Numerical and experimental study on seismic behavior of base-isolated nuclear power plant

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SUMMARY:
A base isolation technique is developed to provide nuclear power plants a larger seismic margin from design earthquakes and standardize the seismic design procedure for various seismic fortification intensities. Considering the seismic demands from facilities and pipes within plants, it is also appealing to isolate the vertical earthquake inputs. For this purpose, a three-dimensional base isolation technique is proposed. It is first numerically examined by simplified models to search for the suitable parameters for base isolation layer. And a set of time history analyses are then conducted to explore the damping effect on the structural responses. 1/15 scaled shaking table tests are conducted on two models using three-dimensional and horizontal-only isolators, respectively, and one primary model without isolation. It is found that three-dimensional isolation systems exhibit the same as the traditional isolation systems in horizontal direction and could avoid dominated frequencies of most facilities within the plants in vertical direction.

Keywords: Three-dimensional base isolation, thick rubber bearing, nuclear power plant, shaking table test

1. INTRODUCTION

The first nuclear power plant in Qinshan of China was constructed in 1985 and supplied electric power generation in 1991. Up to now, there are 6 nuclear power plants in operating, of which 11 reactors could yield 9 million KW electric power. However, it only takes up 2% of total electric power generation of the whole nation. To support China's quick development, more nuclear power plants are being and going to be constructed in China. Since the Fukushima nuclear accident, the safety of these nuclear power plants becomes one of the biggest concerns to human society.

The base isolation technique, which has been successfully applied in traditional civil engineering, is proposed to improve the seismic performance of nuclear power plants. It is a reasonable option which is able to render nuclear power plants a larger seismic margin from design earthquakes and standardize the seismic design procedure for different locations with various seismic fortification intensities. France is the first country to have constructed two isolated nuclear power plants. Consequently, the standard design of nuclear facilities has been propelled (Malushte, 2005). Since the 1980's, Japan has developed a series of research on the isolation technology for nuclear power plants, and published a guideline of the base isolation design for nuclear power plants (JEAG, 2000), systematically discussing structural dynamics and extreme load analysis, seismic response analysis and design, structural reliability and probabilistic safety assessment and qualification management and maintenance of isolators. In 1995, European Atomic Energy Community (EAEC) raised a proposal for design guidelines of base isolated nuclear facilities, mainly using high damping steel-laminated rubber bearings (HDRB) (Martelli, 1995). Numerous experiments and analyses of three dimensional models by both simple bearing models and detailed finite-element were completed, which verified that isolation technology is feasible and economic.

Traditional horizontal isolation technique, however, still allows the seismic energy to pass through vertically into the superstructure. The vertical response commonly vibrates within a frequency range of 10-20Hz, which covers most facility frequencies, indicating an adverse effect of the horizontal base isolation, as shown in Fig.1. Therefore, the concept of three-dimensional base isolation is more appealing.

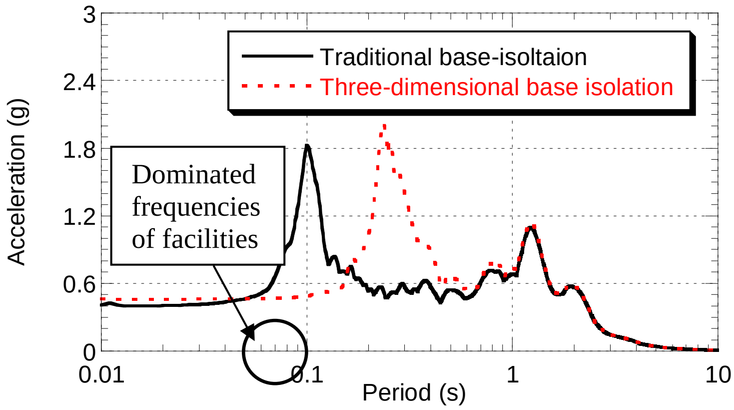


Fig.1 Floor response spectrum of two isolation systems

Proposed is an overall three-dimensional base isolation system which consists of rubber bearings with thick rubber layers and liquid viscous dampers. Thanks to the lager thickness of rubber layers, the vertical vibration frequency is significantly reduced comparing with the traditional isolation system, while the horizontal frequency almost remains. In this study, the design parameters of the three-dimensional base isolation system, such as the horizontal and vertical frequencies and damping ratios, were identified through numerical analysis using a simplified model. Then 1/15 scaled shaking table tests are conducted and reveal that three-dimensional isolation systems exhibit the same as the traditional isolation systems in horizontal direction and could avoid dominated frequencies of most facilities within the plants in vertical direction.

2. SUMMARY OF PREVIOUS STUDY

2.1. Parametric Numerical Study

In previous study, a simplified model was developed to examine the parameters of the base isolation layer, as shown in Fig.2.1.1. The superstructure is simulated by a concentrated mass supported by a flexible link, whose dominated frequency, 5Hz, is from a real NPP. The foundation of the superstructure is taken as the upper raft of the base isolation layer. The mass of the superstructure is taken as 8.95e7kg, while the base raft is 3.61e7kg. The effective height was calculated to reproduce the same overturning moment at the bottom slab, which is 27.5m. Three springs were inserted in the base isolation layer to represent the isolators, two in vertical and one in horizontal. The distance between the two vertical springs is decided by the expected rocking stiffness. Similar implementation is also given to the dashpots which represent the damping coefficients in three directions. To explore the isolation and damping effects, time history analyses were conducted using a set of 20 near fault ground motions (Somerville, 1999). The vertical period varies from 0.05 s to 4 s, and the horizontal period is set as 2.5 s, a typical period for base isolated structure. Previous study (Politopoulos, 2008) indicated that larger damping ratio may result in larger acceleration in the superstructure, so that the damping ratio is selected ranging from 2 to 30% for the vertical direction, and 15% damping ratio is selected for the horizontal direction. The averaged maximum responses of each model are given in Fig.2.1.2. in terms of displacements, velocities and absolute accelerations. It is observed from these figures that: (1) The displacement and velocity responses increase sharply when the vertical period ranges from 0.3 to 2 s. Previous study indicates that the rocking mode dominates once the vertical period is larger than 1 s. Both imply a reasonable vertical period is less than 1 s, although it fails in suppressing the acceleration response. One shall note that, however, the acceleration in the concerned frequencies decreases; and (2) It is suggested that the damping is effective in suppressing the acceleration responses.

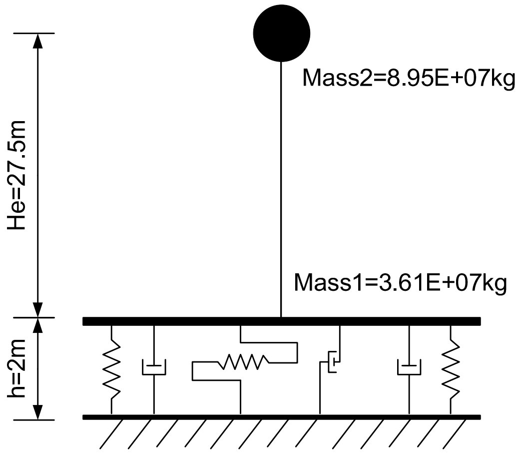


Fig.2.1.1 Simplified NPP model

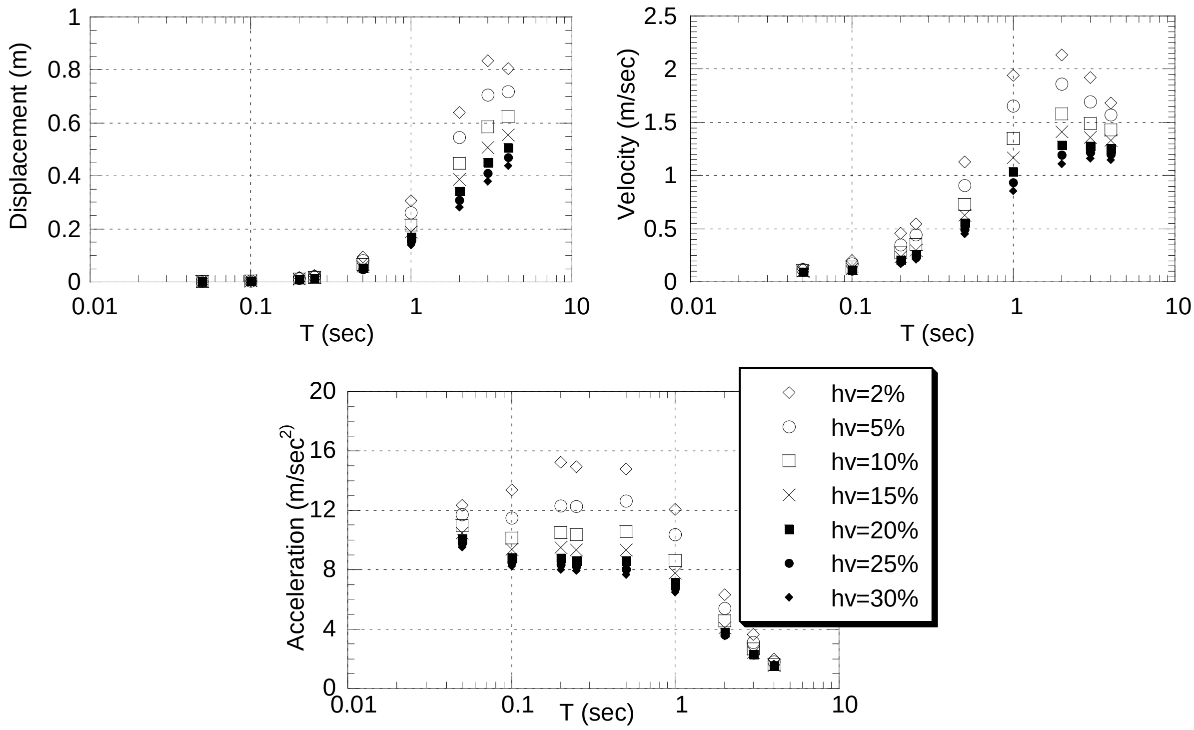


Fig.2.1.2 Seismic responses of simplified NPP model

2.2. Three-Dimensional Isolation Devices

2.2.1. Thick Rubber Bearing

The thick-rubber bearings are designed following a typical procedure commonly used for traditional horizontal rubber bearings. The design shear stiffness and compressive stiffness are 0.221kN/mm and 20.59kN/mm, respectively. Important design parameters of thick rubber isolator are given in Fig.2.2.1. The shape coefficients of the thick rubber bearings, 4.2 and 2.3 respectively for the first and second shape coefficients, are significantly smaller than the lower limits of traditional horizontal bearings. Inspection tests were conducted under different axial pressures, i.e., 1.59MPa and 3.19MPa, corresponding to 75 kN and 150 kN, respectively. The horizontal force was plotted in Fig.2.2.2 (a) with respect to the horizontal displacement. For each case, three amplitudes were adopted, corresponding to the shear strain of the rubber layers of 50%, 100% and 180%, respectively. The thick rubber bearing behaved stably and the stiffness measured at different amplitudes kept almost unchanged. Another specimen was used to examine the compressive stiffness (axial stiffness) of thick rubber bearings. Axial load was first imposed on the specimen, and three cycles with amplitude of the 30% of the applied axial force were conducted. The vertical force was plotted in Fig.2.2.2 (b) with respect to the vertical displacement. It is observed that the compressive stiffness becomes larger when the vertical displacement increases. Finally, the thick-rubber bearing was pushed to 55% of the typical diameter, and ultimate compressive strength was obtained by increasing the axial load continuously. The ultimate strength was found larger than 14.6MPa, which means the thick rubber isolator possess a large stability under large and complex deformation. According to the test conducted above, it indicates that this very type of thick rubber isolator proposed could be applied to the three-dimensional base isolation.

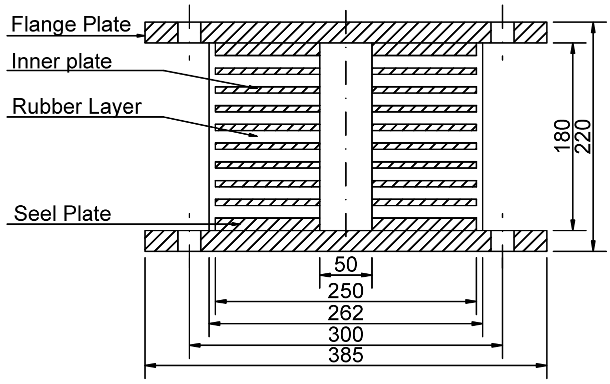
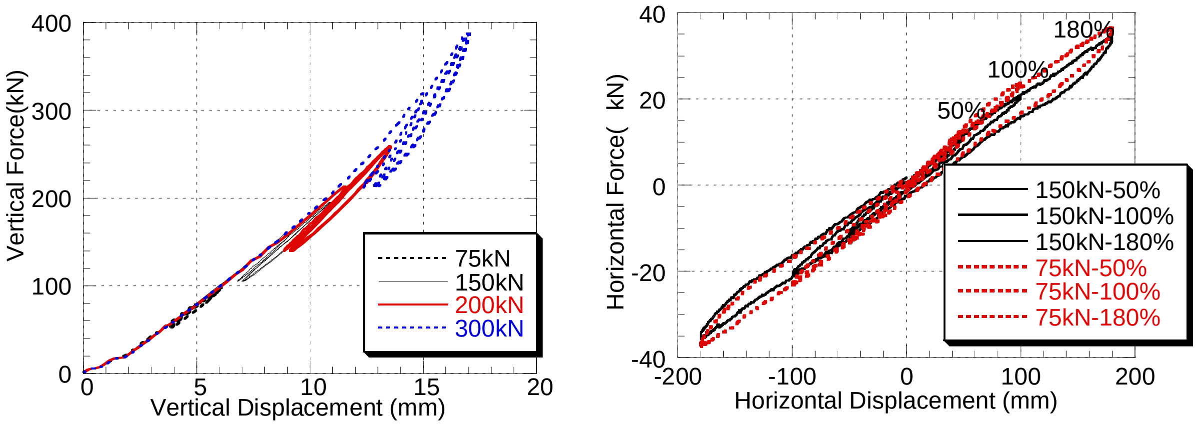


Figure 2.2.1 Configuration of thick rubber bearing



(a) (b)

Figure 2.2.2. Hysteretic curves: (a) Shear stiffness test; (b) Compressive stiffness test

2.2.2. Viscous Dampers

Fluid viscous damper is applied to base-isolation system to suppress the response during the earthquake, which possesses a good energy dissipation capacity shown in Fig.2.2.4. The ideal force output of a viscous damper can be expressed as Eqn.2.2.2, where F_D is the damper force, C is the damping constant, v is the velocity of piston, and α is the exponent. It is observed that the damping constant C is 0.0008kN/s/mm, and the exponent α is 1.66 given in Fig.2.2.3.

$$F_D = Cv^{\alpha}\,\mathrm{sgn}(v) \quad (2.2.2)$$

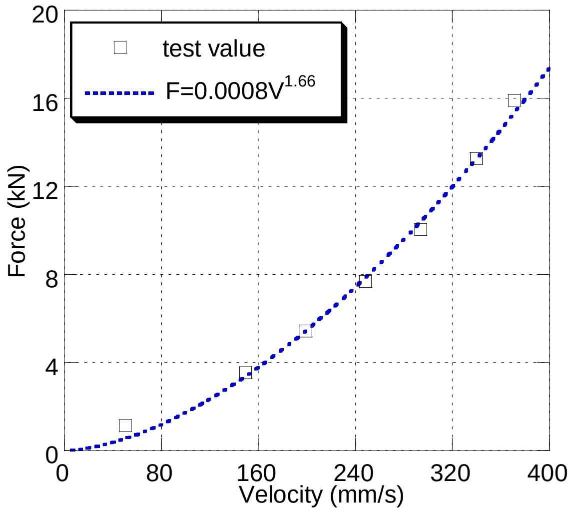


Figure 2.2.3 Hysteretic curves

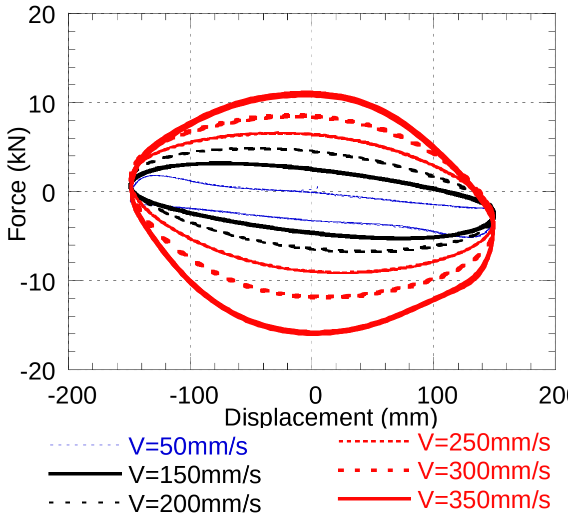


Figure 2.2.4 Energy dissipation capability

3. EXPERIMENTAL STUDY

3.1 Specimen on shaking table

In order to completely demonstrate the isolation effect, shaking table tests are conducted on a base isolated nuclear reactor shell. For the prototype, the horizontal frequency is 4.5Hz when the base of the superstructure is fixed. The mass of the total structure is 3.98e7kg. And the height of shell is 62.5m, while the diameter is 37.8m. Based on law of similitude, three types of 1/15 scaled model, two using traditional base isolation technique and three-dimensional base isolation technique respectively with one primary model without using any base isolation technique, are constructed. Since the gravity acceleration could not be changed during process of scaling and limits of material selected, leading to the lack of model's mass, thus, we do not take the effect of gravity into consider. The similitude ratios between model and prototype are shown in Table.3.1.

Table 3.1 Similitude ratios

time	frequency	displacement	acceleration	force
0.1814	5.5138	0.0667	2.0268	0.0009

Then, by using experimental values of thick rubber isolators and traditional rubber isolators, the dominated frequencies of each model are calculated, shown as Table.3.2. The dominated frequency of primary model without isolation is in the horizontal direction, while its second mode is not simple in vertical direction but cross section of shell deforms like a triangle, which is a higher local mode. And it is significantly observed that, for the three-dimensional base isolation model, its horizontal frequency is almost the same as that of the traditional isolation model, however, its vertical frequency is much smaller that make isolation of facilities and pipes possible.

Table 3.2 Theoretical frequency of scaled models

Theoretical Frequency(Hz)				
Primary Model	Traditional isolation Model		Three-dimensional isolation Model	
Dominated	Horizontal	Vertical	Horizontal	Vertical
30.3	1.2	33.3	1.2	12.3

3.2 Numerical Model

In this part, the shaking table test is examined numerically, by using common finite analysis software, SAP2000 NL(Reference).The numerical model is given in Fig.3.2, consists of rubber isolators and dampers. Four linear links elements are installed in the base isolation layer to simulate performance of the isolators, which using experimental values of shear and compressive stiffness. The compressive stiffness used is obtained when the axis force is 75kN, while the shear stiffness is under 100% shear deformation. By using damper element supplied by the software itself, the liquid viscous dampers used in the shaking table test, which possess a typical kind of nonlinear property, are realized to provide additional damping.

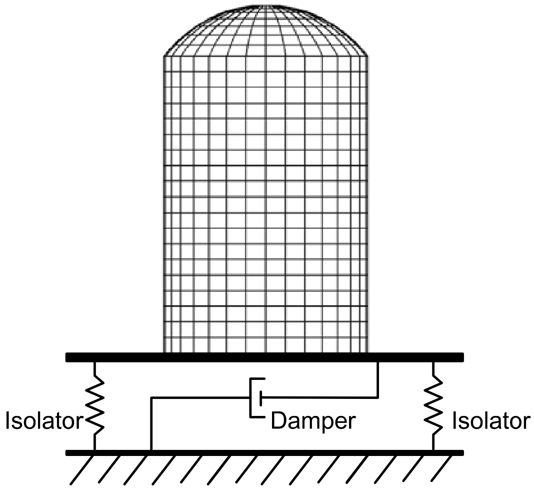


Figure 3.2 Numerical model of base isolation system

3.3 Ground motions for the shaking table tests

Four ground motions applied are El-Centro, Shin-Tokai, Chichi, Fn-tkt, and the response spectrum is given in Fig.3.3. Due to the limited space of paper, only the results of El-Centro and Shin-Tokai are given here. As the Fig.3.3 shows, the dominated frequencies of El-Centro are about 2~5Hz, while that of Shin-Tokai are about 10Hz and 0.3~1Hz. The Shin-Tokai ground motion is recorded from the Tohoku grand earthquake, which is an especially long period ground motion. The ground motion excitation is applied to each scaled model in horizontal and vertical direction, respectively. Based on Chinese Code, the amplitudes applied are selected as 75gal, 150gal and 300gal in horizontal, while vertical amplitude is 2/3 of horizontal amplitude. In shaking table test, the amplitude and time of ground motion are modified by similitude law.

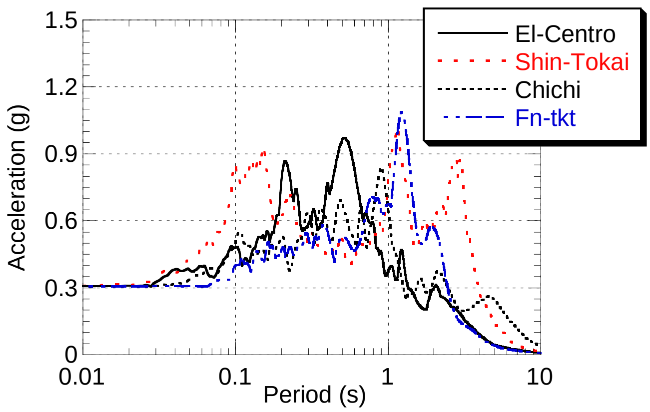


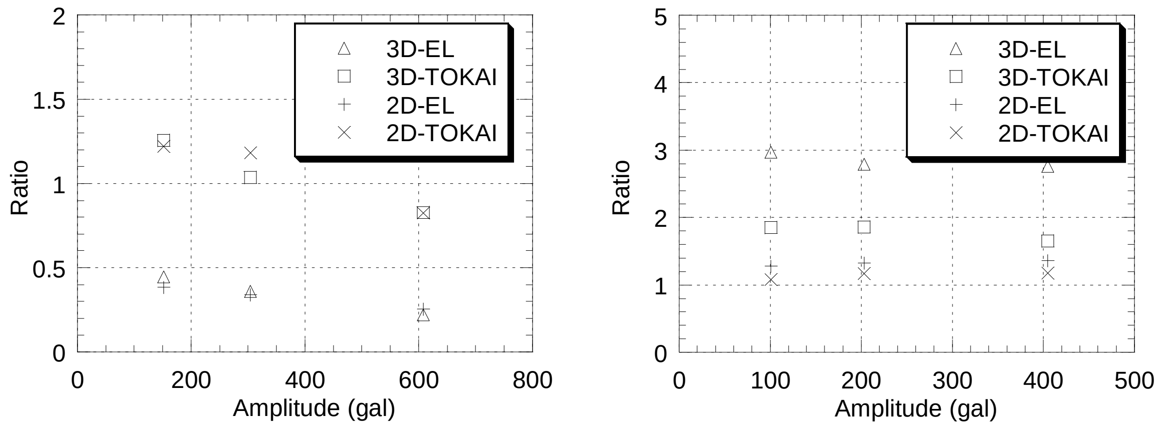
Figure 3.3 Response Spectrum

3.4 Results of Shaking Table Test

In this paper, we take structural displacement and acceleration in horizontal and vertical direction as the significant parameters to verify whether three-dimensional base isolation system is feasible to isolate the facilities and pipes within plants, and reduce the horizontal earthquake inputs efficiently. To measure these structural responses in horizontal and vertical direction, corresponding acceleration sensors are installed on the top of safe shell, while displacement sensors are fixed on base of safe shell. During the shaking table test, 4 types of ground motion mentioned above at the certain scaled amplitude, 152gal, are applied to the three types of structure to detect the difference of structural response caused by types of ground motions. And to verify that at the larger amplitude of ground motion, the three-dimensional base isolation system could exhibit stably, the amplitudes of El-Centro and Shin-Tokai are both increased to 304gal and 608gal.

The results of shaking table tests in time domain are shown in Fig.3.4.1. When taking El-Centro ground motion as the excitation, structural acceleration in horizontal direction of each isolated structure is decreasing sharply, below 50% percents compared to primary structure without any isolation technique, no matter what the amplitude of ground motion is. Meanwhile, for the Shin-Tokai excitation, the structural acceleration is amplified to a certain degree, about 1.2 times, see Fig.3.4.1(a). The traditional base-isolation system, whose vertical frequency is close to the dominated frequency of primary structure, exhibits the similar structural acceleration under excitation of earthquakes. However, for three-dimensional system, which has a smaller vertical stiffness close to dominated frequency of earthquake, the structural acceleration is amplified, about 2 to 3 times shown in Fig.3.4.1(b).

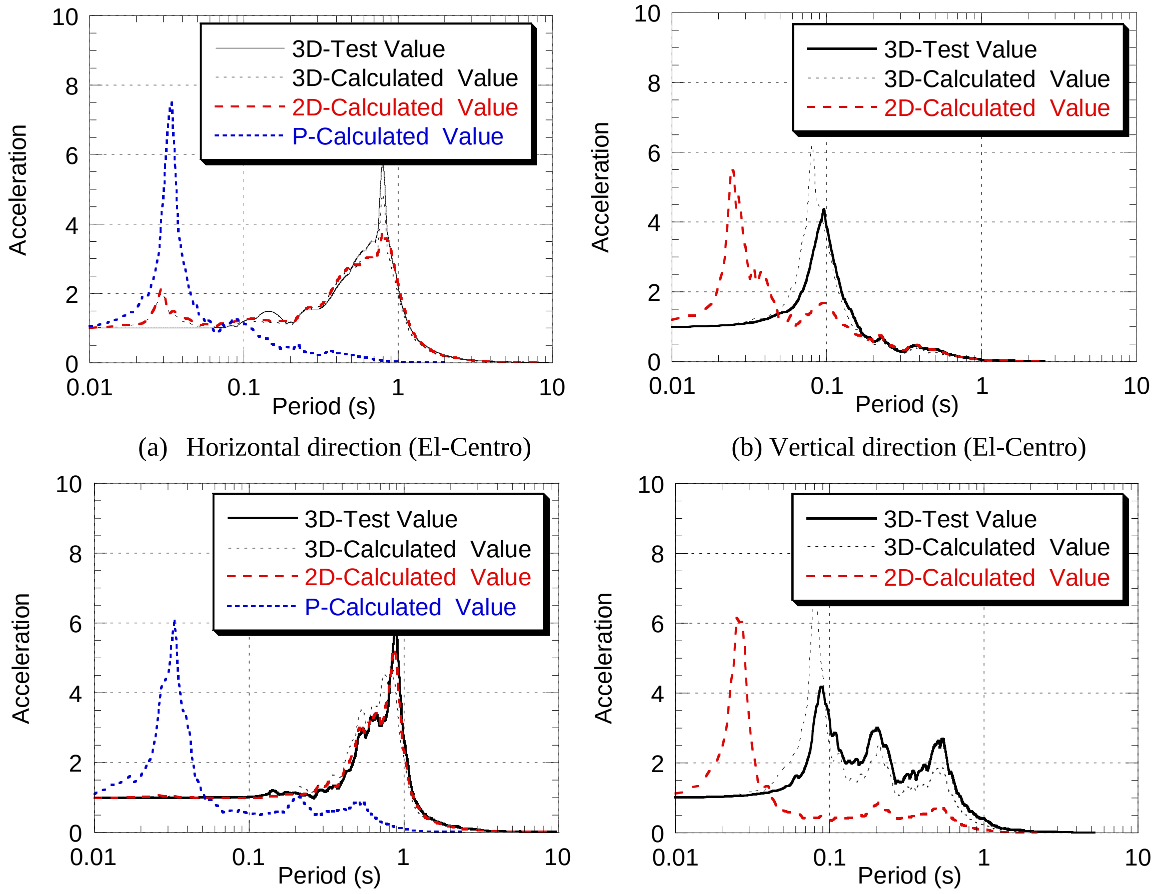
The floor response spectrums contrast includes all three types of structures mentioned above, are obtained from the structural acceleration of the top point of structure by using normalization method, shown in Fig.3.4.2, which illustrate properties of structural response in frequency domain. Due to capacity of shaking table, some load cases are implemented through numerical method. According to contrast of experimental values and calculated values of three-dimensional base system, it is reasonable to convince that the results of numerical analysis could be trusted. And it is not hard to observe from Fig.3.4.1(a),(c) that the horizontal dominated frequencies of these two types of base isolation systems are very close, about 1Hz , and much less than that of primary structure, 30Hz, illustrating that why both two types of base isolation could isolate horizontal earthquake inputs. On the contrary, compared with traditional base isolation system, the dominated frequencies of structural response of three-dimensional base isolation system have been successfully decreased to avoid dominated frequencies of most facilities and pipes within plants, shown in Fig.3.4.2(b),(d), which makes vertical isolation feasible,.



Note: 3D: three-dimensional isolation system; 2D: traditional isolation system;
P: primary isolation system without any isolation technique

(a) Horizontal direction (b) Vertical direction

Figure 3.4.1 Acceleration contrast between isolated structure and primary structure



(a) Horizontal direction (El-Centro) (b) Vertical direction (El-Centro)

(c) Horizontal direction (Shin-Tokai) (d) Vertical direction (Shin-Tokai)

Figure 3.4.2 Floor response spectrum contrast among three different models

4 CONCLUSIONS

1) In contrast to traditional isolation method, the three-dimensional isolation technique could not only reduce horizontal earthquake inputs, but also make it feasible that isolating the facilities in the nuclear power plant verified by shaking table test and numerical analysis.
2) Isolated structure using three-dimensional devices exhibits different performance confront to different earthquake ground motion, which reveals that in the design of nuclear power plants more different ground motion should be considered, especially those are long period ground motion.

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