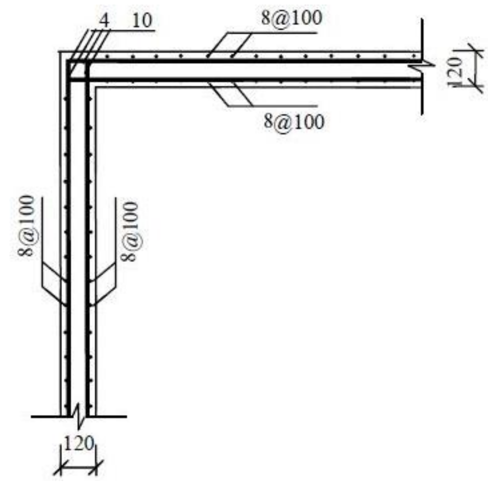
Although many researchers have studied the seismic response of liquid-storage structures by means of theory and shaking table tests, most of these studies were conducted for steel liquid-storage tank. At present, the research on the seismic response reduction of a concrete liquid-storage structure based on shaking table test is limited. Although rubber isolation can reduce the dynamic responses of the liquid-storage structure itself, its control effect on the liquid sloshing wave height is not significant or even produces a magnification effect. To overcome the defects of rubber isolation, researchers have studied the friction sliding



(a) Plan

(b) Elevation

Fig. 2 Model geometry (mm)



(a) Wall panels and corner reinforcement

(b) Floor reinforcement

Fig. 3 Reinforcement distribution (mm)

Table 1 Parameters of the spring-limiting device

project	unit	parameter	project	unit	parameter
Material	-	65Mn steel	Shear modulus	GPa	79
Allowable shear stress	MPa	660	Material diameter	mm	16
Mid diameter of spring	mm	70	Effective coil number	coil	11.5
Height-diameter ratio	-	4.786	Free height	mm	335
Total number of coils	coil	13	Spring index	-	4.375
Curvature correction factor	-	1.363	Stiffness	N/mm	164.1
Helix angle	degree	7.19	Spread length	m	2.86
Compressed height	mm	208	Pitch	mm	27.74

isolation for a liquid-storage structure; most of these studies have been conducted on the friction pendulum bearing. Because of the low cost of the concrete-storage structure, the high cost of the bearing will limit the application of friction pendulum bearing in the concrete liquid-storage structure; therefore, it is necessary to study the seismic response reduction method of low cost and effectiveness that is suitable for the concrete-storage structure. In this study, dynamic responses of non-isolation, sliding isolation with steel bar limiting-devices and sliding isolation with spring limiting-devices CRLSS under El-Centro and Tianjin waves are comparatively studied using shaking table tests. The control effect of sliding isolation on CRLSS and the influence of limiting-device type on the dynamic response of the system are investigated.

2. Shaking table test

2.1 Design of liquid-storage structure model

Considering the basic information, such as the size and carrying capacity of the shaking table, the geometric information of the experimental model is shown in Fig. 2, the reinforcement of the liquid-storage structure is shown in Fig. 3, the tensile strength of the rebar is 400 MPa, and the compressive strength of concrete is 30 MPa (the concrete strength and rebar specification are determined by the design software of Beijing Leading Software Co., Ltd.).

2.2 Design of the sliding isolation with limiting-devices system

Four Teflon sliding isolation bearings were positioned in

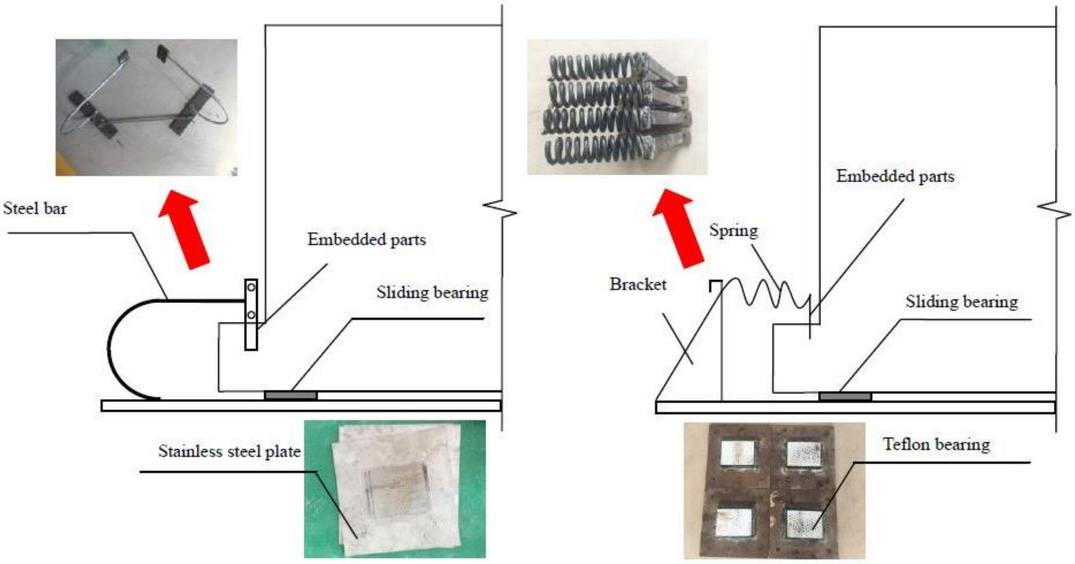


Fig. 4 Sliding isolation with limiting devices

the bottom corner of liquid-storage structure in total, and the smaller friction coefficient was obtained by daubing lubricating grease on Teflon bearing surface. To overcome the large displacement defect of the sliding isolation liquid-storage structure, 8 steel bars and four spring-limiting devices were positioned in the isolation layer; the schematic diagram of limiting-device connection is shown in Fig. 4, the parameters of the spring-limiting device are estimated preliminarily by Eqs. (1)-(5) (Li and Xue 2011), and the detailed parameters are shown in Table 1.

Under the action of unidirectional horizontal earthquake, the sliding bearing will produce horizontal motion in one direction; the frictional force F_f of slip surface is

$$F_f = \mu Mg \tag{1}$$

where μ is the friction coefficient; M is the total mass of the upper system; and g is the acceleration of gravity.

The elastic resilience force F_s generated by horizontal springs is

$$F_s = k_s U \tag{2}$$

where k_s is the spring stiffness and U is the structure displacement.

The conditions for the structure to be reset can be realized by

$$F_s > F_f \tag{3}$$

Because the horizontal stiffness of the Teflon sliding bearing is very small and can be ignored, the horizontal characteristic period of the sliding isolation structure is mainly determined by the horizontal stiffness of the reset spring, namely,

$$T_b = 2\pi\sqrt{\frac{m}{k_s}} \tag{4}$$

The relationships between μ and k_s and between μ and T_b can be obtained by Eqs. (1)-(4)

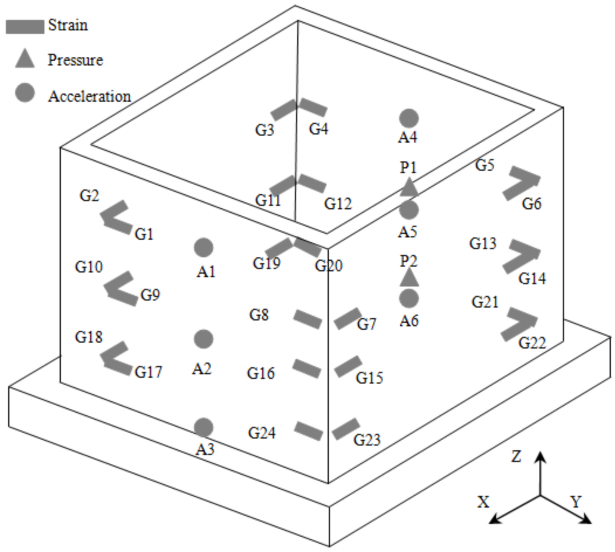
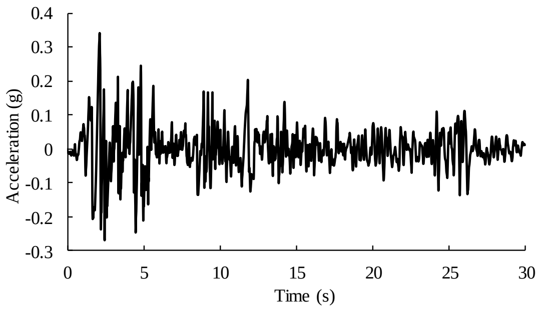


Fig. 5 Layout of the measuring points

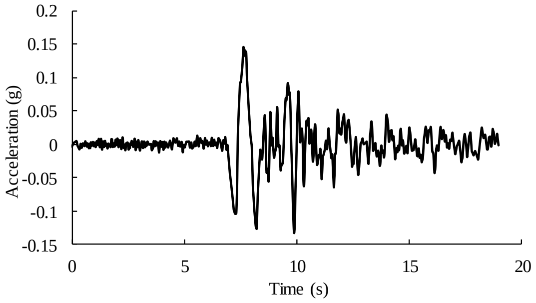
$$k_s > \frac{\mu Mg}{U_{\max}}, \mu < \frac{4\pi^2 U_{\max}}{gT_b} \tag{5}$$

2.3 Loading and testing

The experiment was conducted in the 4 m×6 m earthquake simulation shaking table in the Loess Seismic Engineering Laboratory belonging to the Seismological Bureau of Gansu Province; the shaking table can be loaded in both horizontal and vertical directions. A multi-channel vibration control and test instrument Premax of Yiheng Company and a Donghua 5922 dynamic data acquisition tester were used as the data acquisition system. Six acceleration sensors, 24 concrete waterproof strain gauges and 2 liquid pressure sensors were arranged on the model, and the high-speed camera was used to record the motion state of the structure and the liquid; the layout of the measuring points is shown in Fig. 5.



(a) El-Centro wave



(b) Tianjin wave

Fig. 6 Acceleration time history curves

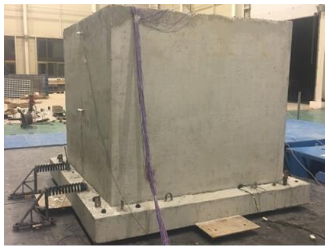
2.4 Test conditions design

To determine the change rule of the dynamic characteristics of the liquid-storage structure, the structure was swept with a sine wave with amplitude of 0.05 g, and the fundamental frequency of the system was obtained according to the transfer function obtained by the measuring point. Two seismic wave records with different spectral characteristics and different development mechanisms are selected: the first one is the north-south near-field El-Centro wave, and the second one is the north-south far-field Tianjin wave; their acceleration time curves are shown in Fig. 6. Because the amplitude of near-field seismic wave is often large, and the amplitude of far-field seismic wave is often small, the PGAs of El-Centro and Tianjin waves are adjusted to 0.22 g; according to Chinese code (GB 50011-2010, 2016), they are equivalent to rare earthquakes of seven degrees. In all cases, the liquid level height is 0.84 m, namely, the liquid-storage ratio is 50%.

2.5 Test models

Because the dynamic response of the isolation structure is small and can ensure the upper structure is not damaged, the shaking table test of sliding isolation structure is conducted first, and then the shaking table test of the non-isolation structure is conducted; the test models are shown in Fig. 7.

(a) Sliding isolation structure with steel bar-limiting devices



(b) Sliding isolation structure with spring-limiting devices

(c) Non-isolation concrete liquid-storage structure

Fig. 7 Test models

3. Test results and analysis

3.1 Dynamic characteristics

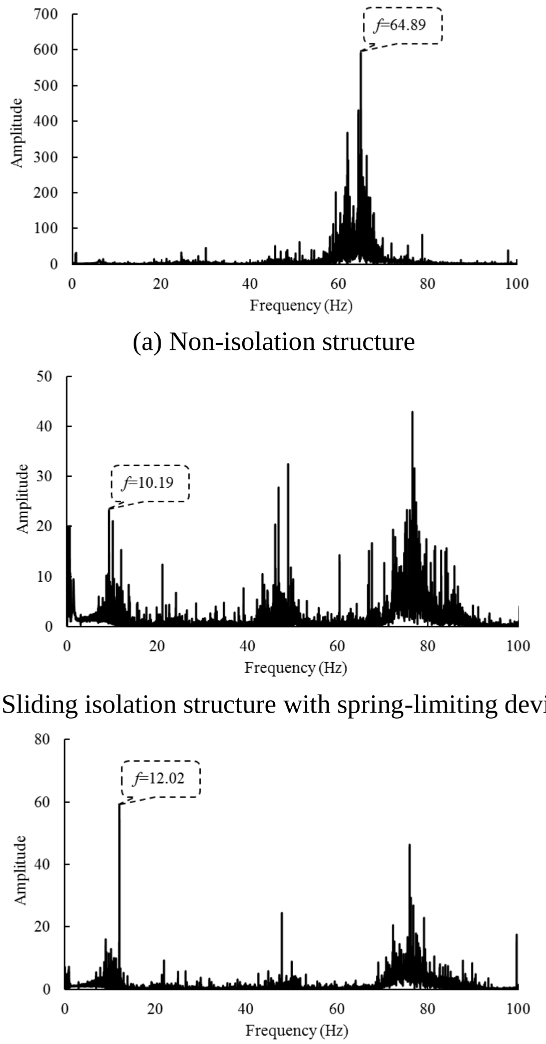
To determine the dynamic characteristics of the model structure, a sine wave with PGA of 0.05 g was used to sweep the model, and then the result of the frequency sweep was analyzed. The amplitude frequency function is obtained by the transfer function between the input of the shaking table and the structural response. Finally, the natural frequency of the liquid-storage structure can be obtained. In the shaking table test, the sine wave $a_g(t)$ is used as the input, and if the acceleration of the measurement point i is $a_i(t)$, then the acceleration transfer function of the measurement point i is

$$H_a(f, z_i) = \frac{G_{xy}(f, z_i)}{G_{xx}(f)} \tag{6}$$

where $G_{xx}(f)$ is the self-power spectrum of the shaking table input sine wave $a_g(t)$ and $G_{xy}(f,z_i)$ is the cross-power spectrum of $a_g(t)$ and $a_i(t)$.

The frequency response function of the non-isolation, sliding isolation with steel bar-limiting devices and sliding isolation with spring-limiting devices CRLSS can be obtained using Eq. (6), as shown in Fig. 8.

As shown in Fig. 8 and Table 2, the first vibration frequency of the non-isolation CRLSS is 64.89 Hz, the first



(a) Non-isolation structure

(b) Sliding isolation structure with spring-limiting devices

(c) Sliding isolation structure with steel bar-limiting devices

Fig. 8 Frequency response functions

Table 2 First-order frequencies of different structures

Structure type	Non -isolation	Sliding isolation-spring	Sliding isolation-steel bar
First order frequency (Hz)	64.89	10.19	12.02

vibration frequency of the sliding isolation concrete liquid-storage structure with spring-limiting devices and the sliding isolation CRLSS with steel bar-limiting devices are reduced to 10.19 Hz and 12.02 Hz, respectively. The results show that the non-isolation CRLSS has very large stiffness; however, after the sliding isolation is implemented, the vibration period of CRLSS is greatly extended and thus helps the structure avoid some resonance response. In addition, the limiting-device type has little effect on the vibration frequency of the sliding isolation liquid-storage structure.

3.2 Dynamic response

3.2.1 Structural acceleration

Figs. 9 and 10 show the acceleration results of the non-isolation, sliding isolation with steel bar-limiting devices and sliding isolation with spring-limiting devices CRLSS under the earthquake action with PGA 0.22 g through the comparison of three types of structure acceleration response to assess the seismic response reduction effect of sliding isolation on liquid-storage structure and the influence of limiting-device type on structure acceleration response.

Table 3 Maximum acceleration of structure (m/s^2)

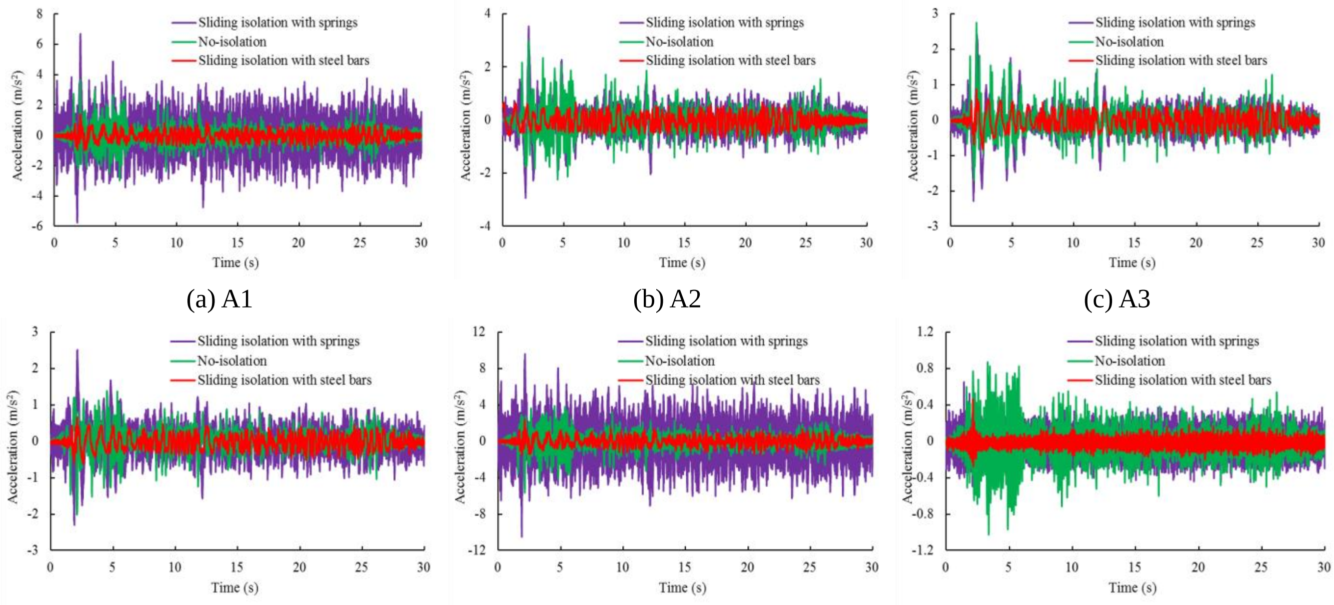
Earthquakes	Structure type	Measuring points					
		A1	A2	A3	A4	A5	A6
El-Centro	No isolation	3.408	2.858	2.754	2.015	5.070	1.023
	Isolation-spring	6.588	3.534	2.340	2.477	9.438	0.644
	Isolation-steel bar	1.002	0.501	0.763	0.581	2.359	0.462
Tianjin	No isolation	3.655	2.817	2.602	2.015	5.656	1.023
	Isolation-spring	5.337	5.092	4.832	3.670	7.769	0.363
	Isolation-steel bar	1.493	1.418	1.322	1.028	2.190	0.271

As shown in Fig. 9, Fig. 10 and Table 3, the acceleration of the sliding isolation liquid-storage structure with steel bar-limiting devices is far less than that of the sliding isolation liquid-storage structure with spring-limiting devices, and in most cases, the acceleration of the sliding isolation liquid-storage structure with spring-limiting devices is greater than that of the non-isolation liquid-storage structure, showing that the control effect on sliding isolation structure acceleration is tightly related with the limiting-device type; the effect of steel bar-limiting device on the seismic response reduction of sliding isolation is minor on the premise of controlling the displacement of structure, but the spring-limiting device seriously weakens the seismic response reduction effect of sliding isolation on the liquid-storage structure.

3.2.2 Liquid sloshing wave height

Liquid sloshing wave height is one of the important dynamic response of liquid-storage structure and is also one of the important factors to be controlled under the action of earthquake because once the wave height is beyond the reserved freeboard height, the liquid will spill over. For the liquid-storage structure used to store chemical items and sewage, the adverse effect of liquid spillage on environment is a key issue; thus, seeking the control method that can reduce liquid sloshing wave height has important meaning. The maximum curve outlines of the non-isolation, sliding isolation with spring-limiting devices and sliding isolation steel bar-limiting devices liquid-storage structure under earthquake action are shown in Figs. 11 and 12, and the bold red line represents a rough outline of liquid sloshing.

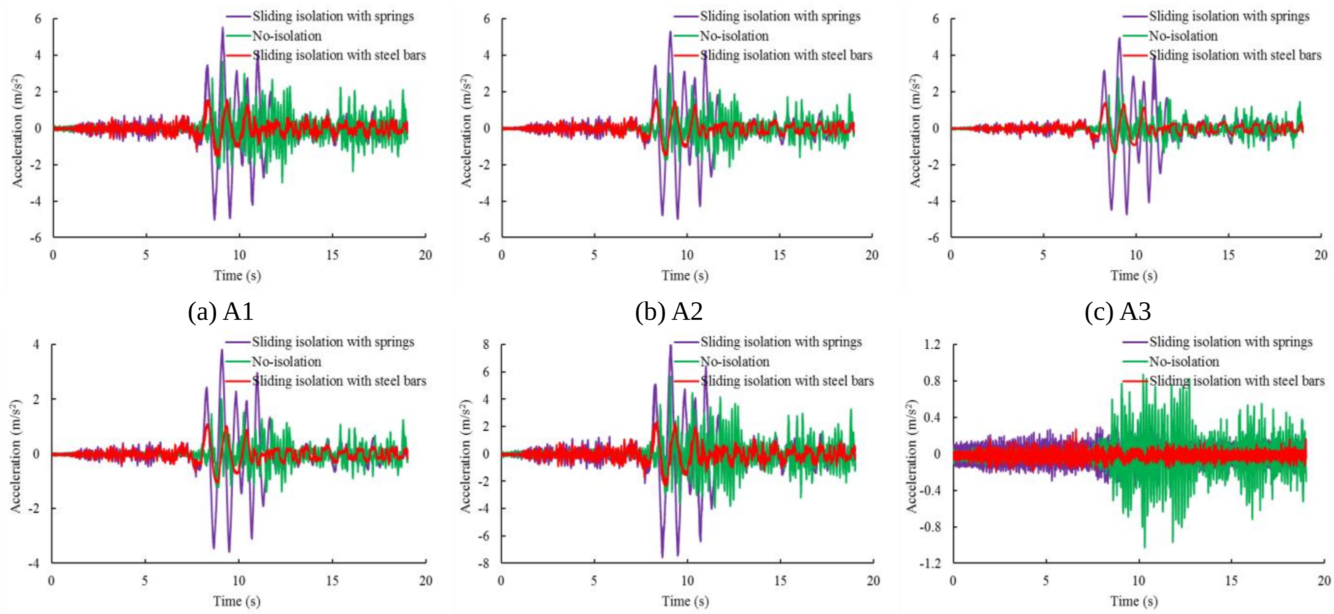
As shown in Figs. 11 and 12, the liquid sloshing wave heights of the non-isolation and sliding isolation with springs-limiting devices liquid-storage structure show nonlinear characteristics, the free surface is broken, the wave height is larger, and compared to the non-isolation structure, sliding isolation with spring-limiting devices



(a) A1 (b) A2 (c) A3

(d) A4 (e) A5 (f) A6

Fig. 9 Liquid-storage structure acceleration under El-Centro wave action



(a) A1 (b) A2 (c) A3

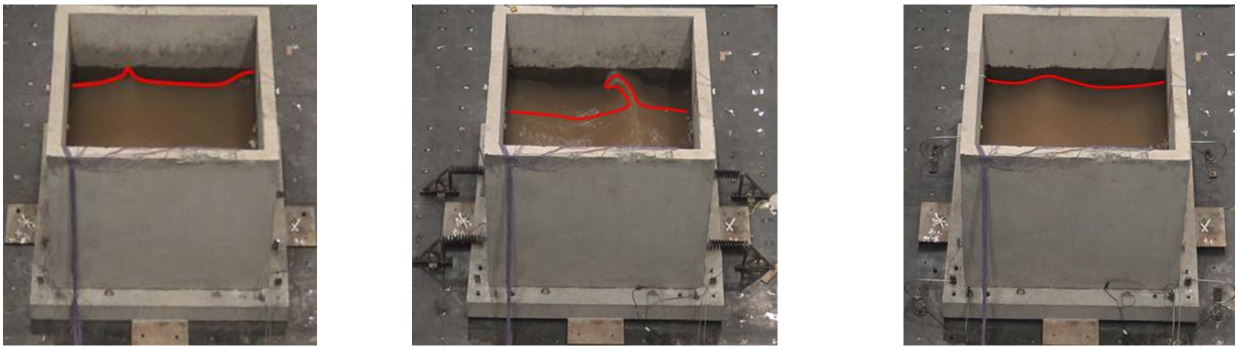
(d) A4 (e) A5 (f) A6

Fig. 10 Liquid-storage structure acceleration under Tianjin wave action

increases the nonlinearity of liquid sloshing, the sloshing wave height is obviously amplified and the liquid curve broken phenomenon is more serious. In this case, the nonlinear liquid sloshing theory should be adopted to more accurately study the dynamic response of the non-isolation and sliding isolation with spring-limiting devices liquid-storage structure under some earthquake actions. By contrast, liquid sloshing of the sliding isolation with steel bar-limiting devices liquid-storage structure has been effectively controlled, the liquid sloshing is gentle, liquid-free surface keeps continuous, sloshing wave height is small, and the common linear potential flow theory is used to obtain the solution satisfying the precision requirement, thus simplifying the analysis of the fluid-structure interaction problem of liquid-storage structure. It is indicated that the limiting-device type has a great influence on the liquid sloshing wave height, and the reasonable design of the limiting-device type can make the sliding isolation have a significant control effect on the liquid sloshing wave height.

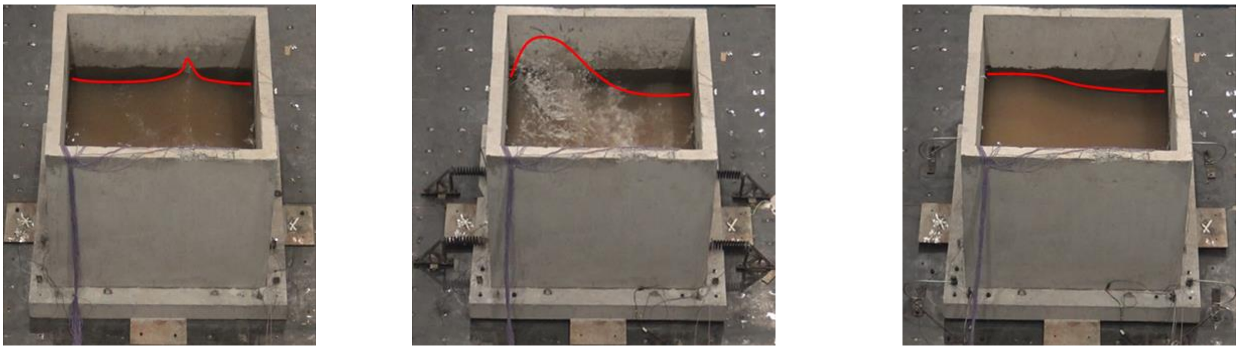
3.2.3 Liquid pressure

In addition to static pressure, the liquid can produce additional hydraulic pressure under the earthquake action, and the pressure of hydraulic pressure can reflect the intensity of liquid sloshing. The liquid pressures of the non-



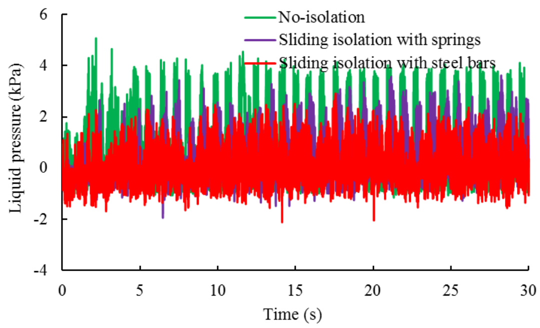
(a) Non-isolation (b) Isolation with spring-limiting devices (c) Isolation with steel bar-limiting devices

Fig. 11 Liquid sloshing wave height under El-Centro wave action

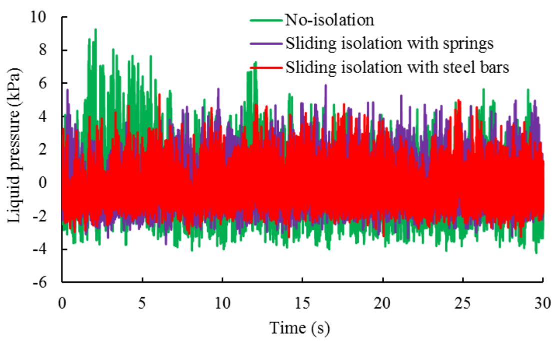


(a) Non-isolation (b) Isolation with spring-limiting devices (c) Isolation with steel bar-limiting devices

Fig. 12 Liquid sloshing wave height under the Tianjin wave action

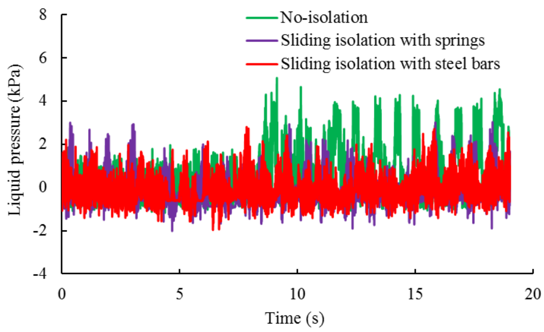


(a) Pressure sensor P1

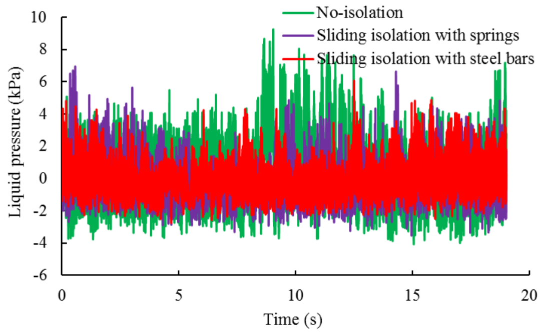


(b) Pressure sensor P2

Fig. 13 Liquid pressure under the El-Centro wave action



(a) Pressure sensor P1



(b) Pressure sensor P2

Fig. 14 Liquid pressure under the Tianjin wave action

isolation, the sliding isolation with spring-limiting devices and the sliding isolation with steel bar-limiting devices liquid-storage structure are shown in Figs. 13 and 14.

As shown in Fig. 15, Fig. 16 and Table 4, the liquid pressure of the non-isolation liquid-storage structure is maximum, the liquid pressure of the sliding isolation with spring-limiting devices liquid-storage structure is secondary, and the liquid pressure of the sliding isolation

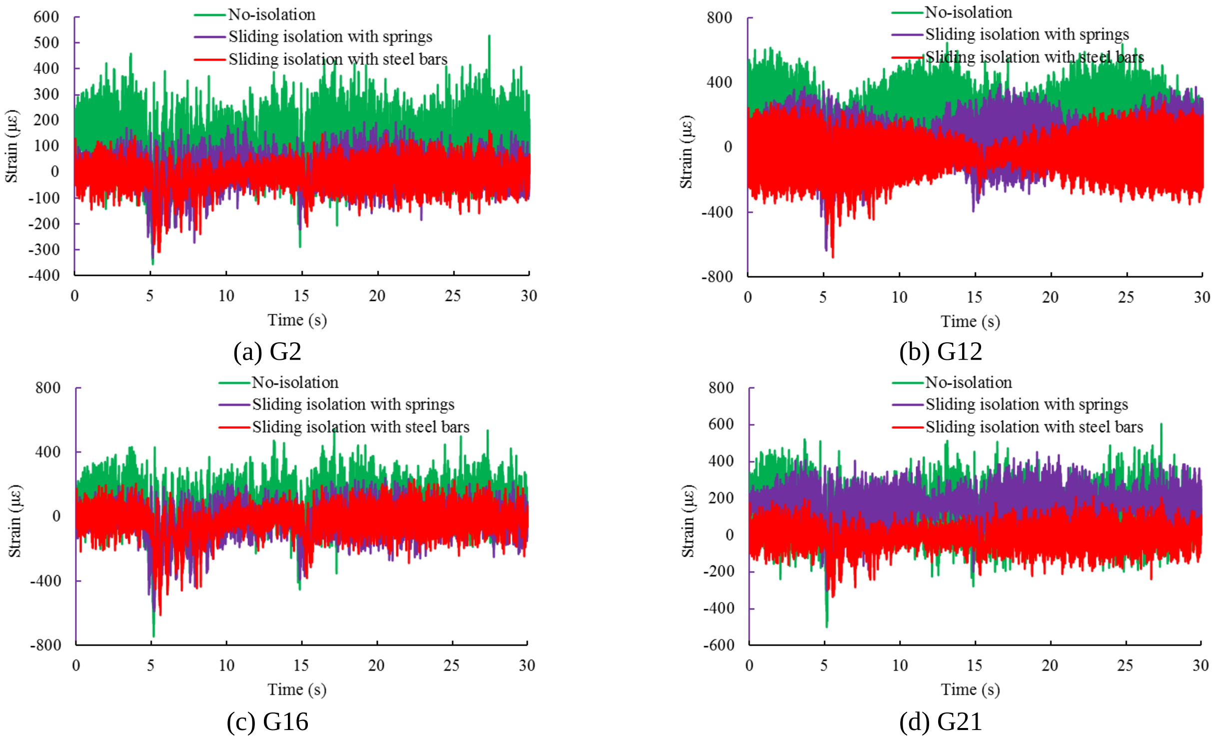


Fig. 15 Wall strain under the El-Centro wave action

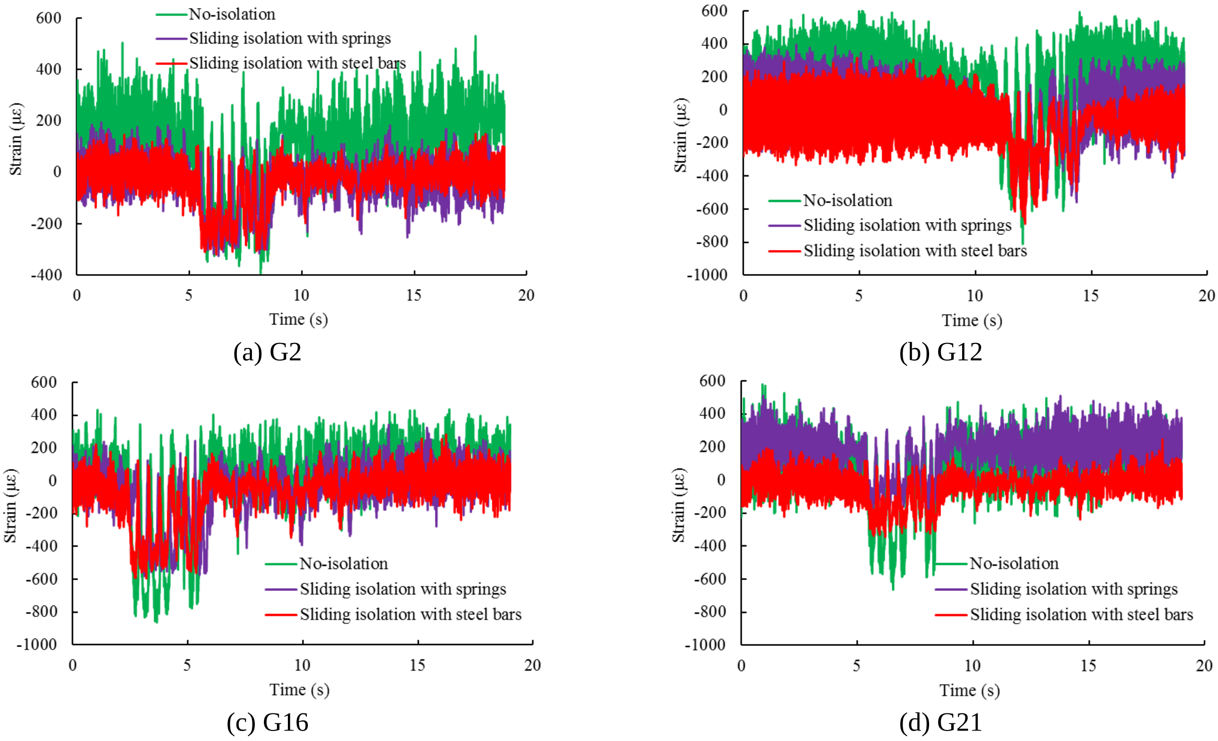


Fig. 16 Wall strain under the Tianjin wave action

with spring-limiting devices liquid-storage structure is minimum, i.e., sliding isolation can significantly reduce the liquid pressure; in addition, the control effect of the sliding isolation with steel bar-limiting devices on liquid pressure is better than that of the sliding isolation with spring-limiting devices, namely, the limiting-device type has a great influence on the liquid pressure.

3.2.4 Wall strain

CRLSS could be damaged by the wallboard cracking via the larger tensile strain, resulting in structure failure (Li *et al*., 2006), and the change of strain can directly reflect the control effect of the seismic response reduction method. Figs. 15 and 16 show the results of the strain measuring points G2, G12, G16 and G21.

Table 4 Maximum liquid pressure acting on structure (kPa)

Earthquakes	Structure type	Measuring points	
		P1	P2
El-Centro	No isolation	4.987	9.251
	Isolation-spring	3.434	5.873
	Isolation-steel bar	2.912	5.302
Tianjin	No isolation	4.969	9.301
	Isolation-spring	3.028	6.936
	Isolation-steel bar	2.803	6.061

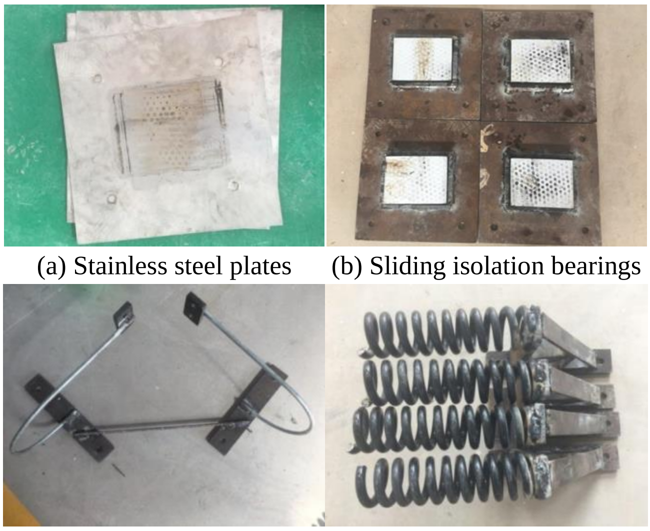
Table 5 Maximum tensile strain of structure (με)

Earthquakes	Structure type	Measuring points			
		G2	G12	G16	G21
El-Centro	No isolation	527.138	646.438	546.559	604.821
	Isolation-spring	172.013	391.192	241.374	452.229
	Isolation-steel bar	147.044	307.960	202.532	213.630
Tianjin	No isolation	529.912	597.382	435.582	579.852
	Isolation-spring	183.111	369.741	341.252	510.491
	Isolation-steel bar	149.818	316.283	282.990	246.922

As shown in Fig. 15, Fig. 16 and Table 5, the wall tensile strain of the non-isolation liquid-storage structure is maximum, the wall tensile strain of the sliding isolation with spring-limiting devices liquid-storage structure is secondary, the wall tensile strain of the sliding isolation with steel bar-limiting devices liquid-storage structure is minimum, and the wall tensile strain of the sliding isolation liquid-storage structure is obviously smaller than non-isolation liquid-storage structure; in addition, the sliding isolation can reduce the tension and compression strain of liquid-storage structure. This finding shows that sliding isolation has a good control effect on the wall tensile strain of the liquid-storage structure, and the limiting-device type will affect the control effect of the sliding isolation on the wall strain.

In summary, the limiting-device type has a great influence on the dynamic responses of the sliding isolation concrete liquid-storage structure. Moreover, Yang *et al*. (2011) obtained a shock mitigation system, which combined the sliding bearings and the energy dissipation components, and the system had an amplification effect on the liquid sloshing wave height of the steel liquid-storage tank; the reason may be that the reset and energy dissipation devices affected the control effect of sliding isolation on the liquid sloshing wave height. Thus, the seismic response reduction effect of sliding isolation on the liquid-storage structure would be weakened or lost if the limiting-device design is not reasonable; therefore, to give full play to the advantages of sliding isolation for the catastrophic control of concrete liquid-storage structures, the reasonable design of spacing devices is worthy of study.

4. The structural inspection after the experiment



(a) Stainless steel plates (b) Sliding isolation bearings

(c) Steel bar-limiting devices (d) Spring-limiting devices

Fig. 17 Changes in the components after the experiment

If the components of the isolated liquid-storage structure are damaged under the earthquake action, they cannot continue to play a role under the aftershocks, and the isolation bearing and the limiting device after the earthquake must be replaced; this will undoubtedly increase the maintenance costs after the earthquake. Thus, it is significant to ensure each component of the sliding isolation concrete liquid-storage structure is perfectly preserved. The changes in each component of the sliding isolation layer after the experiment are shown in Fig. 17.

As shown in Fig. 17, the sliding isolation concrete liquid-storage structure can been perfectly preserved at the end of the earthquake; moreover, the reasonable design of the limiting device is not damaged and can continue to play a role, thus helping to ensure that the control system still plays a role in the seismic response reduction of the upper structure under the aftershocks. Furthermore, the system can be used continually without maintenance after earthquake to reduce the cost of use.

5. Conclusions

To study the seismic response reduction effect of sliding isolation on a liquid-storage structure, three types of liquid-storage structures were designed: the non-isolation, sliding isolation with spring-limiting devices and sliding isolation with steel bar-limiting devices CRLSS. The dynamic characteristics and dynamic responses of the three types of liquid-storage structures were compared, the advantages of sliding isolation for seismic response reduction of liquid-storage structures were studied, and the influence of the limiting-device type on the seismic performance of the sliding isolation liquid-storage structure was discussed. The main conclusions are as follows.

(1) The frequency response function was used to analyze the sweep frequency data. Sliding isolation was found to prolong the vibration period of the liquid-storage structure, and the limiting-device type was

found to have little effect on the vibration period of the sliding isolation liquid-storage structure.

(2) The acceleration of the sliding isolation with steel bar-limiting devices liquid-storage structure is far less than that of the non-isolation liquid-storage structure; however, in most cases, the acceleration of the sliding isolation with spring-limiting devices liquid-storage structure is close to or beyond the acceleration of the non-isolation liquid-storage structure. Although the two types of control measures provide shock absorption on both the liquid pressure and the wall strain, the seismic response reduction effect of sliding isolation with steel bar-limiting devices is better than that of sliding isolation with spring-limiting devices. The first-order frequencies of sliding isolation with spring-limiting devices and with steel bar-limiting devices systems are 10.19 Hz and 12.02 Hz, respectively, and the frequency difference between the two systems is small. Because the two systems have the same ground motion input, the influences of system frequency and earthquake frequency can be negligible. Thus, the influence of the limiting device on the sliding isolation should be further investigated.

(4) The liquid sloshing of the non-isolation and sliding isolation with spring limiting-devices concrete liquid-storage structure is prone to be broken and show strong nonlinearity, and the amplification effect of the liquid sloshing is caused by the spring-limiting devices; in this case, it is necessary to solve the fluid-structure interaction problem using nonlinear liquid sloshing theory. By contrast, liquid sloshing of the sliding isolation with steel bar-limiting devices liquid-storage structure is effectively controlled, the amount of liquid sloshing height is very small, the liquid free surface remains continuous, and the fluid-structure interaction problem can be solved by the linear liquid sloshing theory.

(5) The acceleration, liquid sloshing wave height, liquid pressure and wall tensile strain of sliding isolation with spring-limiting devices liquid-storage structure are obviously larger than that of sliding isolation with steel bar-limiting devices liquid-storage structure. Through the analysis of the control effect on various dynamic responses, the steel bar-limiting device is found to be obviously better than the spring-limiting device. Thus, the limiting device is an important factor affecting the seismic response reduction effect of sliding isolation. To give full play to the seismic isolation advantages of sliding isolation to concrete liquid-storage structure, a reasonable design of a limiting device is particularly important.

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