Vibration characteristic of rubber isolation plate-shell integrated concrete liquid-storage structure

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(Received , Revised , Accepted )

Abstract. To obtain the seismic response of lead-core rubber, shape memory alloy (SMA) - rubber isolation Plate-shell Integrated Concrete Liquid-Storage Structure (PSICLSS), based on a PSICLSS in a water treatment plant, built a scale experimental model, and a shaking table test was conducted. Discussed the seismic responses of rubber isolation, SMA - rubber isolation PSICLSS. Combined with numerical model analysis, the vibration characteristics of rubber isolation PSICLSS are studied. The results showed that the acceleration, liquid sloshing height, hydrodynamic pressure of rubber and SMA - rubber isolation PSICLSS are amplified when the frequency of seismic excitation is close to the main frequency of the isolation PSICLSS. The earthquake causes a significant leakage of liquid, at the same time, the external liquid sloshing height is significantly higher than the internal liquid sloshing height. Numerical analysis showed that the low-frequency acceleration excitation causes a more significant dynamic response of PSICLSS. The sinusoidal excitation with first-order sloshing frequency of internal liquid causes a more significant sloshing height of the internal liquid, but has little effect on the structural principal stresses. The sinusoidal excitation with first-order sloshing frequency of external liquid causes the most enormous structural principal stress, and a more significant external liquid sloshing height. In particular, the principal stress of PSICLSS with long isolation period will be significantly enlarged. Therefore, the stiffness of the isolation layer should be properly adjusted in the design of rubber and SMA - rubber isolation PSICLSS.

Keywords: shape memory alloy; rubber isolation; concrete; liquid storage structure; shaking table test; vibration characteristic

1
2
3 1. Introduction

4
5 Plate-shell integrated concrete liquid-storage
6 structure (PSICLSS) is a new type of water treatment
7 structure, which has been widely used in the water
8 purification system of the Yellow River. Such as the
9 Yellow River Water Pretreatment Project of Shandong
10 Jincheng Chemical Technology Co. Ltd., Yan'an Yellow
11 River Water Diversion Project - Yanshuiyan Sediment
12 Treatment Station, Weinan City Pumping Yellow Water
13 Supply Pushstone Settlement Tool Project, Guanghe
14 County Water Treatment Plant Settlement Tool and other
15 projects (as shown in Fig. 1).

16 According to the investigations of earthquake
17 disasters, earthquakes not only cause the destruction of
18 liquid storage structures, but also cause the leakage of
19 liquid, cause secondary disasters, interrupt the function of
20 life line engineering, and create a massive obstacle to
21 earthquake relief (Gao et al. 2012). For example, the 2008
22 Wenchuan earthquake caused the destruction of part of
23 the liquid storage structure and water supply pipe network,

24 such as cracks at the bottom of the filter tank, caused
25 water leakage in a water plant at Mianyang Santai County
26 (seismic intensity VI degrees). Reaction pools grid
27 dislocation, concrete crushed in Yuanba area (seismic
28 intensity VII degree) water plant. In 2010, the Yushu
29 earthquake in Qinghai caused a large crack on a 500 m²
30 liquid storage tank in the Jiegu town of Yushu (seismic
31 intensity: IX), caused severe water seepage. The 2011
32 Great East Japan Earthquake caused gas supply cuts to
33 360,000 households and water cuts to 750,000 households
34 (Guo and Miao, 2014; Zhou et al. 2012; Sun et al. 2010).
35 It is great significance to study the anti-seismic and shock
36 isolation of urban life line engineering structures, improve
37 the anti-seismic performance of life line structures and
38 earthquake relief ability of cities. The PSICLSS is an
39 important part of the urban life line engineering. Carrying
40 out the shaking table model test on PSICLSS is an
41 important part of studying the anti-seismic, isolation and
42 damping performance of urban life line engineering
43 structures.

44 Studies showed that the base isolation system could
45 effectively reduce the seismic damage of the structure
46 (Radnic et al. 2018). Jadhav and Jangid (2006) observed
47 that the resultant response of the isolation tank is mainly
48 governed by the fault normal component with a minor
49 contribution from the fault parallel component. Nayak and
50 Biswal (2013) studied the effect of frequency content on
the dynamic response of tank-liquid system. The nonlinear seismic response of rectangular liquid tank has been studied. Radnic et al. (2018) found that the hydrodynamic pressure exceeds the hydrostatic pressure by several times, and the resonance excitation sufficiently causes the movement of water. Panchala and Jangid (2013) observed that under near-fault ground motions, the variable curvature friction pendulum system is quite effective in controlling the seismic response of liquid storage tanks. Jadhav and Jangid (2004) studied the seismic responses of liquid storage tanks isolated by elastomeric bearings and sliding bearings are investigated under actual earthquake ground motions. Found that the elastomeric bearing with lead core performs better in comparison to other systems. Cheng et al. (2018a, 2018b 2021, 2020) carried out a shaking table test on the isolation concrete rectangular liquid storage structure, and studied the dynamic response of PSICLSS under the action of long period ground motion, and the results showed that the ground motion will cause the increase of structural stress, and the ground motion would cause liquid sloshing, cause tensile failure of the structure. Therefore, propose a reliable isolation and damping control method for the structure has great significance to improve the seismic capacity of the structure.

![Fig. 1 Plate-shell integrated concrete liquid-storage structure (PSICLSS)](image)

The energy dissipation capacity of lead-core rubber isolation bearing is limited, and the lead is prone to plastic deformation under major earthquakes, which reduces the self-reset ability of the bearing. Therefore, scholars proposed a variety of shape memory alloys (SMA)-rubber combination isolation bearings. Studies showed that the hysteresis loops of SMA-rubber bearing (Fig. 2 (a)) obtained under horizontal compression and shear tests are all full, indicating that this kind of bearing has good energy dissipation capacity (Xue et al. 2005). Miao et al. (2012) showed that the restoring force of SMA-rubber bearing could meet the response of the bearing under dynamic load and reduce seismic damage of the bridge. Liu et al. (2008) found that SMA stranded wire and rubber combination isolation bearing has greater restoring force than ordinary rubber bearing under strong earthquake action by shaking table test. Choi and Rahman et al. (2005, 2013) studied the control capacity of residual displacement and energy dissipation capacity of a SMA-rubber bearing (as shown in Figure 2 (b)) on the bridge. Ozbulut et al. (2010) showed that the SMA-rubber bearing isolation system can effectively reduce the seismic response of highway bridge, and SMA is the primary energy dissipating component in the SMA-rubber isolation bearing. Zheng et al. (2020) studied the seismic performance of a continuous bridge with a superelastic sliding rubber isolation system. The study showed that this isolation system could limit the base shear and the base bending moment of the bridge pier and reduce the seismic damage of the bridge. Cao et al. (2020) compared a SMA-rubber bearing with the traditional lead-core rubber bearing, and found that the SMA-rubber bearing can effectively limit isolation displacement in the case of near-fault ground motion. In summary, it can be seen that SMA can control the deformation of the isolation layer under major earthquakes, and provide a better recovery force for the isolation layer. But most of the researches are limited to structures such as bridges, and the application in liquid storage structures is relatively small. Zhang et al. (2021) presented the influence of viscoelastic parameters, and radius curvature on the free, and forced vibration characteristics of the functionally graded graphene nanoplatelets reinforced composite doubly curved panel on the viscoelastic foundation under low-velocity impact. The frequency information of functionally graded graphene platelets reinforced composite open-shell resting on a non-polynomial elastic substrate involving friction force under residual stresses has been investigated by Dai et al. (2021). Sarkheil and Foumani (2016) studied the free vibration of a rotating joined cylindrical-conical shell. The effect parameters such as rotation speed cone angle, circumferential wave number, length to radius ratio, and shell thickness on the frequencies were investigated. Lee et al. (2002) investigated the free vibration characteristics of the joined spherical-cylindrical shell with various boundary conditions. The effects of the shallowness of the spherical shell and length of the cylindrical shell on the free vibrational behavior of joined shell structure are investigated. Tedesco (1982) developed simple analytical expressions for empty tanks which accurately predicted frequencies and radial mode shapes corresponding to the fundamental mode of vibration. It can be seen that the current research on vibration characteristics is limited to shell structure, and there are few studies on vibration characteristics of the liquid storage structures.

According to the research status of PSICLSS, it can be seen that the liquid storage structures are prone to damage under the action of earthquake. Studies showed that base isolation can reduce the seismic damage of liquid storage structure, while SMA can increase the energy dissipation capacity of isolation layer, limits plastic deformation of isolation layer under strong earthquake, reduce the residual displacement of isolation layer. Therefore, based on the scaled shaking table model test, the dynamic responses of non-isolation, lead-core rubber isolation, and SMA-rubber isolation (as shown in
Fig. 2 (b) PSICLSS are studied. Through numerical model research, the vibration characteristics of isolation PSICLSS are studied. And the displacement of isolation layer, structural stresses and liquid sloshing heights of isolation PSICLSS with different acceleration excitation frequencies and different isolation periods are analyzed.

Fig. 2 SMA- rubber isolation bearing

2 Model design

2.1 Model similarity ratio design

This simulated shaking table test was carried out in the Loess Earthquake Engineering Laboratory of Gansu Seismological Bureau. Taking the PSICLSS in a water treatment plant in Gansu Province as the prototype (as shown in Fig. 1), an experimental model of PSICLSS was designed. This test includes three test models: non-isolation, lead-core rubber isolation, SMA-rubber isolation PSICLSS.

The design of the test model is based on three principles: (1) The test equipment and environmental conditions of the laboratory; (2) Original structural parameters and test objectives; (3) Ensure that the model can basically reflect the dynamic characteristics of the original structure. According to the specific conditions of the test, combined with the performance parameters of the shaking table, the design method of the shaking table test model and the model similarity theory (Zhou and Lu, 2016), the size similarity of the test model is determined, as shown in Tab. 1. In the model test, pure water is stored in the structure, so the material similarity ratio of liquid is 1. Considering that the structure is carried out under the condition of the gravitational field, which involves liquid sloshing height and hydrodynamic pressure, the dynamic characteristic similarity ratio of the structure is 1 (Wang et al. 2020), and the liquid storage height is 1.2 m. The concrete is mixed on site, its compressive strength is 30 MPa. The schematic structure model is shown in Fig. 3 and Fig. 4.

Table 1 Dimensional similar parameters

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Similarity relation</th>
<th>Similarity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$L = L'$</td>
<td>$1/5$</td>
</tr>
<tr>
<td>Displacement</td>
<td>$C_x = C_x'$</td>
<td>$1/5$</td>
</tr>
<tr>
<td>Area</td>
<td>$C_A = C_A^2$</td>
<td>$1/25$</td>
</tr>
<tr>
<td>Angular displacement</td>
<td>$S_\theta = 1.0$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

Table 2 Rubber isolation bearing parameters

<table>
<thead>
<tr>
<th>Outside diameter (mm)</th>
<th>Lead diameter (mm)</th>
<th>Height (mm)</th>
<th>First shape factor</th>
<th>Second shape factor</th>
<th>Shear modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>26</td>
<td>82</td>
<td>29.18</td>
<td>6.44</td>
<td>0.392</td>
</tr>
</tbody>
</table>
2.2 Isolation bearing parameters and layout

The parameters of selected lead-core rubber bearing in the test are shown in Tab. 2. Selected combination mode of SMA-rubber isolation bearing as shown in Fig. 2 (b). The low-temperature hyperelastic SMA is used in the SMA-rubber combination isolation bearing. The structure and liquid are simplified to a concentrated mass, and the demand recovery force of the isolation layer is calculated. In order to avoid large displacement deformation of the isolation layer, and to avoid damage due to insufficient tensile strength of SMA during vibration, the selected SMA wire parameters are determined as follows. The phase transformation temperature of SMA is -5°C, the diameter is 1 mm, the tensile strength is 1500 MPa, and the maximum tensile force is 1.18 kN. Each combination isolation bearing is arranged with two SMA wires, and the effective tensile length of each SMA wire is 600 mm. Fixed pulleys are used to ensure uniform force and deformation of SMA wire. The SMA-rubber isolation bearing is assembled as shown in Fig. 5.

2.3 Setting of test conditions and monitoring points

8 acceleration sensors (A1-A8) are installed on the outer plate of PSICLSS, an acceleration sensor (A9) is installed on the shaking table. Monitor the acceleration response of the structure and the input acceleration along the X direction and Z direction respectively. In the test, El Centro and CHI-CHI ground motion records are selected as the input acceleration (as shown in Fig. 7). El Centro ground motion recording is a frequently used ground motion record, the El Centro ground motion records are shown in Tab. 3. El Centro ground motion records are shown in Tab. 3.

<table>
<thead>
<tr>
<th>Isolation measure</th>
<th>Input acceleration</th>
<th>Input direction</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA-rubber</td>
<td>El Centro</td>
<td>X</td>
<td>0.4</td>
</tr>
<tr>
<td>isolation</td>
<td>CHI-CHI</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Rubber isolation</td>
<td>El Centro</td>
<td>X</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>CHI-CHI</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Non-isolation</td>
<td>El Centro</td>
<td>X</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>CHI-CHI</td>
<td></td>
<td>0.4</td>
</tr>
</tbody>
</table>
record was captured from the El Centro station in the Imperial Valley earthquake of 1940. CHI-CHI ground motion recording is a long period ground motion record, it has obvious low frequency component, the CHI-CHI ground motion record was captured from the TCU068 station in the CHI-CHI earthquake of 1999. 6 test conditions (as shown in Tab. 3) are designed to study the dynamic response of the structure under the action of ordinary ground motion and long-period ground motion under each isolation condition. The shaking table test site is shown in Fig. 8.

![Fig. 8 Site photo of shaking table test](image)

3 Test result

3.2 Dynamic response characteristic

The peak accelerations of the non-isolation, rubber isolation and SMA-rubber isolation PSICLSS are shown in Fig. 10-11.

As can be seen from peak accelerations in Fig. 10, the peak acceleration gradually increases along the direction of the plate height under different tests. Moreover, the acceleration responses of rubber and SMA-rubber isolation PSICLSS are amplified than non-isolation structure. Under the action of El Centro ground motion, the peak acceleration at the top of the non-isolation PSICLSS is greater than that of the CHI-CHI ground motion. However, the peak acceleration at the top of rubber and SMA-rubber isolation PSICLSS under El Centro ground motion is less than that under CHI-CHI ground motion.

3.1 Structural frequency response

In order to obtain the vibration mode frequency of the structure in each isolation condition, 0.05g sine wave was applied to the structure to sweep the frequency before the test in each isolation condition. The structure amplitude-frequency functions are analyzed using the transfer function between the input acceleration of the shaking table and the structural acceleration response, and the frequency response curve is obtained, as shown in Fig. 9.

According to the frequency response functional curve, the main frequency of the PSICLSS is 18.52Hz, the main frequency of the rubber isolation PSICLSS is 2.03Hz, and the SMA-rubber isolation PSICLSS is 2.27Hz. The main frequency of the structure decreases obviously with the addition of isolation layer, while the stiffness of the isolation layer increases with the addition of SMA wire. The main frequency of the SMA-rubber isolation PSICLSS is higher than that of the lead-core rubber isolation PSICLSS.

![Fig. 9 Frequency response](image)
1 peak acceleration at the top of the non-isolation PSICLSS is 5.87 m/s², which is 0.70 times larger than that at the bottom of the structure. The maximum acceleration at the top of the rubber isolation PSICLSS is 11.65 m/s², which is 0.57 times larger than that at the bottom of the structure. The maximum acceleration at the top of the SMA-rubber isolation PSICLSS is 10.06 m/s², which is 0.65 times larger than the peak acceleration at the bottom of the structure.

Under the action of CHI-CHI ground motion, the peak acceleration at the top of the non-isolation PSICLSS is 5.62 m/s², which is 0.59 times larger than that at the bottom of the structure. The peak acceleration at the top of the rubber isolation PSICLSS is 12.64 m/s², which is 0.50 times larger than that at the bottom of the structure. The peak acceleration at the top of the SMA-rubber isolation PSICLSS is 10.11 m/s², which is 0.29 times larger than that at the bottom of the structure.
The displacements of the rubber and SMA-rubber isolation layers are shown in Fig. 12. As can be seen from Fig. 12, the maximum displacement of the rubber isolation layer under the action of El Centro earthquake is 54.01 mm, and the maximum displacement of SMA-rubber isolation layer is 37.26 mm. The maximum displacement of the rubber isolation layer under the action of CHI-CHI ground motion is 59.29 mm, and the maximum displacement of SMA-rubber isolation layer is 51.09 mm. The displacement of the SMA-rubber isolation layer is smaller than rubber isolation layer. Under the action of El Centro earthquake, SMA reduces the displacement of the isolation layer by 26.18%. Under the action of CHI-CHI ground motion, SMA reduces the displacement of the isolation layer by 13.72%. The displacement of the rubber isolation layer under the action of CHI-CHI earthquake is 9.77% larger than that of El Centro earthquake, and the displacement of the isolation layer of the SMA-rubber isolation layer under the action of CHI-CHI earthquake is 34.11% larger than that of El Centro earthquake.

3.3 Liquid sloshing characteristic

The peak liquid hydrodynamic pressures under different isolation conditions are shown in Fig. 13. The liquid hydrodynamic pressure curves at monitoring point W12 are shown in Fig. 14. It can be seen from Fig. 13 that the liquid hydrodynamic pressure at monitoring point W12 in the non-isolation, rubber isolation and SMA-rubber isolation PSICLSS is the maximum. This is because the horizontal liquid diameter of the internal liquid W12 monitoring point is the largest, resulting in the largest liquid pulse pressure, so the hydrodynamic pressure at this monitoring point is the largest. The liquid hydrodynamic pressure at the external liquid monitoring point WO2 is larger than that at WO1. Under the action of El Centro earthquake, the maximum liquid hydrodynamic pressure in the internal liquid of non-isolation structure is 2.40 kPa, and in the external liquid is 1.46 kPa. The maximum liquid hydrodynamic pressure in the internal liquid of rubber isolation PSICLSS is 4.73 kPa, and in the external liquid is 2.75 kPa. The maximum liquid hydrodynamic pressure in the internal and external liquid of the SMA-rubber isolation PSICLSS is 3.91 kPa and 2.19 kPa respectively.

Under the action of CHI-CHI ground motion, the maximum liquid hydrodynamic pressure in internal liquid of the non-isolation PSICLSS is 2.31 kPa, and in the external liquid is 1.35 kPa. The maximum liquid hydrodynamic pressure in internal liquid of the rubber isolation structure is 5.43 kPa, and in the external liquid is 1.95 kPa. The maximum liquid hydrodynamic pressure in the internal and external liquid of the SMA-rubber isolation PSICLSS is 4.85 kPa and 1.80 kPa respectively.

Through comparison, it can be seen that both rubber and SMA-rubber bearing cause significant increase of liquid hydrodynamic pressure in PSICLSS, and the liquid hydrodynamic pressure caused by rubber bearing is greater than that caused by SMA-rubber bearing. Under the action of CHI-CHI ground motion, the liquid hydrodynamic pressures at monitoring point W1 and W14 were reduced by SMA-rubber bearing. In other words, both rubber and SMA-rubber bearing cause significant increase of local liquid hydrodynamic pressure, while the local liquid hydrodynamic pressure of SMA-rubber isolation PSICLSS decreases under the action of long period earthquake.

The liquid hydrodynamic pressure of the non-isolation PSICLSS caused by the El Centro earthquake is greater than that caused by the CHI-CHI earthquake. The internal liquid hydrodynamic pressure of rubber and SMA-rubber isolation PSICLSS caused by the El Centro earthquake is less than that caused by the CHI-CHI earthquake, while the external liquid hydrodynamic pressure caused by the El Centro earthquake is greater than that caused by the CHI-CHI earthquake. It can be seen from Fig. 14 that, under the action of El Centro and CHI-CHI earthquake, the time history curves of liquid hydrodynamic pressure are closely related to the input accelerations, and the peak liquid hydrodynamic pressures occur at the time of peak acceleration.

![Fig. 13 Peak hydrodynamic pressure](image-url)
A high-speed camera is used to track and capture the response of liquid sloshing height in the test, and the maximum liquid sloshing height in each isolation condition is obtained, as shown in Fig. 15 and Fig. 16. As can be seen from Fig. 15 and Fig. 16, both rubber and SMA-rubber isolation cause the increase of liquid sloshing height, resulting in severe nonlinear splashing phenomenon of liquid, resulting in liquid leakage. The liquid sloshing height in the internal and external liquid of rubber isolation PSICLSS is the largest. The liquid sloshing height of rubber isolation and non-isolation PSICLSS under the action of long period earthquake is larger than that under ordinary earthquake. The external liquid sloshing height of PSICLSS is higher than that of the internal liquid.

4 Analysis of experimental phenomena

Through analysis, it can be seen that the dynamic response of the structure is significantly enlarged after the use of rubber and SMA-rubber isolation bearing. In order to better analyze the acceleration response of structural plate and the amplification effect of liquid hydrodynamic pressure before and after isolation, the amplification coefficient of structural response was defined as

$$\rho = \frac{R_{iso} - R_{non-is}}{R_{non-is}}$$

where, $R_{non-is}$ is the dynamic response of non-isolation PSICLSS, $R_{iso}$ is the dynamic response of isolation PSICLSS.
4.1 Acceleration amplification coefficient

The acceleration amplification coefficients under the action of El Centro and CHI-CHI ground motions are obtained, as shown in Fig. 17. According to the acceleration amplification coefficients in Fig. 17, it can be seen that under the action of El Centro and CHI-CHI earthquake, the acceleration response of the isolation PSICLSS is significantly amplified compared with non-isolation PSICLSS. Moreover, the acceleration amplification coefficients of the rubber and SMA-rubber isolation structure under the action of CHI-CHI earthquake are larger than those under the action of El Centro earthquake. Under the action of El Centro earthquake, the acceleration amplification coefficients at the bottom of the rubber and SMA-rubber isolation structure are the largest. The acceleration response of the rubber isolation structure is 1.13 and 0.79 times larger than that of the non-isolation structure, and the acceleration response of the SMA-rubber isolation structure is 0.77 times larger than that of the non-isolation structure.

4.2 Liquid hydrodynamic pressure amplification coefficient

The liquid hydrodynamic pressure amplification coefficients under the action of El Centro and CHI-CHI ground motions are obtained, as shown in Fig. 18.
pressure amplification coefficients at monitoring point W02 are the largest. The maximum amplification coefficient caused by rubber isolation is 0.89, and caused by SMA-rubber isolation is 0.51.

Under the action of CHI-CHI ground motion, the maximum liquid hydrodynamic pressure amplification coefficient in the rubber isolation PSICLSS is 1.42, which appears at monitoring point W13. The amplification coefficient of external liquid hydrodynamic pressure at the monitoring point W01 is the largest, with a maximum value of 0.51.

The maximum liquid hydrodynamic pressure amplification coefficient in the SMA-rubber isolation PSICLSS is 1.10, which appears at monitoring point W12. The amplification coefficient of external liquid hydrodynamic pressure at the monitoring point W01 is the largest, with a maximum value of 0.33. The liquid hydrodynamic pressure at monitoring points W11 and W14 all decrease.

4.3 Influence of isolation layer on acceleration spectrum characteristics

Fourier transformations are performed on the input acceleration and the acceleration at the bottom of the structure. The acceleration characteristics of the structure before and after isolation are analyzed, and then the isolation control ability of the isolation layer is evaluated.

The Fourier spectra of the input acceleration and the acceleration at the bottom of structure under the action of El Centro and CHI-CHI ground motions are obtained, as shown in Fig. 19 and Fig. 20. As can be seen from the analysis of El Centro acceleration spectrum characteristics in Fig. 19, the rubber and SMA-rubber isolation layer significantly change the spectral characteristics of the acceleration, which significantly amplifies the frequency amplitude of the input acceleration. When the rubber isolation is used, the frequency amplitude of the input acceleration is 3.06. After the isolation, the acceleration amplitude frequency does not change, making the frequency amplitude reaches 14.89, magnifies about 4.87 times. When the SMA-rubber isolation is used, the amplitude of the input acceleration frequency is 3.10. After isolation, the acceleration amplitude frequency does not change, which making the frequency amplitude reaches 16.98, magnifies about 4.48 times.

As can be seen from the analysis of CHI-CHI acceleration spectrum characteristics in Fig. 20, rubber and SMA-rubber isolation significantly change the spectral characteristics of acceleration, which not only significantly reduces the amplitude and frequency of acceleration, but also significantly amplifies the frequency amplitude of acceleration. When the rubber isolation is used, the input acceleration amplitude frequency and frequency amplitude is 0.98 Hz and 2.18, but after isolation, the acceleration amplitude frequency becomes 1.99 Hz, making the frequency amplitude reaches 11.55, which is magnified by 4.30 times. When the SMA-rubber isolation is used, the input acceleration amplitude frequency and frequency amplitude is 0.98 Hz and 2.17, but after isolation, the acceleration amplitude frequency becomes 1.99 Hz, making the frequency amplitude reaches 11.55, which is amplified by 2.70 times.

According to the analysis of Fourier spectrum characteristics of acceleration and frequency response function of the structure, it can be seen that the main frequencies of rubber and SMA-rubber isolation PSICLSS are coincident with the low frequency parts of the input El Centro and CHI-CHI acceleration. This causes the resonance of the rubber and SMA-rubber isolation PSICLSS during the test. Therefore, under the action of El Centro and CHI-CHI ground motion, the acceleration frequency amplitudes of the rubber and SMA-rubber isolation structure were significantly amplified, and the acceleration, liquid hydrodynamic pressure and liquid sloshing height of the PSICLSS were magnified compared with the non-isolation PSICLSS. Cause the stiffness of SMA-rubber isolation layer is larger than that of rubber isolation layer, the main frequency of SMA-rubber isolation PSICLSS is larger than that of rubber isolation PSICLSS, so the dynamic response of SMA-rubber isolation PSICLSS is lower than that of rubber isolation PSICLSS.
5. Vibration characteristics of isolation PSICLSS

The experimental results showed that under the action of El Centro and CHI-CHI ground motion, the rubber isolation PSICLSS has an obvious resonance response. However, the effects of resonance on the displacement of the isolation layer, the principal stress of the structure and the peak liquid sloshing height are not evaluated effectively. Therefore, based on the PSICLSS model, the ADINA finite element analysis was established, to analyze the influence of isolation periods and excitation frequencies. Linear elastic model is used for concrete, the potential energy is set as 1.99 m/s

The principal stress and hydrodynamic pressure of the scaled PSICLSS model were analyzed by numerical simulation in literature Qi et al. (2021). It can be seen that the maximum principal stress of the structure appears at the connection position of the external conical shell and the upper plate. The distribution law of hydrodynamic pressure at each monitoring point obtained from the test is similar to numerical simulation result. The acceleration time-history curves obtained from numerical analysis and model test are similar. Time-history curves of hydrodynamic pressure obtained from test and numerical simulation are similar. Through comparison, it can be seen that the numerical simulation results of the PSICLSS are similar to the experimental results.

The liquid sloshing frequencies of PSICLSS obtained through analysis are shown in Tab. 4, in which the first-order sloshing frequency of the internal liquid is equal with second-order sloshing frequency, and the third-order sloshing frequency is equal to fourth-order sloshing frequency.

In order to better analyze the vibration characteristics of isolation PSICLSS, sinusoidal acceleration excitation \( \alpha(t) = A\sin(\omega t) \) is input to the structure, where \( A \) is the acceleration excitation amplitude, and the input acceleration amplitude is set as 1 m/s

### Table 4 Input sinusoidal excitation frequency

<table>
<thead>
<tr>
<th>No.</th>
<th>Excitation frequency /Hz</th>
<th>Frequency ratio</th>
<th>Frequency characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.116</td>
<td>0.50</td>
<td>First-order sloshing frequency of the external liquid</td>
</tr>
<tr>
<td>2</td>
<td>0.162</td>
<td>0.70</td>
<td>Second-order sloshing frequency of the external liquid</td>
</tr>
<tr>
<td>3</td>
<td>0.231</td>
<td>1.00</td>
<td>First-order sloshing frequency of the internal liquid</td>
</tr>
<tr>
<td>4</td>
<td>0.278</td>
<td>1.20</td>
<td>Third-order sloshing frequency of the internal liquid</td>
</tr>
<tr>
<td>5</td>
<td>0.322</td>
<td>1.39</td>
<td>Fifth-order sloshing frequency of the internal liquid</td>
</tr>
<tr>
<td>6</td>
<td>0.487</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.559</td>
<td>2.42</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.671</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.725</td>
<td>3.13</td>
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</tr>
<tr>
<td>10</td>
<td>0.862</td>
<td>3.73</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 21 shows the peak displacement response of the isolation layer under different excitation frequencies and isolation periods. Fig. 21 shows the peak principal stress response of the structure, and Fig. 23 and 24 show the internal and external liquid sloshing height.
29 stress of the isolation PSICLSS with isolation period 3s is 30 the largest, and the maximum value is 2.8 MPa. The 31 principal stress of the structure with isolation period 2.5s 32 reaches 2.69 MPa, that is, both working conditions will 33 cause serious damage to the structural concrete. When the 34 frequency ratio is 2.9, the principal stress of the PSICLSS 35 with the isolation period of 2.5s is the smallest, and the 36 minimum value is 0.82 MPa.

Fig. 21 Displacement of isolation layer

Fig. 22 Stress of Plate-shell integrated concrete LSS

It can be seen from Fig. 22 that low-frequency excitation has a great influence on the principal stress of the structure. When the excitation frequency ratio is 1, the principal stresses of the structures with different isolation periods are bigger, and the principal stresses of the structures are also magnified with the increase of isolation periods. When the excitation frequency is small, the principal stress of the structure is bigger than that of the high frequency excitation. The external liquid sloshing has a great influence on the principal stress of the structure, while the internal liquid sloshing frequency has a small influence on the principal stress of the structure. When the excitation frequency ratio is 1, the principal

Fig. 23 Sloshing height of internal liquid

Fig. 24 Sloshing height of external liquid

As can be seen from Fig. 23, under the action of first order sloshing frequency of internal liquid, the height of internal liquid sloshing height is higher than that of other excitation frequencies. With the increase of isolation period, the height of internal liquid sloshing height first increases and then decreases. When the isolation period is 2.0 s, the maximum sloshing frequency of the internal liquid caused by the 0.559 Hz sinusoidal excitation is 5.08 Hz. Therefore, it is verified that the liquid sloshing height in the rubber isolation PSICLSS is higher than that of non-isolation and SMA-rubber isolation PSICLSS during the test.

As can be seen from Fig. 24, the external liquid sloshing height caused by low frequency excitation increases with the increase of the isolation period. When the isolation period is 3 s, the maximum external liquid sloshing height caused by the 0.231 Hz sinusoidal
excitation is 4.22 m. Under the sinusoidal excitation of the first-order sloshing frequency of the internal liquid, the sloshing height of the external liquid is bigger when the isolation period is 2s. Therefore, it is explained that the external liquid sloshing height caused by long period ground motion excitation is the largest in the test process.

6. Conclusion

Based on the shaking table model test, seismic responses of rubber isolation and SMA-rubber isolation PSICLSS are studied, and studied vibration characteristics of the isolation PSICLSS by the numerical simulation, have the following conclusions:

(1) The acceleration response of the structure increases gradually along the height of the outer plate. Under the action of earthquake, the hydrodynamic pressure of the internal liquid is bigger than that of the external liquid, and the maximum hydrodynamic pressure of the internal liquid appears between the lower and upper conical shell.

(2) El Centro and CHI-CHI acceleration excitation frequencies are close to the main frequencies of the rubber and SMA-rubber isolation PSICLSS, causing structural resonance, and significantly amplifying the frequency amplitude of acceleration above the isolation layer, and causing liquid hydrodynamic pressure and sloshing height increase, resulting in liquid leakage. Due to the participation of SMA, the displacement of the SMA-rubber isolation layer and the peak acceleration of PSICLSS are smaller than rubber isolation PSICLSS. The liquid hydrodynamic pressure and sloshing height caused by SMA-rubber bearing are smaller than those of the rubber bearing.

(3) Under the action of long period ground motion, the acceleration response of PSICLSS and displacement of rubber and SMA-rubber isolation layer are larger than those under ordinary ground motion. Compared with ordinary ground motion, long period ground period displacement increases the liquid hydrodynamic pressure and sloshing height.

(4) By studying the vibration characteristics of the isolation PSICLSS, it can be seen that the excitation of low-frequency ground motions causes a significant increase in the displacement of the isolation layer. The sloshing frequency of the external fluid has a large effect on the response of the structure. Under the excitation of the first-order sloshing frequency of the external liquid, the principal stress of the PSICLSS is bigger. The principal stresses of the structures with the isolation of 2.5s and 3s are much greater than structures with other isolation periods. Under the action of the sinusoidal acceleration with the first-order sloshing frequency of the internal liquid, the internal liquid sloshing height of the structure is larger, and the principal stress of the structure is less affected.

(5) Resonance will cause a sharp increase in structural acceleration, liquid sloshing height and hydrodynamic pressure, which is extremely unfavorable to the isolation PSICLSS. Therefore, in the seismic isolation design of such structures, the stiffness of the isolation layer should be properly adjusted to avoid the overlapping of the vibration period of the structure with the excellent period of the site, resulting in the resonance phenomenon during earthquakes.

68 Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

69 Data Availability Statement

Design drawings, model parameters, initial earthquake acceleration, model test results that support the findings of this study are available from the corresponding author upon reasonable request.

80 Acknowledgments

This paper is a part of the National Natural Science Foundation of China (Grant number: 51968045).

83 References


12 jfluidstructs. 2018.04.020.
The response to the reviewers

Reviewer 1:
The paper investigates the seismic performance of Plate-Shell Integrated Concrete Liquid-Storage Structure (PSICLSS) using a scale test model of the structure. The experimental dynamic responses of non-isolation and hybrid isolation PSICLSS were analyzed. The paper is interesting, and some specific comments are:

1. The paper provided extensive experimental results and it will be interesting to have a comparison with the analytical results for the optimal design of PSICLSS. The necessary section on the analytical response for the PSICLSS shall be added.

Revised. The authors compared the finite element analysis results and the test results in the paper https://doi.org/10.1080/19648189.2021.1955748, and the results showed that the structural acceleration and water pressure response during the test are well verified by using finite elements, therefore, the authors cite the relevant conclusions in the paper to increase the reliability of the research of the paper. (Page 11 lines 18-31)

2. The dynamic properties of the SMA-rubber isolation and Rubber isolation installed in the PSICLSS such as the isolation period, damping ratio, and friction coefficient shall be provided.

Reply. The specific parameters of the rubber isolation bearing are given in the paper (Table 2), but the specific parameters of the SMA-rubber vibration isolation bearing are not described in detail in this paper because there are many design factors for the SMA-rubber vibration isolation bearing, including the diameter size of SMA wire, the selection of pulley, the fixation of SMA wire, the friction coefficient between SMA wire and pulley, etc. The authors will further analyze the specific influence parameters of SMA-rubber vibration isolation bearing and the influence parameters of damping ratio of SMA-rubber bearing at a later stage, thus analyzing the application of SMA-rubber vibration isolation bearing in fluid storage structure more effectively.

3. The force-deformation behavior of the SMA considered shall be shown and the basis of selecting 1 mm wire with the tensile strength is 1500 MPa shall be specified.

Revised. In this paper, the tensile strength of SMA wire was considered to avoid the fracture of SMA wire under the action of earthquake, and the deformation of the isolation layer during the earthquake was also considered to select the appropriate length of SMA wires. The authors have added the basis for SMA wire selection in the paper based on expert opinions. (Page 4 lines 8-14)


Revised. According to the experts' opinions, 8 references have been added and the relevant part of the introduction in the text has been revised (Page 2 lines 5-14 and 60-93). The added references are as follows:

5. The presentation of the paper needs to be further improved to the level of international journal standards.

Revised. According to expert advice, the expression of the paper has been revised. (All modified parts are highlighted, and the detailed list of modifications is attached at the end)

Reviewer 2:

An interesting problem on the Vibration characteristic of rubber isolation plate-shell integrated concrete liquid-storage has been investigated by the authors; in general, I’m optimistic toward the paper, however, ALL the following major comments should be addressed completely:

1) Author may explain deficiencies or shortcomings of other studies to make a bridge to introducing the novelty of their work.

Revised. Based on the expert opinions, the introduction section was further sorted out and the deficiencies of existing studies were added. (Page 2 lines 5-14 and 60-93).

2) The text should be checked for some minor typical errors.

Revised. The errors in this paper were corrected based on expert opinion. (All modified parts are highlighted, and the detailed list of modifications is attached at the end)

3) The applications of this work must be discussed.

Reply. The scope of application of the structure is described in the first paragraph of the paper, and the research in this paper will provide theoretical guidance for the seismic isolation design of the structure and provide guidelines for related research.

4) The literature review on shear deformation effect is very poor. Authors must improve this point by discussing recent works such as:

Composite Structures 255, 112990; Composite Structures 257, 113150; Composite Structures 257, 113152; Composite Structures 263, 113599; Composite Structures 269, 114000

Revised. According to the experts’ opinions, some references have been added and the relevant contents of the introduction have been sorted out. (Page 2 lines 5-14 and 60-93). The added references are as follows:


5) Equations must be checked.
**Revised.** The formulas in the text were checked and the errors found were corrected. (Page 11 line 40)

6) The presented results must be more discussed.
**Revised.** The results presented in the paper were discussed according to the expert opinions (Page 7 lines 32-36). Section 4.3 of the text explored the experimental phenomena and analyzed the intrinsic causes of the experimental phenomena.

7) Authors should add some physical explanation to improve the quality of the paper. Conclusion section must be extended in a few words via main finding and advantages of the methodology.
**Revised.** The conclusion section has been revised according to the experts’ comments. (Page 13 lines 11-66)

8) The reference is not adequate and too short, the authors should cite the following papers in your formulation and introduction.
* An iterative simulation algorithm for large oscillation of the applicable 2D-electrical system on a complex nonlinear substrate
* Bending and stress responses of the hybrid axisymmetric system via state-space method and 3D-elasticity theory
* On the chaotic behavior of graphene-reinforced annular systems under harmonic excitation
* Computer simulation via a couple of homotopy perturbation methods and the generalized differential quadrature method for nonlinear vibration of functionally graded non-uniform
* Coupled particle swarm optimization method with genetic algorithm for the static–dynamic performance of the magneto-electro-elastic nanosystem
* Intelligent wave dispersion control of an inhomogeneous micro-shell using a proportional-derivative smart controller
* The computational modeling for the static analysis of axially functionally graded micro-cylindrical imperfect beam applying the computer simulation
* Nonlinear forced vibration analysis of functionally graded non-uniform cylindrical microbeams applying the semi-analytical solution
* On the modelling of the vibration behaviors via discrete singular convolution method for a high-order sector annular system
* Electroelastic high-order computational continuum strategy for critical voltage and frequency of piezoelectric NEMS via modified multi-physical couple stress theory
* Improving seismic performance of portal frame structures with steel curved dampers
* Simulation of steel–concrete composite floor system behavior at elevated temperatures via multi-hybrid metaheuristic framework
* Evaluating the bond strength of FRP in concrete samples using machine learning methods
* Seismic performance assessment of a novel ductile steel braced frame equipped with steel curved damper
* Low-velocity impact, resonance, and frequency responses of FG-GPLRC viscoelastic doubly curved panel
* Assessment of composite beam performance using GWO–ELM metaheuristic algorithm
*Economic application of structural health monitoring and internet of things in efficiency of building information modeling

*Bending analysis of FG-GPLRC axisymmetric circular/annular sector plates by considering elastic foundation and horizontal friction force using 3D-poroelasticity theory

*Prediction of the bending and out-of-plane loading effects on formability response of the steel sheets

Revised. According to the expert opinion, some references were added, but the above papers were not cited due to the poor relevance of the content of the above papers to this paper. However, the authors have reviewed and added some of the relevant literature. (Page 2 line 5-14 and 60-93, added the references are list before)

The list of all the changes:

1. Abstract:
   1) Line 3, “shock absorption control effects” revised to “seismic responses”
   2) Line 4, “bearing” revised to “PSICLSS”
   3) Lines 5-6, “The results showed that when the frequency of seismic excitation is close to main frequency of the isolation PSICLSS, the acceleration, liquid sloshing height, hydrodynamic pressure of rubber and SMA - rubber isolation PSICLSS both amplified.” revised to “The results showed that the acceleration, liquid sloshing height, hydrodynamic pressure of rubber and SMA - rubber isolation PSICLSS are amplified when the frequency of seismic excitation is close to the main frequency of the isolation PSICLSS.”
   4) Line 9 and 10, “bigger” revised to “a more significant”
   5) Line 11, “stress” revised to “stresses”
   6) Line 11, “biggest” revised to “most enormous”.
   7) Line 12, “bigger” revised to “a more significant”
   8) Lines 13-14, “Therefore, we should appropriately adjust the stiffness of isolation layer in rubber and SMA - rubber isolation PSICLSS design.” revised to “Therefore, the stiffness of the isolation layer should be properly adjusted in the design of rubber and SMA - rubber isolation PSICLSS.”

Page 1

1) Line 17, “disaster” revised to “disasters”, “earthquake” revised to “earthquakes”
2) Line 18, “structure” revised to “structures”
3) Line 20, “huge” revised to “massive”
4) Lines 24-25, “such as the bottom of the filter tank cracks” revised to “such as cracks at the bottom of the filter tank”
5) Line 26, “pool” revised to “pools”
6) Line 38, deleted the word “the”
7) Lines 39-43, “Carry out the shaking table model test on PSICLSS, it is an important part of the research on the anti-seismic, isolation and damping performance of urban lifeline engineering structures.” revised to “Carrying out the shaking table model test on PSICLSS is an important part of studying the anti-seismic, isolation and damping performance of urban lifeline engineering structures.”
8) Line 44, “can” revised to “could”
9) Lines 46-49, “Jadhav and Jangid (2006) showed that the response of the tank to near-fault ground
motions seem to approach those provided from equivalent trigonometric pulses especially for isolation periods greater than 3s.” revised to “Jadhav and Jangid (2006) observed that the resultant response of the isolation tank is mainly governed by the fault normal component with a minor contribution from the fault parallel component”

Page 2

1) Line 3, deleted “through shaking table test”
2) Line 6, “cause” revised to “causes”
3) Lines 6-15, added the sentences “Panchala and Jangid (2013) observed that under near-fault ground motions, the variable curvature friction pendulum system is quite effective in controlling the seismic response of liquid storage tanks. Jadhav and Jangid (2004) studied the seismic responses of liquid storage tanks isolated by elastomeric bearings and sliding bearings are investigated under actual earthquake ground motions. Found that the elastomeric bearing with lead core performs better in comparison to other systems.”
4) Line 16, added word “a”
5) Line 18, added word “the”
6) Line 19, added word “and”
7) Line 21, “will” revised to “would”
8) Line 24, “is” revised to “has”
9) Lines 41-45, “Liu et al. (2008) through shaking table test showed that SMA stranded wire and rubber combination isolation bearing have greater restoring force than ordinary rubber bearing under strong earthquake act.” revised to “Liu et al. (2008) found that SMA stranded wire and rubber combination isolation bearing has greater restoring force than ordinary rubber bearing under strong earthquake action by shaking table test.”
10) Line 51, “main” revised to “primary”
11) Line 53, added the word “a”
12) Line 55, “can” revised to “could”
13) Lines 61-94, added sentences “In summary, it can be seen that SMA can control the deformation of the isolation layer under major earthquakes, and provide a better recovery force for the isolation layer. But most of the researches are limited to structures such as bridges, and the application in liquid storage structures is relatively small. Zhang et al. (2021) presented the influence of viscoelastic parameters, and radius curvature on the free, and forced vibration characteristics of the functionally graded graphene nanoplatelets reinforced composite doubly curved panel on the viscoelastic foundation under low-velocity impact. The frequency information of functionally graded graphene platelets reinforced composite open-shell resting on a non-polynomial elastic substrate involving friction force under residual stresses has been investigated by Dai et al. (2021). Sarkheil and Foumani (2016) studied the free vibration of a rotating joined cylindrical-conical shell. The effect parameters such as rotation speed cone angle, circumferential wave number, length to radius ratio, and shell thickness on the frequencies were investigated. Lee et al. (2002) investigated the free vibration characteristics of the joined spherical-cylindrical shell with various boundary conditions. The effects of the shallowness of the spherical shell and length of the cylindrical shell on the free vibrational behavior of joined shell structure are investigated. Tedesco (1982) developed simple analytical expressions for empty tanks which accurately predicted frequencies and radial mode shapes corresponding to the fundamental mode of vibration. It can be seen that the current research on vibration characteristics is limited to shell structure, and there are few studies on
vibration characteristics of the liquid storage structures.”

14) Line 103, “scale” revised to “scaled”

Page 3
1) Line 4, “stress” revised to “stresses”, “height” revised to “heights”
2) Line 6, “frequency” revised to “frequencies”, “period” revised to “periods”
3) Line 35, added word “the”

Page 4
1) Line 3, “The parameters of lead-core rubber bearing selected in the test are shown in Tab. 2.” revised to “The parameters of selected lead-core rubber bearing in the test are shown in Tab. 2.”
2) Line 5, “select the” revised to “selected”.
3) Line 7, added the word “is”
4) Lines 8-14, added the sentences “The structure and liquid are simplified to a concentrated mass, and the demand recovery force of the isolation layer is calculated. In order to avoid large displacement deformation of the isolation layer, and to avoid damage due to insufficient tensile strength of SMA during vibration, the selected SMA wire parameters are determined as follows.”
5) Line 33, added the word “the”
6) Line 35, “sensor” revised to “sensor’s”

Page 5
1) Line 12, added the word “the”
2) Line 4, deleted the word “outer plate”
3) Line 15, deleted the word “of the”

Page 7
1) Line 1, added the word “the”
2) Line 2, “layer” revised to “layers”
3) Line 27, deleted the words “time history curve”
4) Lines 32-36, added the sentences “This is because the horizontal liquid diameter of the internal liquid WI2 monitoring point is the largest, resulting in the largest liquid pulse pressure, so the hydrodynamic pressure at this monitoring point is the largest.”
5) Lines 41, 43, 50 and 52, deleted the words “the maximum liquid hydrodynamic pressure”
6) Lines 57, 59, 60, 63 and 64, “isolation” revised to “bearing”
7) Line 78, deleted the words “the time history curve of liquid hydrodynamic pressure in”
8) Line 80, “curve” revised to “curves”, “is” revised to “are”
9) Line 81, “acceleration” revised to “accelerations”
10) Line 82, deleted the word “all”

Page 8
1) Line 6, deleted the word “will”
2) Line 13, “normal” revised to “ordinary”

Page 9
1) Line 12, deleted the word “at the bottom”
2) Line 15, “The external liquid hydrodynamic pressure amplification coefficients of monitoring point WO2 in rubber and SMA-rubber isolation PSICLSS are the largest. The maximum liquid hydrodynamic pressure amplification coefficient caused by rubber isolation is 0.89, and the maximum liquid hydrodynamic pressure amplification coefficient caused by SMA-rubber isolation is 0.51.” revised to “In rubber and SMA-rubber isolation PSICLSS, the external liquid hydrodynamic pressure amplification coefficients at monitoring point WO2 are the largest. The maximum amplification coefficient caused by rubber isolation is 0.89, and caused by SMA-rubber isolation is 0.51.”

Page 10
1) Line 18, “point” revised to “points”
2) Lines 24-26, “The Fourier transform of the input acceleration at the shaking table and the acceleration at the bottom of the structure is used to obtain the Fourier spectrum characteristics of the acceleration.” revised to “Fourier transformations are performed on the input acceleration and the acceleration at the bottom of the structure.”
3) Line 34, added the word “the”
4) Line 37, “amplified” revised to “amplifies”
5) Line 41, “reach” revised to “reaches”
6) Line 42, “magnified by” revised to “magnifies”
7) Lines 45-46, “which makes the frequency amplitude reach 16.98, magnified by about 4.48 times.” revised to “which makes the frequency amplitude reach 16.98, magnified by about 4.48 times.”
8) Line 53, “amplified” revised to “amplifies”
9) Line 66, deleted the word “the analysis of”
10) Line 77, deleted the word “all”
11) Line 78, deleted the words “those of”
12) Line 79, “higher” revised to “larger”
13) Line 80, deleted the word “shock”
14) Line 81, “higher” revised to “larger”

Page 11
1) Line 7, added the word “an”
2) Line 15, added the word “the”
3) Lines 18-31, added the sentences “The principal stress and hydrodynamic pressure of the scaled PSICLSS model were analyzed by numerical simulation in literature Qi et al. (2021). It can be seen that the maximum principal stress of the structure appears at the connection position of the external conical shell and the upper plate. The distribution law of hydrodynamic pressure at each monitoring point obtained from the test is similar to numerical simulation result. The acceleration time-history curves obtained from numerical analysis and model test are similar. Time-history curves of hydrodynamic pressure obtained from test and numerical simulation are similar. Through comparison, it can be seen that the numerical simulation results of the PSICLSS are similar to the experimental results.”
4) Line 36, “with” revised to “to”
5) Line 40, “a(x) = A sin(\omega t)” revised to “a(t) = A sin(\omega t)”
6) Table 4, “First order” revised to “First-order”, “Second order” revised to “Second-order”, “Third order” revised to “third-order”, “Five order” revised to “Fifth-order”

**Page 12**
1) Line 4, “and the” revised to “The”
2) Line 11, “second order” revised to “second order”
3) Line 19, “stress” revised to “stresses”

**Page 13**
1) Line 2, “first order” revised to “first-order”
2) Lines 11-15, “Based on the shaking table model test of the non-isolation, rubber isolation and SMA-rubber isolation PSICLSS under the action of ordinary and long period ground motion, and studied vibration response of the isolation PSICLSS through the numerical simulation, have the following conclusions:” revised to “Based on the shaking table model test, seismic responses of rubber isolation and SMA-rubber isolation PSICLSS are studied, and studied vibration characteristics of the isolation PSICLSS by the numerical simulation, have the following conclusions.”
3) Line 18, “ground motion” revised to “earthquake”
4) Lines 23-29, “El Centro and CHI-CHI acceleration excitation frequencies are close to the main shock frequencies of the isolation PSICLSS, cause the resonance of rubber and SMA-rubber isolation PSICLSS. Both of which significantly magnify the frequency amplitude of acceleration above the isolation layer. As a result, the acceleration, displacement, liquid hydrodynamic pressure and the sloshing height are enlarged, and the liquid leakage is caused.” revised to “El Centro and CHI-CHI acceleration excitation frequencies are close to the main frequencies of the rubber and SMA-rubber isolation PSICLSS, causing structural resonance, and significantly amplifying the frequency amplitude of acceleration above the isolation layer, and causing liquid hydrodynamic pressure and sloshing height increase, resulting in liquid leakage.”
5) Line 34, added the word “bearing”
6) Line 35, deleted the word “isolation”
7) Line 39, deleted the word “the action of”
8) Lines 39-42, “Moreover, the liquid hydrodynamic pressure of rubber and SMA-rubber isolation PSICLSS is partially increased under the action of long period ground motion compared with ordinary ground motion, and the liquid sloshing height of non-isolation PSICLSS increased.” revised to “Compared with ordinary ground motion, long period ground motion increases the liquid hydrodynamic pressure and sloshing height.”
9) Lines 43-48, “Under the excitation of low-frequency ground motions, the isolation PSICLSS will cause a significant increase in the displacement of the isolation layer.” revised to “By studying the vibration characteristics of the isolation PSICLSS, it can be seen that the excitation of low-frequency ground motions causes a significant increase in the displacement of the isolation layer. The sloshing frequency of the external fluid has a large effect on the response of the structure.”
10) Lines 50-53, “The principal stress of the structure with the isolation period of 2.5s and 3s much greater than the other isolation periodic structures. At the same time, the sloshing height of the external liquid is also larger.” revised to “The principal stresses of the structures with the isolation
period of 2.5s and 3s are much greater than structures with other isolation periods.”

11) Lines 58-66, “Resonance will cause the acceleration of the structure, the liquid sloshing height and the hydrodynamic pressure increase sharply, which is extremely unfavorable to the isolation PSICLSS. Therefore, the stiffness of the isolation layer should be appropriately adjusted during the design of the isolation on this kind of structure, avoid resonance phenomenon during seismic excitation.” revised to “Resonance will cause a sharp increase in structural acceleration, liquid sloshing height and hydrodynamic pressure, which is extremely unfavorable to the isolation PSICLSS. Therefore, in the seismic isolation design of such structures, the stiffness of the isolation layer should be properly adjusted to avoid the overlapping of the vibration period of the structure with the excellent period of the site, resulting in the resonance phenomenon during earthquakes.”


Page 14


