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Division V

SEISMIC EXPERIMENTAL STUDY OF HUGE COMPLEX STORAGE TANK IN NUCLEAR ISLAND BASED ON FLUID-STRUCTURE INTERACTION

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ABSTRACT

Nuclear Power Plant (NPP) generally contains various huge water storage tanks. The In-containment Refuelling Water Storage Tank (IRWST) of the 3rd generation passive pressurized NPP is a typical complex water storage tank. Compared with the regular tanks, this tank is quite different with 4 additional difficulties: irregular geometry, top plate impacted, submerged components and non-single structure type. The complex seismic Fluid-Structure Interaction (FSI) for IRWST and its important submerged components is studied by the shake table tests.

New scaling similarity criterions for FSI seismic tests are proposed to preliminarily solve the problem about the dynamic properties of the structure and fluid cannot be scaled uniformly. Test model is simplified and integrally scaled with the consideration about the external structures. The Particle Image Velocimetry (PIV) is explanatorily adopted for the dynamic measurement of the underwater planar flow field and 3D surface wave. The impulsive and sloshing components of the dynamic pressures are separated by the band-pass filtering according to the test phenomenon. The low-frequency component duration of seismic input is studied by time-frequency analysis. The test responses of the structure and water are consistent with the prediction, and can be applied for the engineering and further numerical simulation.

INTRODUCTION

The In-containment Refuelling Water Storage Tank is the important component of the passive core cooling system for the 3rd generation passive pressurized NPP, and is the most complex tank in the Nuclear Island (NI). The structure, flow field and FSI under the earthquake are quite complicated. IRWST structure is composed of mass concrete at bottom, a concrete slab at top, an arc steel plate walls in the west and Steel-plate Composite (SC) walls, shown in Figure 1. IRWST max length and width are 38.7m and 15.7m. IRWST water depth is 10.65m, and the headroom height between water level and top plate is only 0.4m. Meanwhile, kinds of components are submerged such as the Passive Residual Heat Removal Heat Exchanger (PRHR HX), Automatic Depressurization System (ADS) sparger, steel frames, pipes, etc.

Compared with the regular water storage tanks, IRWST is quite different with 4 additional difficulties.

- Irregular geometry: half of the wall is arc with internal stiffeners, and the other is flat with various flow channels.
- Top plate impacted: The narrow headroom leads to repeated sloshing impact.

- Submerged components: The submerged equipment, pipes and structures disturb the flow field, and their seismic responses are also the research objective.
- Non-single structure type: the steel plate walls are much more flexible than SC walls.

Therefore, due to the complex flow field and high nonlinearity, the traditional theoretical calculation and simple FSI analysis are not accurate enough to simulate the seismic effect.

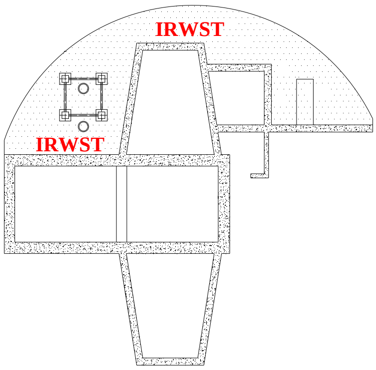


Figure 1: In-containment Refuelling Water Storage Tank (IRWST)

New scaling similarity criterions are creatively proposed for the complex seismic FSI tests of IRWST and submerged components. It preliminarily solves the problem about the dynamic properties of the structure and fluid cannot be scaled uniformly. Meanwhile, the scaling method is adopted for the impulsive and sloshing pressures, and the prototype dynamic pressures are derived by the scaling similarities and amplification factors of the shake table results. The time-frequency analysis methods such as wavelet analysis are adopted to study the influence of the low-frequency component duration. The tests study various shake table input and test models, and there are 130 test conditions in total to achieve comprehensive comparative conclusions. This paper focuses on some typical test conditions.

These test results are also used for the further comparison between the tests and numerical simulations, and improving the FSI analysis method for the complex water storage tank.

DESIGN OF IRWST TESTS

New Scaling Similarity Criterions for FSI Seismic Tests

Limited by the test materials, there is a general problem about dynamic distortion that the structure and fluid dynamic properties cannot be scaled uniformly in the current tank FSI seismic tests. The IRWST test model is integrally scaled as ratio 1:8, and the test material properties of the fluid and structures are the same as the prototype's. The IRWST tests are not destructive tests, and the strain similar scale is low.

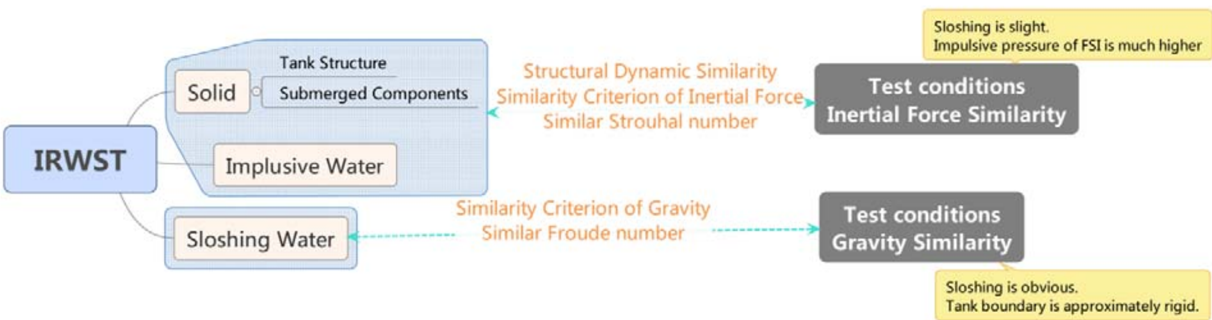


Figure 2: Scaling similarity criterions for IRWST FSI seismic tests

The scaling similarity criterions for IRWST FSI seismic tests are shown in Figure 2. The solid part and impulsive water are researched based on the structural dynamic similarity and inertial force similarity criterion that are commonly used in the traditional structural shake table tests. However, it is indicated that the Froude numbers in these similarity criterions are not similar which means the fluid gravity is not similar. The Froude number is the key constant for water sloshing.

Therefore, it is proposed that: For each seismic input, both inertial force similarity criterion and gravity similarity criterion are adopted respectively to distinguish the integral impulsive effect and the sloshing effect. In engineering, it solves the problem about the dynamic properties of the structure and fluid cannot be scaled uniformly.

Test Model Simplification

According to the above scaling similarity criterion, the prototype tank is scaled to the test size, and the test model is appropriately simplified. All test components are designed based on the stiffness equivalent calculation for the dynamic properties.

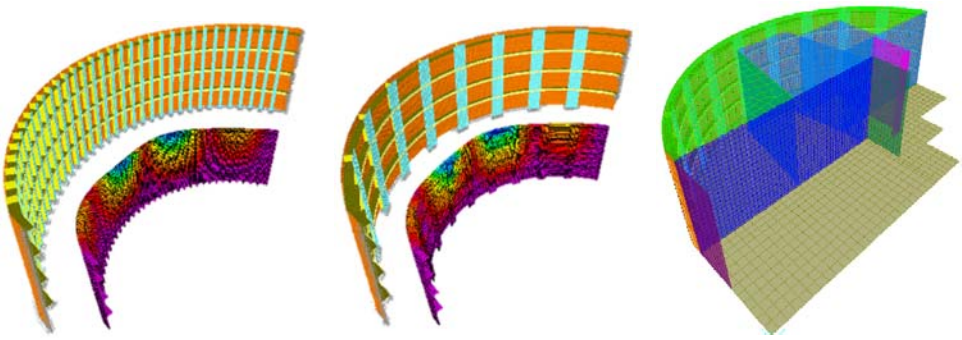


Figure 3: Stiffness equivalent calculation for the IRWST test model

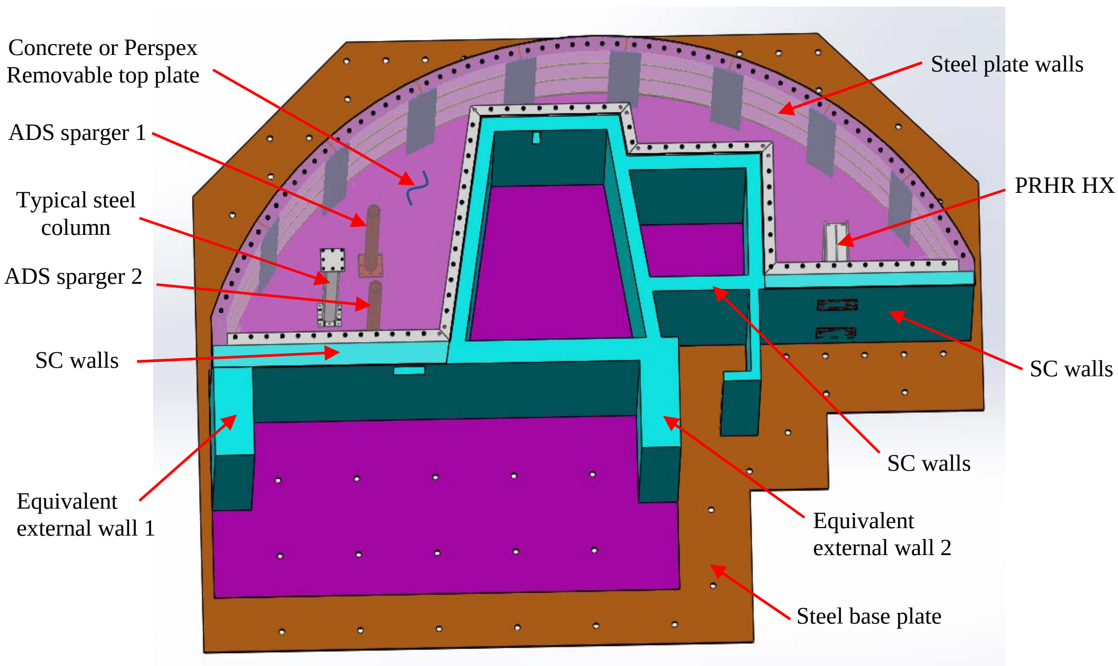


Figure 4: Simplified test model

The actual IRWST is a part of the reactor building, and connected with other structures. The IRWST tests should consider the IRWST real dynamic response in the Nuclear Island. The equivalent external walls are supplemented to simulate the external supporting structure, shown in Figure 3. Simplified Test model is shown in Figure 4.

Seismic Input and Test Conditions

Multidimensional comparisons are studied by 130 shake table tests. Various types of seismic waves: white noises, artificial waves, observed waves, sine beat waves, sine waves. Various water levels: fulfilled level, standard design level, free sloshing level. Various ZPAs, different top plates, and with or without submerged components and damping plate are also involved. However, due to limited space, this paper is mainly focused on the basic test conditions.

The operating frequency range of the shake table is 0.1~120Hz with excellent control precision. And the highest frequency 120Hz is quite necessary for the structures with large stiffness to capture the high frequency response. The IRWST test model is shown in Figure 5. The dynamic pressure, acceleration and wave height are mainly measured, and the displacement and strain are measured for local areas.

Figure 5: IRWST test model on the shake table

The Particle Image Velocimetry (PIV) is explanatorily adopted for the dynamic measurement of the underwater planar flow field and 3D surface wave, shown respectively in Figure 6 and Figure 7. This high precision stereo-measurement is a supplement of the traditional point measurement.

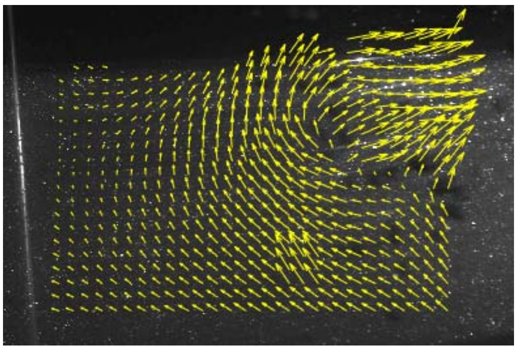


Figure 6: Particle velocity vector

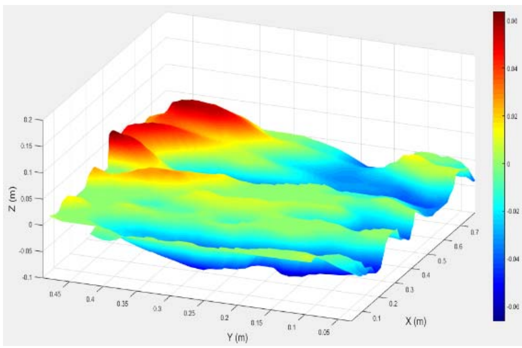


Figure 7: 3D surface wave

DATA ANALYSIS METHOD

Filtering Separation of Impulsive and Sloshing Dynamic Pressures

The impulsive and sloshing dynamic pressures are simulated by the different test conditions. According to the scaling similarity criterions, the impulsive dynamic pressure can be directly simulated by the test conditions of the inertial force similarity which the sloshing effect is negligible. However, the dynamic pressures in the test conditions of the gravity similarity contain both the sloshing component and impulsive component. These impulsive component is quite large and incorrectly simulated, and it is too conservative to directly take the dynamic pressure as the sloshing pressure. Therefore, the filtering separation method is adopted for the test conditions of the gravity similarity to separate the sloshing component from the original dynamic pressure.

The Power Spectral Density (PSD) of the wave height in the typical gravity similarity condition is shown in Figure 6. The wave height PSD is mainly concentrated below 3Hz. Considering the water similarity scale, the prototype water frequency is 1.06Hz which is a quite wide range of the sloshing frequency for large tanks. The sloshing effect is directly consistent with the wave height. Thus the separation frequency $f_{sloshing}$ of the test sloshing pressure is 3Hz.

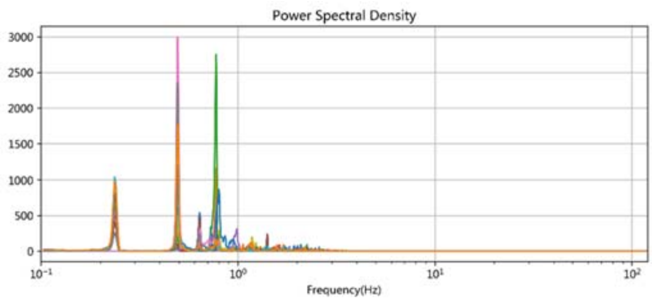
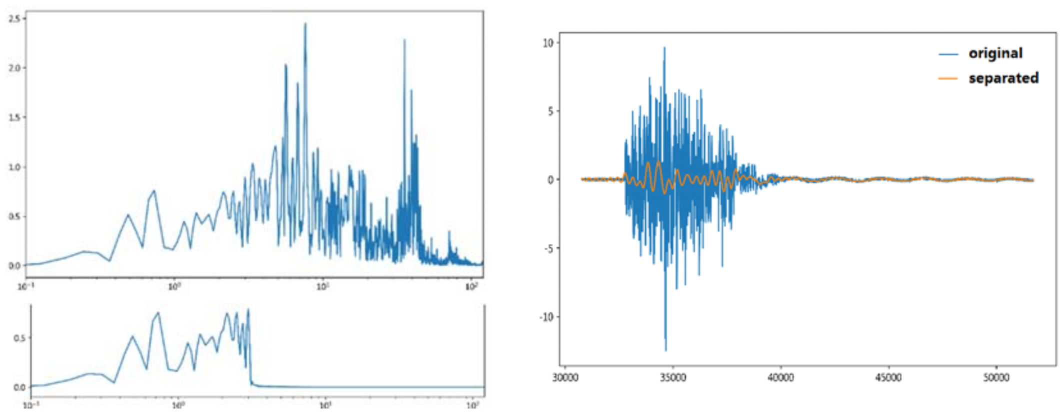


Figure 6: Wave height PSD of the typical gravity similarity condition

Considering the effective frequency range of the shake table, the band-pass filtering at 0.1Hz~3Hz is adopted for the sloshing pressure separation. For a typical bottom dynamic pressure, the original and filtered Fourier amplitude spectrums show the transparent separating effect in Figure 7(a). The time histories of the original and separated dynamic pressures are shown in Figure 7(b). The peak dynamic pressure is greatly reduced for the bottom point.



(a) Fourier amplitude spectrums (b) Dynamic pressure time histories

Figure 7: Filtering separation typical result and comparison

The filtering separation result of the dynamic pressure time history P_{fmin_fmax} is Equation (1). The peak values of the separated pressure components can be combined by Square Root of the Sum of the Squares (SRSS) method into original peak value as Equation (2).

$$P_{fmin\_fmax} = P_{fmin\_fsloshing} + P_{fsloshing\_fmax} \tag{1}$$

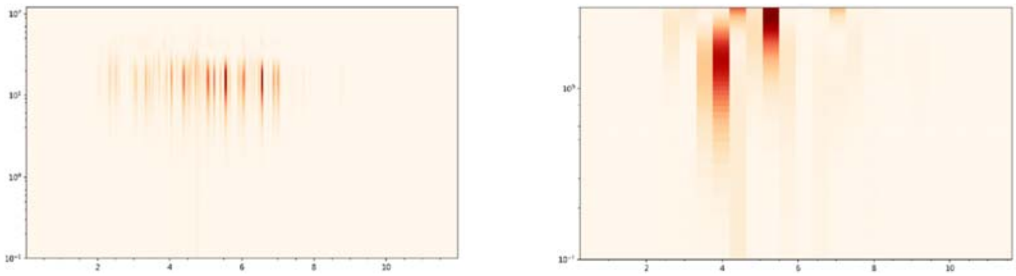
$$P_{fmin\_fmax\_peak} \approx \sqrt{P_{fmin\_fsloshing\_peak}{}^2 + P_{fsloshing\_fmax\_peak}{}^2} \tag{2}$$

For all dynamic pressures in the typical test conditions, the peak pressure by SRSS combination is an average of 0.994 original peak pressure. Meanwhile, ASCE 4-16 (2017) specifies that SRSS is an appropriate combination method for obtaining the mean peak response when combining the impulsive and convective modal maximums. It is indicated that the filtering separation also have the similar physical meaning for the separated sloshing pressure.

Actually, the separated sloshing pressure conservatively includes a bit low-frequency component of the impulsive pressure. Otherwise, the sloshing impact on the top is a severe transient effect that contains high-frequency component. Therefore, the dynamic pressures at the top plate and top of walls are conservatively not separated.

Time-frequency Analysis

In the 311 earthquake tests, it is discovered that the sloshing effects may be quite different with the seismic inputs that have the similar response spectrums but different time domains. The low frequency component duration affects the water sloshing. Using Short Time Fourier Transform (STFT) and Wavelet Transform (WT) with Ricker wavelet, the shake table time history input is analysed for the time-frequency properties.



0.1~120Hz, Bandwidth 0.05s | 0.1~3Hz, Bandwidth 0.5s

Figure 8: Short Time Fourier Transform

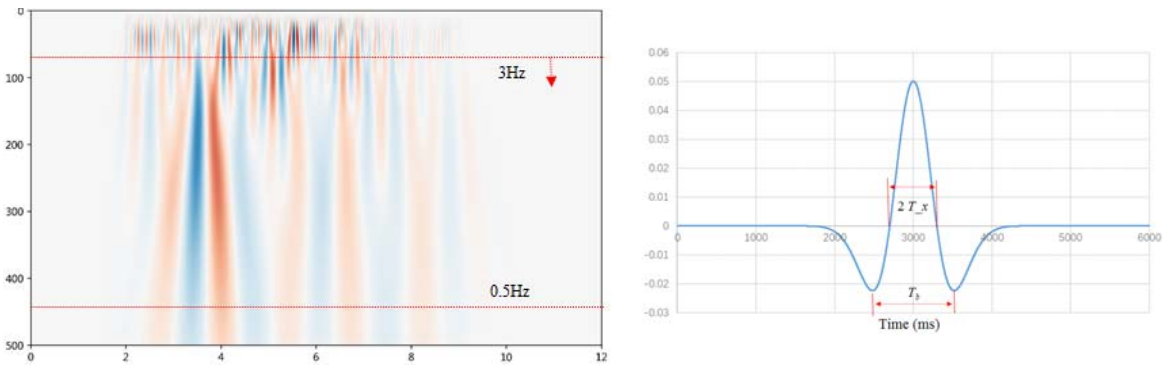


Figure 9: Wavelet Transform with Ricker wavelet

TEST RESULTS AND ANALYSES

Dynamic Properties of Basic Test Model

The FSI dominant horizontal natural frequencies and structure damping ratios are identified by the frequency response functions in the white noise conditions. And the water sloshing frequencies are identified by the wave height PSD. The dominant natural frequencies of the structure and water are shown in Table 1. Besides, the calculated vertical natural frequencies of the structure and water are much higher that exceed the shake table limit.

Table 1: Dominant horizontal natural frequencies of the structure and water

Model	Dominant Natural Frequencies (Hz)				
	Impulsive modes			Sloshing modes	
	SC Walls		Steel Plate Walls	Water	
	X	Y	Normal	1st order	2nd order
Basic test model	90.1	99.5	80.0	0.492	0.771

The structural damping ratios of the impulsive modes are identified. The strain similarity scale is 1:8 which is much less than 1, and the tests are non-destructive. Thus the test model remains elastic during the whole tests. According to ASCE 4-16 (2017), the test model should be classified as Response Level 1. ASCE 4-16 (2017) specifies that the damping ratios of the impulsive modes of liquid-containing metal and concrete tanks are 2% and 3% respectively for Response Level 1. Therefore, the test damping ratio is consistent with the ASCE 4-16 (2017) specification.

Test Results of Basic Test Conditions

The vertical response spectra of the IRWST test top plate are similar to the base input's, and the horizontal X/Y response spectra of the IRWST test top plate are shown in Figure 10. Compared with the design spectra, the test spectra match well in the low and mid frequency range, and can be well enveloped by the design spectra in the higher frequency range.

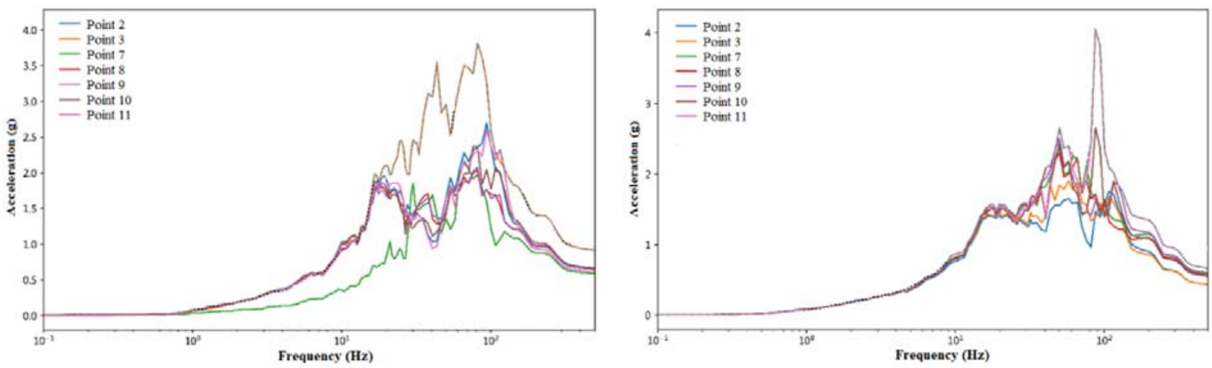


Figure 10: IRWST top plate X/Y response spectra in comparison with the design spectra

For the purpose of the sloshing impact visualization, the test conditions with perspex top plate are supplemented. The typical sloshing and impact on the perspex top plate in the test condition of the gravity similarity are shown in Figure 12. On the contrary, the sloshing in the test conditions of the inertial force similarity is negligible, and it is in complete agreement with the similarity criterions.

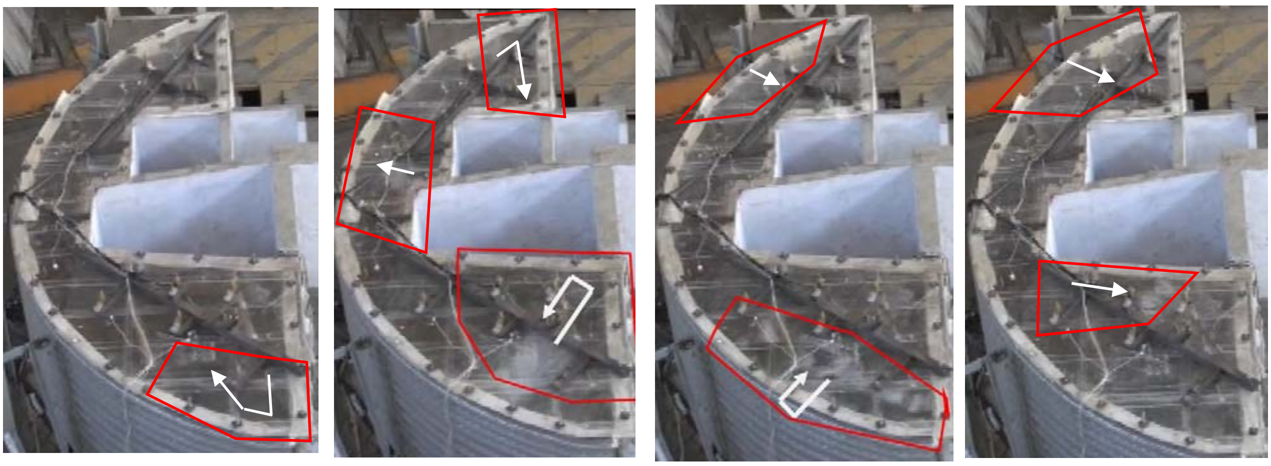


Figure 11: Sloshing and impact on the perspex top plate in the test condition of the gravity similarity

The sloshing effect is mainly concentrated on the water surface range where the dynamic pressures are dominated by the sloshing components. As the increasing of the water depth, the impulsive components rapidly increase, and the sloshing components observably reduce on the contrary. In the mid and bottom IRWST, the impulsive pressures are much greater than the sloshing pressures. The dynamic peak pressure for the walls and submerged components are shown in Figure 11.

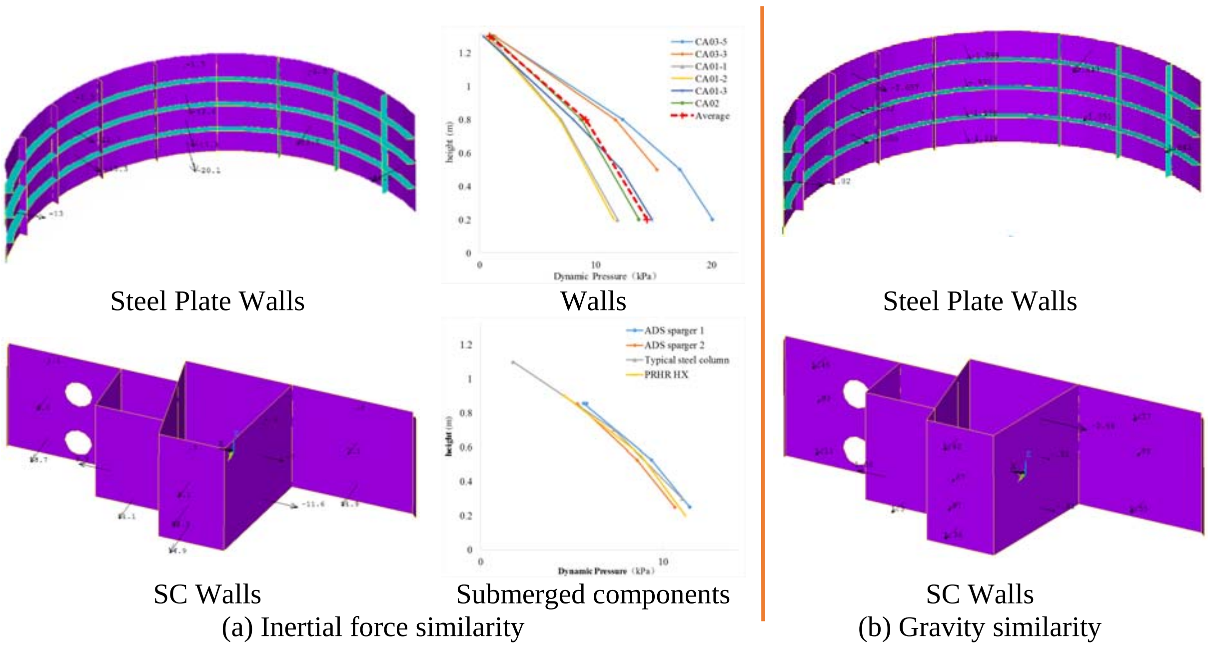
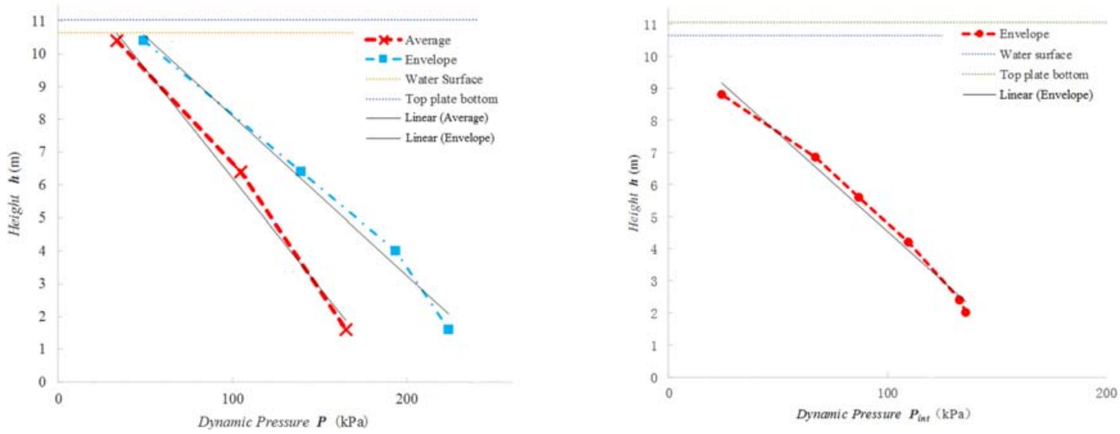


Figure 12: Dynamic peak Pressure for the walls and submerged components

Considering the limitation and discreteness of the shake table capacity, the amplification factors are introduced for the dynamic pressures to envelope the deviation between the target response spectra and the test bottom response spectra. These factors compare the accelerations at the impulsive and sloshing dominant frequencies, Zero Period Accelerations (ZPAs) and the Root Mean Square (RMS) accelerations of the target frequency ranges.

According to the scale similarities and amplification factors, the impulsive and sloshing components are scaled to the prototype components. As demonstrated above, the dynamic peak pressures can be derived by the SRSS method from the impulsive and sloshing peak pressures. The prototype dynamic peak pressures of the walls and submerged components are shown in Figure 13. The vertical distributions of the dynamic peak pressures seem like conic curves. For the engineering application, the vertical distributions can be simplified as linear curves.



(a) Walls (b) Submerged components

Figure 13: Derived dynamic peak pressure for the prototype

In addition, the further numerical simulations have been accomplished and based on the ALE algorithm in LS-DYNA. The comparison showed that the analyses and tests match well at the dominant natural frequencies, dynamic peak pressure distribution, sloshing effect and so on. Meanwhile, the prototype simulation proves the rationality of the new test similarity criterions.

CONCLUSION

The complex seismic FSI for IRWST and submerged components is researched by the shake table tests. The new scaling similarity criterions for FSI seismic tests can preliminarily solve the problem about the dynamic properties of the structure and fluid cannot be scaled uniformly. The impulsive and sloshing components of the dynamic pressures can be separated by the band-pass filtering, and the prototype pressures can be derived by the combination of the scaled components. The test results of the basic test conditions indicate that seismic responses of the fluid and structure are consistent with the prediction, and can be applied for the engineering and further numerical simulation.

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