

Seismic Isolation Performance of SMA Reinforced Hybrid Isolation Concrete Liquid Storage Structures

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Abstract

The Plate-Shell Integrated Concrete Liquid-Storage Structure (PSICLSS) is an emerging form of water treatment infrastructure. To elucidate its dynamic response mechanism and evaluate the seismic mitigation performance of an SMA-reinforced hybrid isolation system, this study employed finite element analysis (FEA) and shaking table testing to investigate the structural dynamic response characteristics and liquid sloshing behavior under seismic excitation. Shaking table tests were conducted under both unidirectional and bidirectional seismic excitations to further characterize the dynamic responses of the PSICLSS. The results demonstrate that the beams of the PSICLSS are susceptible to tensile failure under seismic loading, whereas the bottom supporting columns and lower slab are vulnerable to shear failure. The structural acceleration response exhibits an increasing amplification effect with increasing plate elevation, and the hydrodynamic pressure of the internal liquid is consistently greater than that of the external liquid. The proposed SMA-reinforced hybrid isolation layer demonstrates effective seismic mitigation performance by reducing the acceleration response of the PSICLSS and lowering the peak hydrodynamic pressure; however, it also results in increased liquid sloshing height. When vertical seismic excitation is considered, the hydrodynamic pressure increases significantly, while the residual displacement of the isolation layer decreases correspondingly.

Keywords

liquid storage structure, shaking table test, shape memory alloy, SMA reinforced hybrid isolation

1 Introduction

With the rapid development of industrial and agricultural production and the continuous improvement of living standards, increasing demands have been placed on water treatment technologies. As a result, advanced water treatment equipment and facilities have been increasingly developed and implemented in practical engineering applications. The Plate-Shell Integrated Concrete Liquid-Storage Structure (PSICLSS, Fig. 1), as a novel type of water treatment structure, has been widely applied in wastewater treatment facilities.

Previous seismic damage investigations have demonstrated that earthquakes can cause severe damage to liquid-storage structures. Historical earthquakes, such as the 1952 Kern County earthquake in California and the 1964 Alaska earthquake, caused extensive damage to oil storage tanks and triggered fires. Similarly, the 1995

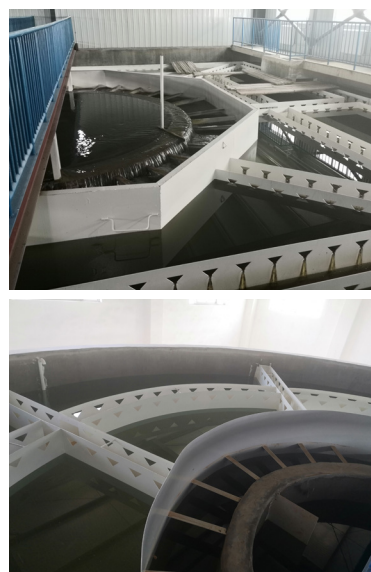


Fig. 1 Engineering application of PSICLSS

Hanshin earthquake in Japan and the 2001 Gujarat earthquake in India resulted in water storage tank failures and liquid leakage [1]. Therefore, investigating the seismic response mechanisms and developing effective isolation strategies for PSICLSS are essential for improving the resilience of urban lifeline infrastructure and ensuring rapid post-earthquake recovery.

In recent years, extensive investigations have been conducted on the seismic performance, isolation techniques, and vibration control of steel liquid-storage structures, especially spherical and cylindrical tanks [2–7]. Similar research has also been reported for concrete liquid-storage structures [8–11]. Nevertheless, investigations into the seismic behavior and vibration control of PSICLSS remain relatively scarce.

Research has demonstrated that hybrid isolation systems integrating lead-rubber bearings (LRBs), rubber isolation bearings (RBs), sliding bearings (SBs), and viscous fluid dampers can effectively mitigate stochastic structural responses under seismic excitation and enhance structural reliability in high-rise buildings. Such hybrid systems provide satisfactory vibration mitigation performance under moderate earthquakes while maintaining displacement constraints during rare seismic events [12]. To overcome the limitations of conventional sliding isolation systems, researchers have proposed hybrid configurations combining LRBs and SBs [13].

Yu et al. [14] investigated the seismic performance of novel damping plate-restrained flat friction sliding bearings in highway bridges. Narjabadifam et al. [15] proposed hybrid isolation systems incorporating LRBs and linear/nonlinear dampers at the base or superstructure levels, and evaluated their performance against high-damping rubber bearings (HDRBs), friction pendulum systems (FPSs), and fixed-base structures. Furthermore, the combination of tuned mass dampers (TMDs) and isolation bearings has been recognized as an effective approach for enhancing the seismic performance of high-rise structures. Pawar and Salgar [16] investigated the optimal placement of TMDs in base-isolated structures. Li et al. [17] demonstrated that reducing the number of isolators by 40% could effectively reduce system stiffness, while incorporating viscous dampers into the isolation layer improved displacement control performance.

Additionally, Deringöl and Güneyisi [18] investigated a hybrid isolation system combining friction damping and base isolation, and found that this approach exhibited superior seismic performance compared with conventional

systems employing friction dampers, lead-rubber bearings, friction pendulum bearings, or high-damping rubber bearings individually.

Shape memory alloys (SMAs) have attracted increasing attention in concrete structures, structural strengthening, energy dissipation devices, and seismic isolation systems due to their exceptional superelasticity and high energy dissipation capacity [19]. Experimental studies have demonstrated that hybrid isolators incorporating SMA strands and laminated rubber bearings possess strong restoring forces and enhanced damping characteristics [20]. Moreover, SMA-based isolation systems have shown promising self-centering capabilities in bridge structures, effectively reducing residual displacements following seismic events [21–27]. For PSICLSS, SMA-sliding isolation systems have been reported to achieve effective recentering performance without increasing structural seismic responses [28]. In addition, both conventional elastomeric bearings and SMA-based rubber bearings have exhibited satisfactory seismic isolation performance in curved bridge applications [29].

This study combines finite element analysis (FEA) and shaking table tests to investigate the seismic response characteristics of PSICLSS, including acceleration response, hydrodynamic pressure, and liquid sloshing behavior. A novel SMA-LRB-SB hybrid isolation system is proposed to enhance the seismic performance of PSICLSS. This system integrates SMA wires with LRBs and SBs, combining their complementary roles: the SMA wires provide strong re-centering capability, the LRBs contribute stable elastic-plastic deformation and hysteretic energy dissipation, and the SBs offer seismic isolation together with friction-based energy dissipation. The effectiveness of the proposed isolation system is systematically evaluated in terms of structural acceleration response, isolation layer displacement, hydrodynamic pressure, and liquid sloshing characteristics.

2 Model test

2.1 Experiment design

The shaking table test was conducted at the Loess Earthquake Engineering Laboratory of the Gansu Seismological Bureau, and the specifications of the shaking table are summarized in Table 1. The scaled physical model was developed based on the prototype PSICLSS shown in Fig. 1. Considering the experimental requirements and shaking table capacity, a geometric similarity ratio of 0.109 was selected, the material similarity ratio is taken as 1. The detailed configuration and dimensions of

Table 1 Shake table parameters

Parameter	Technical specifications
Table dimensions	4 m × 6 m
Load-bearing	20 t
Maximum bearing capacity	When loaded separately in the X and Z directions, the maximum acceleration of X is 20 t; the maximum acceleration of Z is 15 t. When loaded jointly in the X and Z directions, the maximum acceleration of X is 20 t; the maximum acceleration of Z is 15 t.
Maximum acceleration	When loaded separately in the X and Z directions, X: 1.7 g (at 25 t), Z: 1.2 g (at 15 t) When loaded jointly in the X and Z directions, X: 1.2 g (at 15 t), Z: 1.0 g (at 15 t)
Operating frequency range	When loading in the X and Z directions separately, X: 0-70 Hz, Z: 0-50 Hz When loading in the X and Z directions jointly, X: 0-50 Hz, Z: 0-50 Hz

the PSICLSS model are presented in Figs. 2–4. To reproduce the liquid sloshing behavior and hydrodynamic pressure effects, the dynamic similarity ratio was set to 1. The model was cast on-site using concrete with a designed compressive strength of 30 MPa [30].

The outer plate of the PSICLSS model was instrumented with eight acceleration sensors (A1–A8), and an additional acceleration sensor (A9) was mounted on the shaking table to measure the input seismic acceleration. Six hydrodynamic pressure sensors were installed

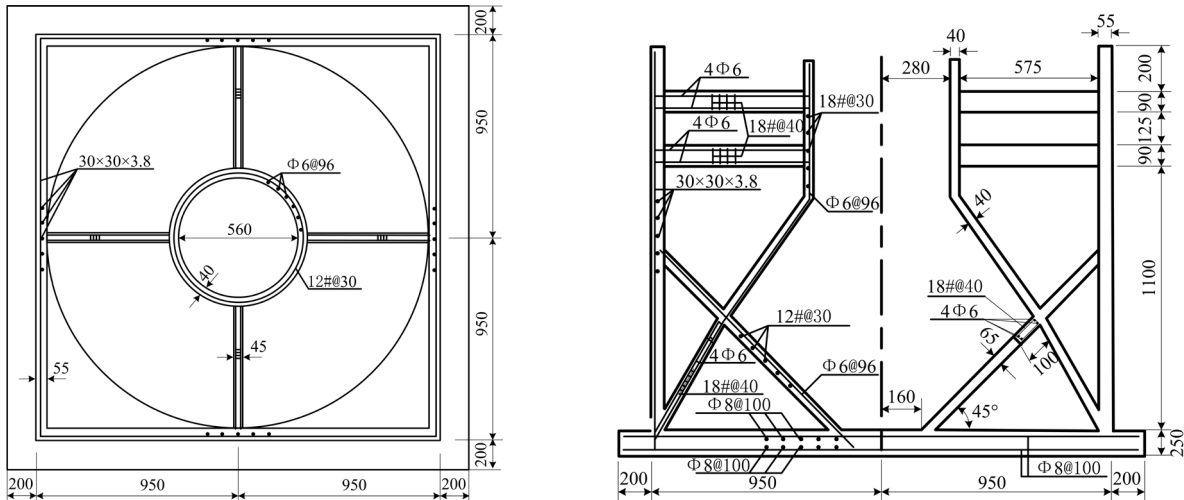


Fig. 2 Model design of PSICLSS (mm)

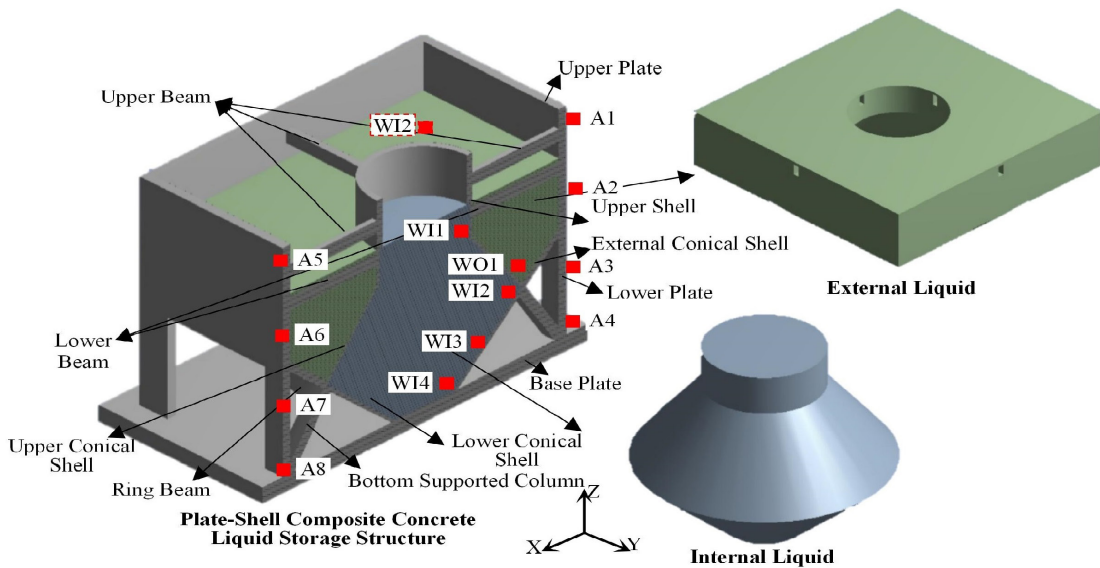


Fig. 3 Model and sensors arrangement of PSICLSS

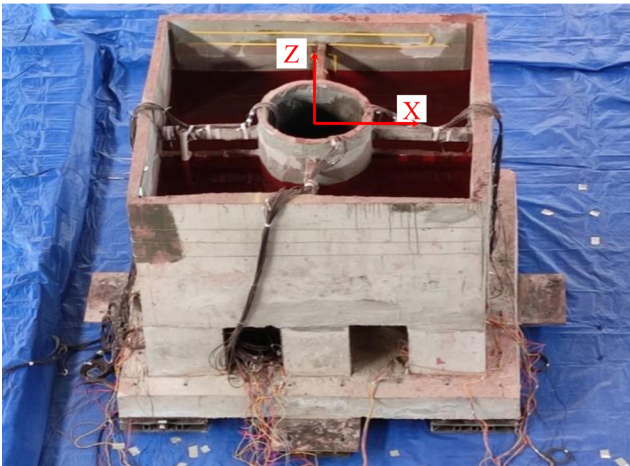


Fig. 4 Model of shaking table test

to capture the liquid pressure response, including four sensors (W11–W14) located in the internal liquid and two sensors (WO1–WO2) located in the external liquid. Furthermore, a cable displacement sensor was installed in the isolation layer to measure the displacement response of the isolation system.

2.2 Structural frequency response

Before conducting the formal shaking table tests, a sinusoidal sweep excitation with an amplitude of 0.05 g was imposed on the isolated PSICLSS model under each isolation condition to determine its fundamental frequency. The dynamic characteristics of the structure were identified based on the transfer function between the input acceleration recorded by the shaking table and the structural acceleration response. The obtained frequency response curve is shown in Fig. 5.

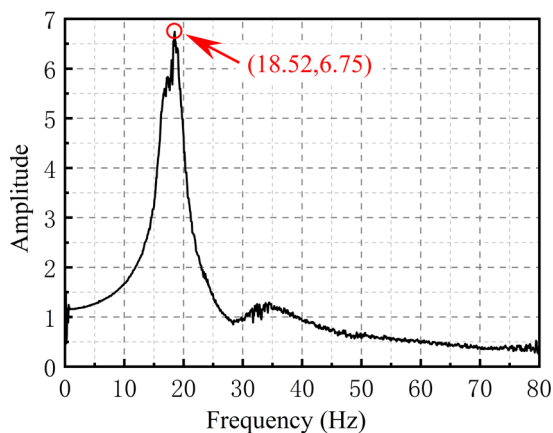


Fig. 5 Frequency response

2.3 Structural responses

The East-West component of the El Centro earthquake record (Fig. 6, captured from the El Centro station in the Imperial Valley earthquake of 1940) was adopted as the input ground motion, which was applied in the X direction with a peak ground acceleration (PGA) of 0.4 g. The peak acceleration responses of the PSICLSS model are presented in Fig. 7. For clarity, the "positive plate" is defined as the wall facing the direction of seismic excitation, whereas the "negative plate" represents the wall opposite to the excitation direction.

As illustrated in Fig. 7, the acceleration response of the PSICLSS model increases progressively with plate elevation, indicating an evident amplification effect along the height direction. The acceleration amplification ratio of the negative plate is consistently higher than that of

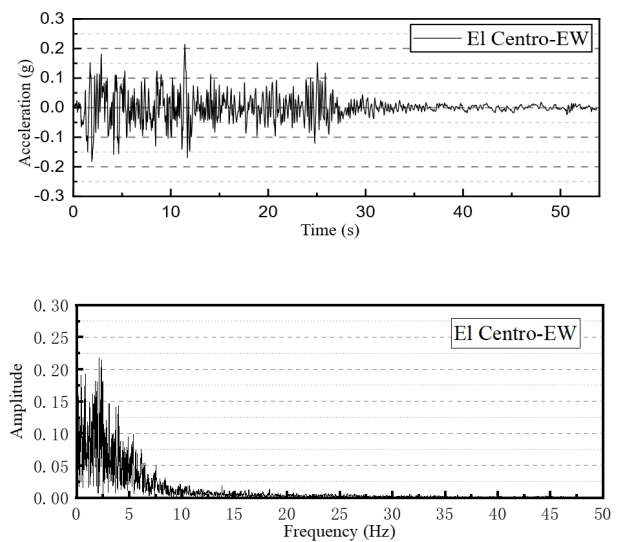


Fig. 6 Input acceleration for the shaking table test

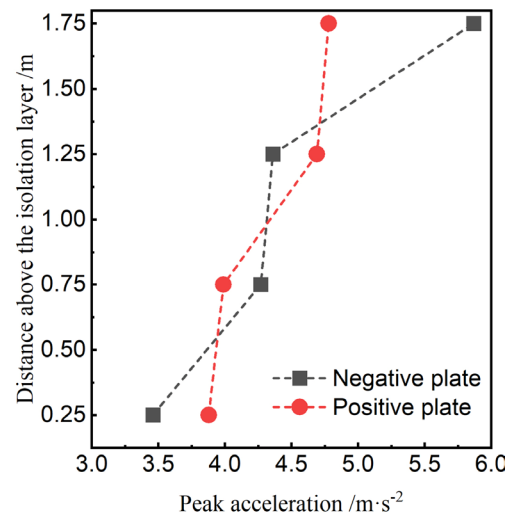


Fig. 7 Peak acceleration

the positive plate. Specifically, the peak accelerations recorded at the bottom and top of the negative plate are 3.46 m/s^2 and 5.87 m/s^2 , respectively. In comparison, the corresponding peak accelerations of the positive plate are 3.88 m/s^2 at the bottom and 4.78 m/s^2 at the top.

2.4 Liquid sloshing characteristics

The peak hydrodynamic pressure responses under seismic excitation are presented in Fig. 8. The maximum liquid sloshing height of the PSICLSS model is shown in Fig. 9.

As illustrated in Fig. 8, the hydrodynamic pressure response of the internal liquid is significantly greater than that of the external liquid under seismic excitation. The maximum internal hydrodynamic pressure occurs at monitoring point WI2, reaching 2.40 kPa , whereas the maximum external hydrodynamic pressure is recorded at monitoring point WO2, with a value of 1.46 kPa .

As illustrated in Fig. 9, the liquid sloshing response exhibits pronounced nonlinear behavior, and the maximum sloshing height is observed at the corner of the external structure.

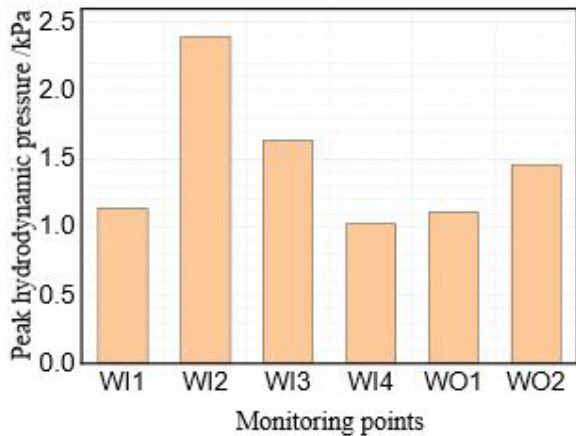


Fig. 8 Hydrodynamic pressure

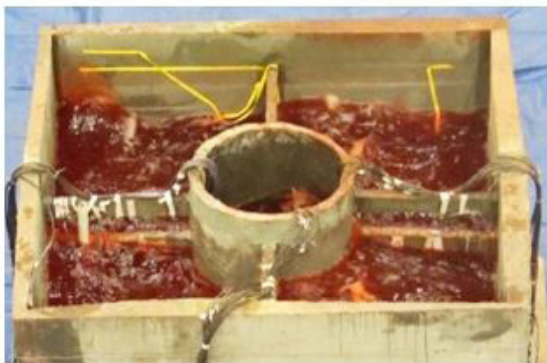


Fig. 9 Liquid sloshing height

3 Fluid-structure response of PSICLSS

3.1 Fluid-structure interaction theory

3.1.1 Two-way fluid-structure coupling

In most fluid–structure interaction (FSI) problems, fluid-induced tractions generate structural deformation, while the resulting structural motions simultaneously influence the fluid flow field. Such two-way interaction between the fluid and structure requires coupled FSI simulations, which are commonly known as two-way coupling analyses.

The governing equations of fluid–structure interaction systems form a nonlinear system regardless of whether the solid material model is linear or nonlinear, owing to the intrinsic nonlinearity of the fluid flow equations. During the iterative solution process, convergence is evaluated based on two independent criteria: stress residuals and displacement residuals. The stress residual convergence criterion is defined as follows [31]:

$$r_\tau = \frac{\underline{\tau}_f^k - \underline{\tau}_f^{k-1}}{\max\{\underline{\tau}_f^k, \varepsilon_o\}} \quad (1)$$

The displacement-based convergence criterion is given by:

$$r_d = \frac{\underline{d}_s^k - \underline{d}_s^{k-1}}{\max\{\underline{d}_s^k, \varepsilon_o\}} \quad (2)$$

r_τ – Normalized residual of fluid stress for convergence check;

r_d – Normalized residual of fluid displacement for convergence check;

$\underline{\tau}_f^k$ – Vector of fluid surface tractions obtained at the k -th iteration;

$\underline{\tau}_f^{k-1}$ – Vector of fluid surface tractions obtained at the $((k-1))$ -th iteration;

$\underline{d}_s^k$ – Vector of fluid-structure interface displacements obtained at the k -th iteration;

$\underline{d}_s^{k-1}$ – Vector of fluid-structure interface displacements obtained at the $((k-1))$ -th iteration;

ε_o – Small constant threshold to avoid division by zero when the magnitude of stress/displacement vectors approaches zero;

k – Iteration step number in the two-way FSI iterative loop.

3.2 Response of PSICLSS

The PSICLSS model shown in Fig. 1 was designed according to Chinese design codes, and the corresponding ADINA finite element model was established as illustrated in Fig. 10 [32]. The structural concrete was assigned a cube

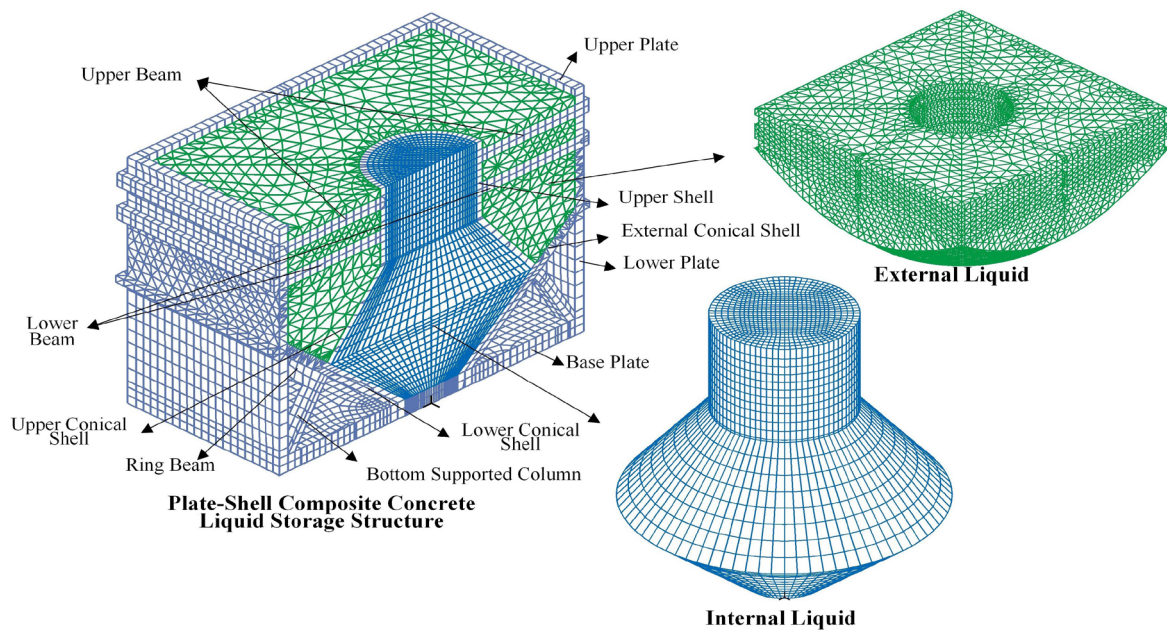


Fig. 10 Model of PSICLSS

compressive strength of 30 MPa and a standard tensile strength of 2.01 MPa. HPB300 and HRB400 steels were adopted for the distributed and load-bearing reinforcement, respectively. The designed liquid storage height was 12 m, and the contained liquid was modeled as a potential-based fluid with a density of 1000 kg/m^3 . Three-dimensional solid elements were used to represent the structure, while three-dimensional fluid elements based on subsonic potential flow theory were employed to simulate the liquid domain. A potential interface boundary condition was applied at the free surface of the liquid. The structure was assumed to be fixed at the bottom boundary, and the fluid–structure interface was defined as the FSI coupling interface. The fixed-base boundary condition was adopted in the numerical model to ensure consistency with the shaking table test and improve the reliability of model validation. The Newton–Raphson method was employed for nonlinear iterative calculations [31]. In the two-way FSI simulation based on potential-based fluid elements, the fluid domain was not subjected to full-field ALE mesh updating. Instead, only the FSI interface nodes moved with the structural deformation as a moving wall boundary, while the free-surface nodes were iteratively adjusted to satisfy the dynamic and kinematic boundary conditions associated with weakly nonlinear liquid sloshing. Rayleigh damping with a damping ratio of 5% was introduced into the structural domain based on the first two natural frequencies, following a commonly used simplified approach for concrete structures in seismic response analysis.

3.2.1 Model validation

In order to verify the shaking table test and numerical analysis results, the finite element analysis model of the scaled shaking table test model was established [32, 33]. The El Centro acceleration was input to the scaled finite element analysis model, and the dynamic responses were obtained. The acceleration time-history curves of monitoring point A5 and hydrodynamic pressure time-history curves of monitoring point WI2 obtained from the numerical analysis and shaking table test are shown in Fig. 11.

From Fig. 11(a), it can be seen that the variation rule of the acceleration is similar, but the peak acceleration measured by numerical analysis is slightly larger than that obtained from the shaking table test. From Fig. 11(b), it can be seen that time-history curves of hydrodynamic pressure obtained from shaking table test and numerical simulation are similar. The peak hydrodynamic pressure at monitoring point WI2 obtained in the test is slightly lower than that of the numerical simulation, which is because the ideal model adopted in the numerical simulation. And the monitoring point WI2 of hydrodynamic pressure in the test is slightly lower than the connection position of the upper conical shell and lower conical shell. Through the experimental study, it can be seen that the numerical simulation results of the liquid storage structure are similar to the experimental results. The results of numerical analysis and test have similar reaction rules.

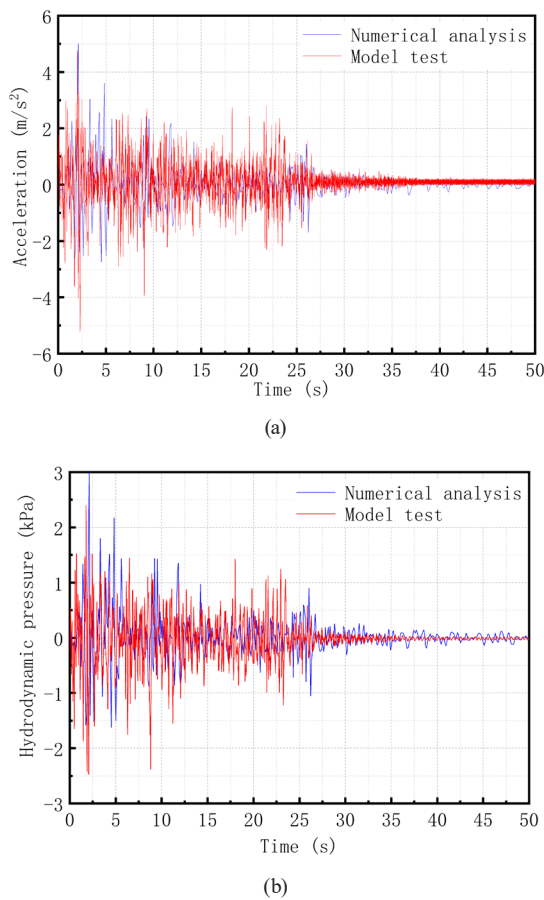


Fig. 11 Acceleration and hydrodynamic pressure time-history curves:
(a) acceleration of A5, (b) hydrodynamic pressure of WI2

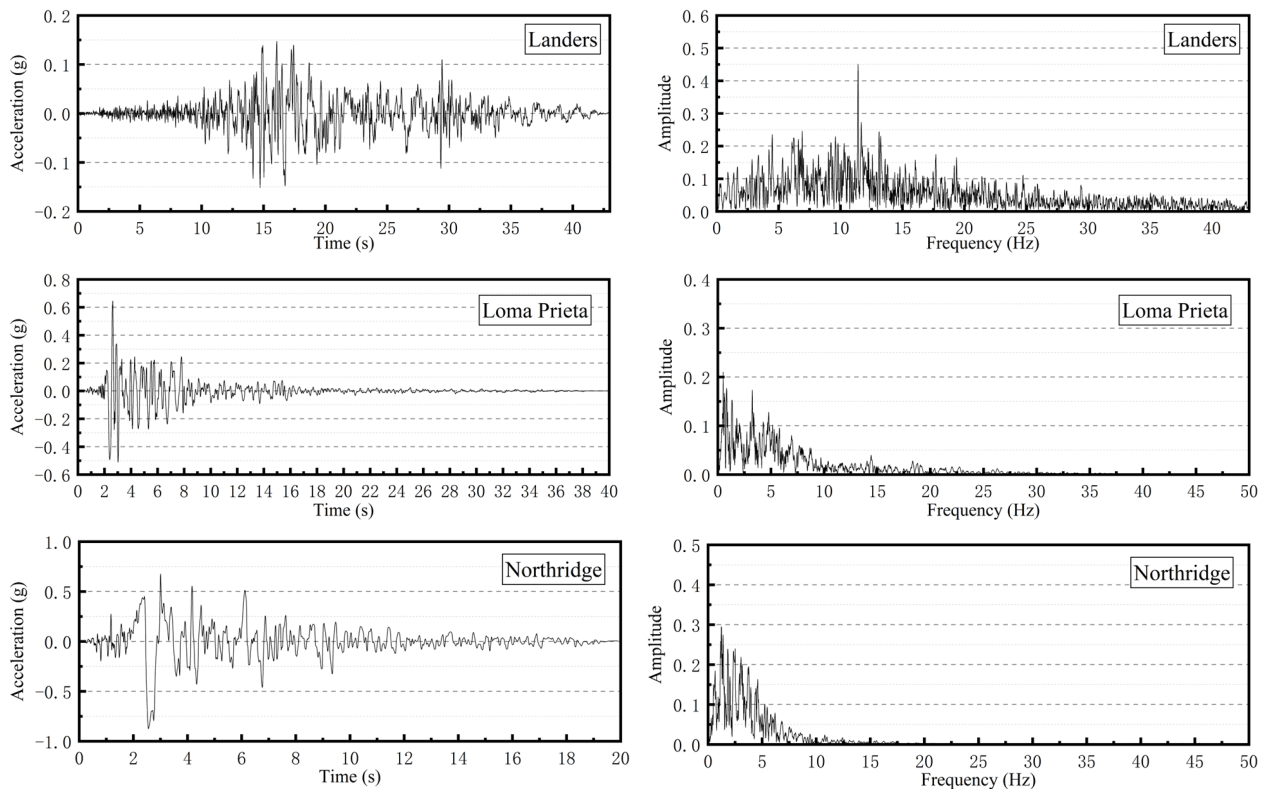


Fig. 12 Input acceleration

3.2.2 Response of PSICLSS

Four representative earthquake records, including El Centro, Landers (captured from the SCE station in the Landers earthquake of 1992), Loma Prieta (captured from the CDMG station in the Loma Prieta earthquake of 1989), and Northridge (captured from the CDMG station in the Northridge earthquake of 1994), were selected as seismic inputs to investigate the failure mechanisms and dynamic responses of PSICLSS (Fig. 12). These ground motions possess different spectral characteristics and were uniformly scaled to a PGA of 0.4 g to provide consistent excitation intensity. The acceleration time histories of the selected records are shown in Fig. 12. The plate displacement response, stress distribution, hydrodynamic pressure distribution, and liquid sloshing characteristics of PSICLSS under different seismic excitations were subsequently evaluated.

The displacement responses of the outer plate and internal shell of the PSICLSS under different seismic excitations are illustrated in Fig. 13. In the following sections, the "positive" direction refers to the direction of seismic excitation input, while the "negative" direction indicates the opposite direction.

As illustrated in Fig. 13, the displacement responses of the structural plates exhibit consistent variation characteristics under different seismic excitations. For the outer plate, the displacement amplification decreases within the

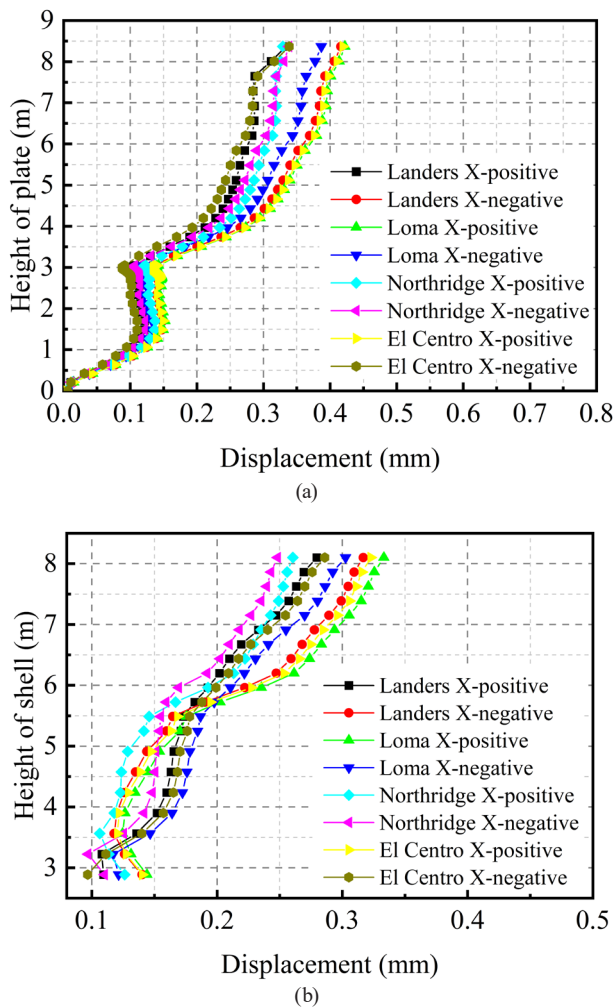


Fig. 13 Displacement of plate: (a) outer plate, (b) internal shell

elevation range of 1.5–3 m. This region corresponds to the overlapping area between the internal and external conical shells, where the structural interaction provides limited contribution to horizontal displacement and deformation. In comparison, the internal shell presents a distinct response characteristic, with displacement decreasing initially and subsequently increasing along the elevation direction.

Comparison among the four ground motions indicates that the El Centro and Loma Prieta earthquakes produce relatively larger positive displacement responses of the structural plates. Under the Northridge excitation, the outer plate exhibits the smallest positive displacement, while the internal shell shows the smallest negative displacement. Specifically, the maximum positive displacements of the outer plate and internal shell under the Loma Prieta earthquake reach 0.42 mm and 0.33 mm, respectively.

The distributions of principal stress and shear stress in the structural components are obtained from the finite element analysis and are presented in Fig. 14. In the figure, the symbols "■" and "*" indicate the locations of

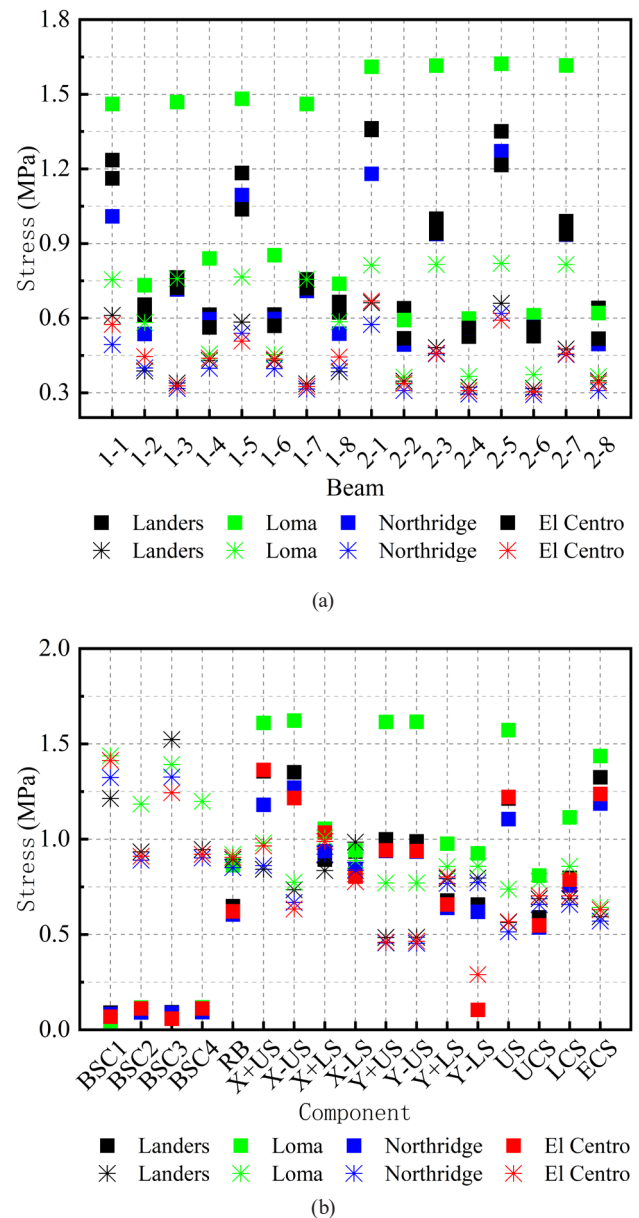


Fig. 14 Stress of PSICLSS: (a) beam, (b) Other components

principal stress and shear stress, respectively. The corresponding component numbers are consistent with those defined in Fig. 10.

The stress results indicate that, under seismic excitation, the beams mainly exhibit a tensile-dominated stress response, with principal stresses exceeding shear stresses. Among the four ground motions, the Loma Prieta earthquake produces the most severe stress response in the structural beams. The beams located along the X- and Y-directions experience relatively higher principal stresses compared with other structural components. Conversely, the bottom support columns and bottom ring beam exhibit shear-dominated behavior, where shear stresses exceed principal stresses. The upper plate,

upper shell, and outer conical shell are mainly subjected to principal stress, whereas the lower conical shell, upper conical shell, and lower slab show comparable levels of principal and shear stresses. The maximum principal and shear stresses of the beams under the Loma Prieta earthquake are 1.62 MPa and 0.82 MPa, respectively. The maximum shear stress of the bottom support columns reaches 1.44 MPa, indicating that these components are more vulnerable to shear failure.

3.2.3 Liquid sloshing characteristics

The liquid sloshing response exhibits significant dependence on the spectral characteristics of the input ground motions. The Landers, Northridge, and El Centro earthquakes generate relatively larger external liquid sloshing heights, with the maximum values concentrated at the corners of the external liquid domain. Conversely, the Northridge earthquake induces the most severe internal liquid sloshing response. The maximum external liquid sloshing heights under the Landers, Loma Prieta, Northridge, and El Centro earthquakes reach 2.31 m, 0.44 m, 2.82 m, and 1.13 m, respectively.

The hydrodynamic pressure response of the internal liquid is significantly higher than that of the external liquid under seismic excitation, indicating a stronger liquid–structure interaction effect within the enclosed liquid domain. Among the four selected ground motions, the Loma Prieta earthquake generates the most severe internal hydrodynamic pressure response, with a maximum value of 18.48 kPa. The El Centro earthquake results in the lowest internal hydrodynamic pressure, with a peak value

of 8.23 kPa, whereas the maximum pressures induced by the Landers and Northridge earthquakes reach 9.57 kPa and 12.57 kPa, respectively.

4 Seismic responses of SMA reinforced hybrid isolation PSICLSS

4.1 Isolation layer setup

To address the high mass and elevated center of gravity of the PSICLSS, a novel SMA-reinforced hybrid isolation system was developed to simultaneously control acceleration response, isolation displacement, and residual deformation. The proposed system combines SBs, LRBs, and SMA wires, exploiting their complementary functions. The SBs primarily reduce acceleration transmission by extending the structural natural period, whereas the LRBs enhance energy dissipation through equivalent damping and restrict excessive isolation displacement. The SMA wires provide additional recentering capability through their superelastic behavior, thereby reducing residual displacement after earthquakes. Based on the structural mass distribution and force equilibrium requirements, four SBs and two symmetrically arranged SMA–LRB composite bearings were adopted to ensure uniform deformation and reliable performance of the isolation layer. The design parameters of the LRBs and SBs used in the SMA-reinforced hybrid isolation system are summarized in Fig. 15. A novel SMA–LRB composite isolation bearing was developed by integrating low-temperature superelastic SMA wires with LRBs. The corresponding SMA parameters are shown in Fig. 15(c), the mechanical properties of SMA are shown in reference [29]. Each SMA–LRB bearing contains two

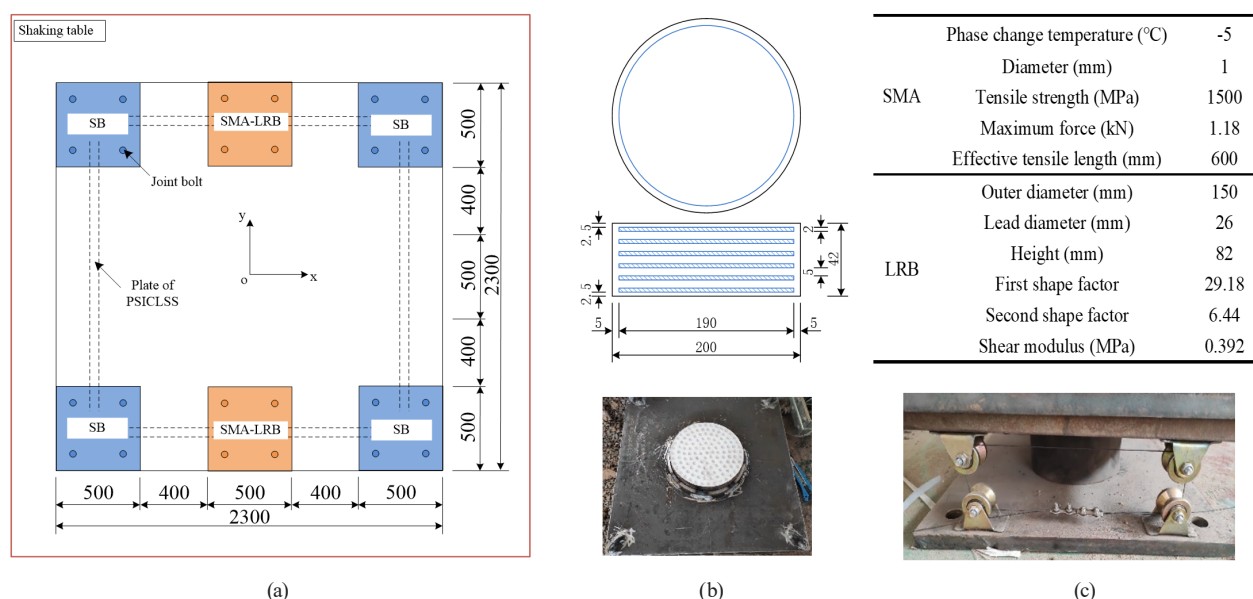


Fig. 15 SMA reinforced hybrid isolation system (mm): (a) Layout of isolation system (mm), (b) SB (mm), (c) SMA-LRB

SMA wires with an effective tensile length of 600 mm. Four fixed pulleys are installed to achieve uniform force transmission and compatible deformation of the SMA wires. The proposed hybrid isolation layer comprises two SMA-LRB composite bearings and four SBs, and the detailed configuration is illustrated in Fig. 15.

4.2 Structural frequency response

The frequency response curves of the isolated PSICLSS is presented in Fig. 16. The results indicate that the fundamental frequency of the isolated PSICLSS is 11.25 Hz. Compared with the non-isolated structure, the SMA-reinforced hybrid isolation layer effectively decreases the fundamental frequency and broadens the frequency distribution range, demonstrating an increase in structural flexibility and a reduction in stiffness.

4.3 Structural responses

The El Centro earthquake record was selected as the input ground motion for the isolated PSICLSS. Two loading conditions, including unidirectional excitation along the X direction and bidirectional excitation along the X and Z directions, were investigated. For the bidirectional excitation case, the peak acceleration ratio between the X and Z components was set to 1:0.65. The peak acceleration responses of the isolated PSICLSS under an X-directional PGA of 0.4g are shown in Fig. 17.

As illustrated in Fig. 17, the SMA-reinforced hybrid isolation layer provides effective control of the acceleration response of the PSICLSS. Compared with the non-isolated structure, the peak accelerations of the isolated PSICLSS are significantly reduced, with maximum acceleration reduction ratios of 40.60% and 29.96% observed at the top

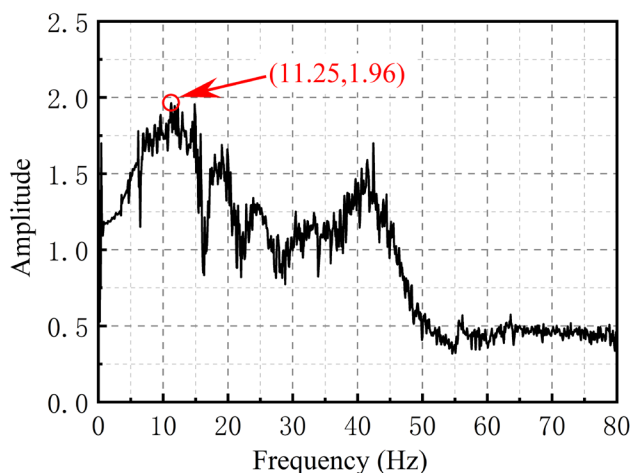


Fig. 16 Frequency response

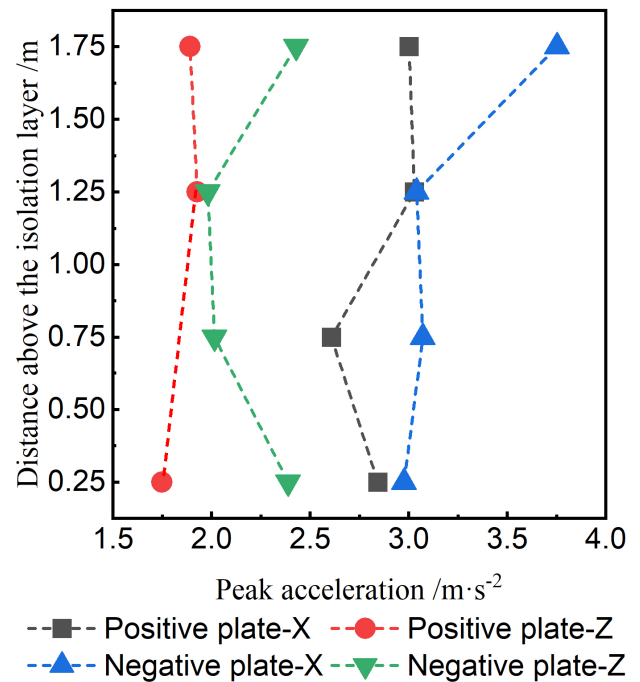


Fig. 17 Peak acceleration under bidirectional earthquake

and bottom of the structure, respectively. The introduction of vertical seismic excitation has a limited influence on the horizontal acceleration response.

The displacement response of the SMA-reinforced hybrid isolation layer was recorded using displacement sensors, and the corresponding results are presented in Fig. 18.

As illustrated in Fig. 18, the SMA-reinforced hybrid isolation layer exhibits a maximum displacement of 50.45 mm and a residual displacement of only 3.75 mm under horizontal seismic excitation. The small residual displacement demonstrates the excellent self-centering performance provided by the SMA wires, allowing the isolation layer to effectively recover after the earthquake. Under

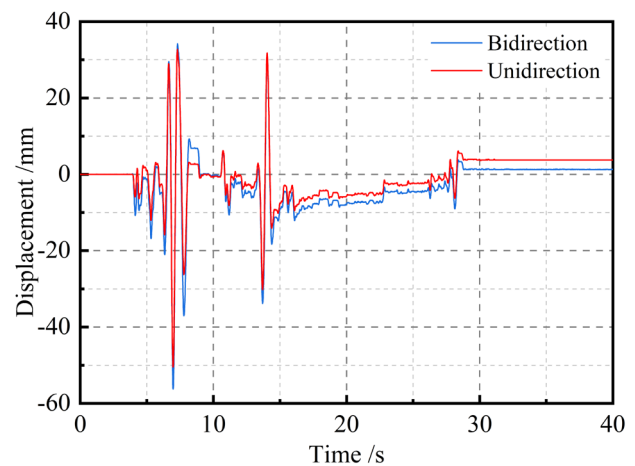


Fig. 18 Displacement of isolation layer bidirectional earthquake

combined horizontal and vertical seismic excitation, the maximum isolation displacement increases to 56.24 mm, while the residual displacement decreases to 1.26 mm. Due to vertical seismic forces, the vertical pressure on the sliding isolation system is reduced, thereby decreasing the restoring friction force, resulting in smaller residual displacements of the structure under bidirectional seismic actions. This phenomenon indicates that vertical seismic motion amplifies the horizontal deformation demand but enhances the recentering behavior of the isolation system.

4.4 Liquid sloshing characteristics

The peak hydrodynamic pressure responses of the isolated PSICLSS under seismic excitation are presented in Fig. 19.

As illustrated in Fig. 19, the SMA-reinforced hybrid isolation system effectively reduces the peak hydrodynamic pressures of both internal and external liquids compared with the non-isolated PSICLSS. Although the pressures at several internal liquid monitoring points show slight increases, the overall external hydrodynamic pressures are significantly mitigated. Specifically, under unidirectional seismic action, the maximum external hydrodynamic pressure of the hybrid isolated PSICLSS is 2.37 kPa, corresponding to a reduction of 0.92% compared with the non-isolated structure, while the isolated PSICLSS exhibits a maximum value of only 1.01 kPa, representing a reduction of 30.58%. Therefore, the proposed SMA-reinforced hybrid isolation layer demonstrates superior control performance for external liquid hydrodynamic pressure.

The introduction of vertical seismic excitation significantly modifies the liquid sloshing behavior of the PSICLSS. A considerable increase in hydrodynamic pressure is observed at monitoring point WI4, resulting in

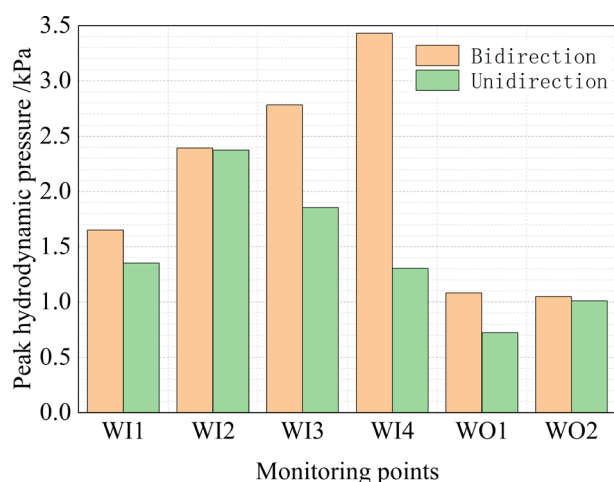
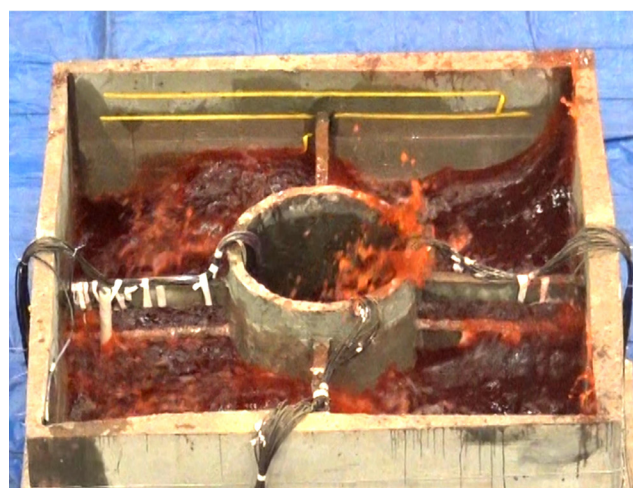


Fig. 19 Hydrodynamic pressure

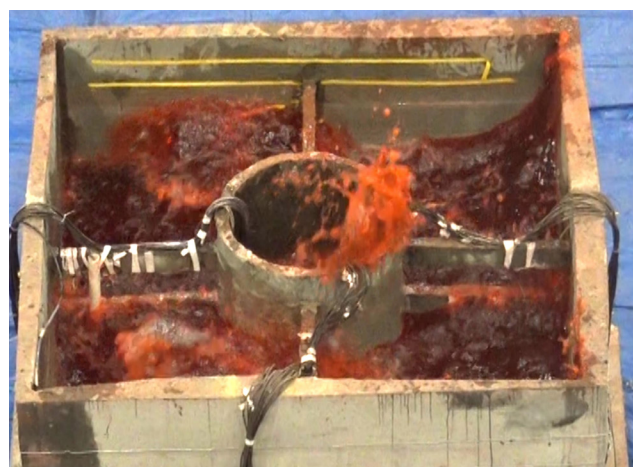
increases of 30.76% and 6.59% in the peak hydrodynamic pressures of the internal and external liquids, respectively. In addition, the distribution pattern of hydrodynamic pressure is altered by vertical excitation. The maximum pressure location of the internal liquid shifts from the junction between the upper and lower conical shells to the bottom region of the structure, while the external liquid also exhibits a redistribution of peak pressure locations.

The peak liquid sloshing heights under different test conditions are presented in Fig. 20.

As illustrated in Fig. 20, the internal and external liquids in the isolated PSICLSS exhibit strong nonlinear sloshing behavior. Compared with the non-isolated condition, the isolation system results in increased liquid sloshing heights, which is mainly attributed to the enhanced flexibility of the isolated structure. The internal liquid exhibits a significantly larger sloshing height than the external



(a)



(b)

Fig. 20 Liquid sloshing height of isolated PSICLSS: (a) unidirectional earthquake, (b) bidirectional earthquake

liquid due to the stronger confinement effect and liquid–structure interaction. Comparison between Figs. 20(a) and 20(b) indicates that vertical seismic excitation has a negligible influence on the overall sloshing height of the internal liquid, although the nonlinear sloshing characteristics remain pronounced. Meanwhile, the external liquid shows only slight variation under the combined horizontal and vertical seismic excitation.

5 Conclusions

This study systematically investigated the seismic response characteristics of the PSICLSS and evaluated the effectiveness of the proposed SMA-reinforced hybrid isolation system through shaking table tests and finite element analyses. The major findings, engineering implications, and potential future research directions are summarized as follows.

The PSICLSS exhibits distinct seismic failure characteristics, with beams along the X- and Y-directions primarily governed by tensile stress and bottom support columns and lower slabs dominated by shear stress. The maximum principal stress of beams reaches 1.62 MPa under the Loma Prieta earthquake, while the maximum shear stress of bottom support columns reaches 1.44 MPa. The internal liquid consistently experiences higher hydrodynamic pressure than the external liquid, and the pressure concentration region varies with ground motion characteristics.

The SMA-reinforced hybrid isolation system effectively improves the seismic performance of the PSICLSS by reducing the fundamental frequency from 18.52 Hz to 11.25 Hz and enhancing energy dissipation. The isolation layer exhibits excellent self-centering behavior, with

residual displacements limited to 3.75 mm and 1.26 mm under horizontal and combined horizontal–vertical excitations, respectively. The proposed system reduces structural acceleration by up to 40.60% and decreases peak external hydrodynamic pressure by 30.58%.

The proposed isolation system inevitably increases liquid sloshing responses, particularly the nonlinear sloshing behavior of the internal liquid. Nevertheless, its horizontal vibration control performance remains stable under vertical seismic excitation. Although vertical excitation increases internal hydrodynamic pressure and modifies its distribution, the system effectively mitigates structural stress concentrations and reduces the risks of tensile and shear failures, demonstrating promising engineering applicability.

Although the proposed study demonstrates the effectiveness of the SMA-reinforced hybrid isolation system, only one type of isolation bearing was investigated. Future work will focus on comprehensive parametric studies of the bearing properties and systematic comparisons with alternative isolation systems to further clarify the optimal design parameters and enhance the reliability of seismic performance evaluation.

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