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EXPERIMENTAL STUDY ON VERTICAL COMPONENT SEISMIC ISOLATION SYSTEM WITH CONED DISK SPRING

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ABSTRACT

In Japan, several kinds of three-dimensional seismic isolation system for next-generation nuclear power plant such as fast reactors have been studied in recent years. We proposed a structural concept of a vertical component isolation system, assuming a building adopting a horizontal base isolation system. In this concept, a reactor vessel and major primary components are suspended from a large common deck supported by isolation devices consisting of large coned disk springs. In order to verify the isolation performance of the vertical component isolation system, 1/8 series of shaking table tests using a scale model were conducted. The test model was composed of 4 vertical isolation devices, common deck and horizontal load suspension system. For the design earthquake, the system smoothly operated, and sufficient isolation characteristics were shown. The simulation analysis results matched well the test results, so the validity of the design technique was able to be verified. As the result, the prospect that the vertical isolation system applied to the FBR plant could technically realize was obtained.

1. INTRODUCTION

Although the horizontal force of an earthquake ground motion is sufficiently reduced by a base isolation system with laminated rubber bearings, the vertical force is transmitted directly. If a three-dimensional isolation were achieved by adding a vertical isolation system, it would substantially enhance plant economy and safety. In order to realize a three-dimensional isolation system, two types of systems can be considered. One is a three-dimensional base isolation system, and the other is a combination of base horizontal isolation and vertical component isolation. In FBR plants, structural problems in which the consideration for vertical motion is required are uplift of fuel assemblies, reactivity change and buckling of reactor vessel. Since vertical isolation coverage can be limited to the area in which a reactor vessel and primary coolant system are installed, we have constructed a structural concept of a vertical component isolation system called “common deck vertical isolation system” [1].

When the vertical isolation system is adopted in individual component separately, the relative displacement will be dynamically taken in the primary coolant system piping, because each response characteristic is different. In order to avoid this problem, a reactor vessel and major primary components are suspended from a large slab structure called “common deck”, and vertical isolation devices are installed between the deck and substructures. Coned disk springs were chosen for spring element of the vertical isolation device. The disk spring can be stacked in various configurations. By stacking the coned disk springs of the same shape in parallel, it is possible to increase support load per one device. By stacking this set more and more in several series, large stroke can be achieved.

We designed the vertical isolation device with coned disk springs and steel beam dampers for FBR plants, which could be achieved vertical isolation frequency of 1Hz and damping ratio of 20%. Full scale coned disk spring and damper performance tests were carried out, and the validity of design method was confirmed [2]. In this paper, a series of shaking table test using a 1/8 scale model of the common deck vertical isolation system is described.

2. OUTLINE OF VERTICAL ISOLATION SYSTEM

2.1 Isolation Device

We designed the vertical isolation device with coned disk springs and steel beam dampers for FBR plants, which could be achieved vertical isolation frequency of 1Hz and damping ratio of 20%.

A coned disk spring for seismic isolation device has following features. 1) The restoring force characteristics show nonlinearity. 2) The effect of the ground end cannot be disregarded. 3) The effect of the friction becomes remarkable, because large number of coned disk is stacked. Considering these features, a single coned disk is designed using the following equation by Curti and Orland [3]. And, the equation of Niepage [4] which can appropriately consider the effect of the friction is also used in the design of the isolation device.

A schematic drawing of the isolation device is shown in Fig.1. The coned disk spring is made of the ordinary high tensile spring steels, Japanese Industrial Standard (JIS) SUP10, which is almost the same as SAE 6150 in USA. Outside diameter of the coned disk was set to be 1m and thickness was set to be 27mm, considering current productivity from the viewpoint of machining and heat treatment. By stacking 5 disks in parallel and 14 sets in series, the isolation device is made up 70 disks in total. The middle washers are inserted between coned disk springs of the serial stack in order to prevent side slip. And, the center guide is installed inside of disks. The unloaded height of a stack becomes about 2.5m. Steel beam dampers with the hysteretic behavior are installed at the upper part of the device. In order to increase the low cycle fatigue strength, a tapering beam damper was designed. It is possible to produce the necessary damping force, when the device was combined with 3 dampers per one device.

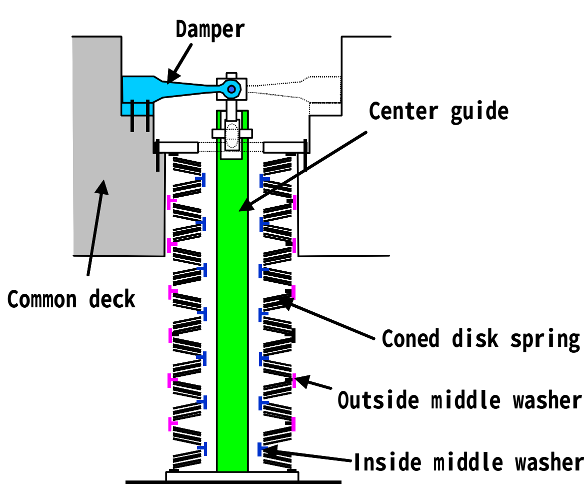


Fig. 1 A schematic drawing of the isolation device

2.2 Plant layout

Application of the common deck isolation system to a 750MWe sodium cooled loop type FBR plant [5] is shown in Fig.2. In this plant, the common deck supports reactor vessel and two integrated components which combined the intermediate heat exchanger with the pump. The deck becomes a rectangle of 32m×12m size. The thickness of the deck is made to be about 2m in order to ensure the necessary rigidity. Total installation weight is about 57MN, and it is supported by 20 isolation devices. Considering weight distribution and rigidity allocation, the isolation device was mainly placed at circumference of reactor vessel and peripheral part of the deck. It is necessary to establish horizontal load support structure such as cantilever column and key for the horizontal seismic load and thermal expansion load.

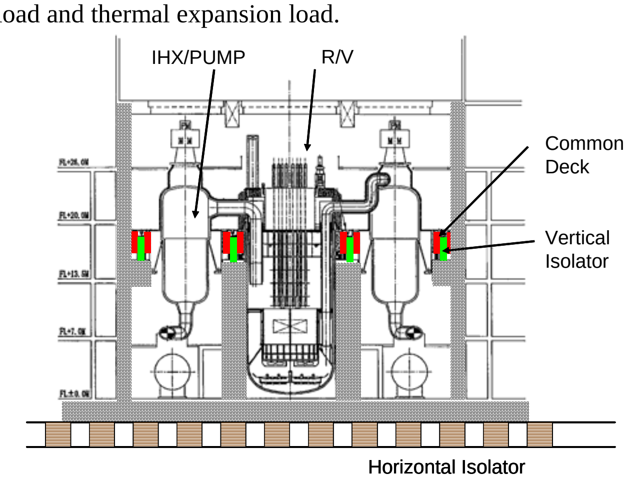


Fig.2 Plant layout

3. SHAKING TABLE TEST

3.1 Test model

Objectives of the shaking table test are to confirm the isolation performance of the proposed isolation system during the earthquake.

The test model was composed of 4 vertical isolation devices, which were reduced at the ratio of the length in 1/8, common deck and horizontal load suspension system. The law of similarity is shown in Table 1, and the dimension of the test model is shown in Tables 2.

Table.1 Law of Similarity

Physical Quantity	Dimension	Test model / Actual system
Length	L	1/n
Time	T	$1/n^{1/2}$
Mass	M	$1/n^2$
Velocity	L/T	$1/n^{1/2}$
Acceleration	L/T^2	1
Stress	$M(L/T^2)/L^2$	1

(n=7.7)

Table.2 Dimension of the test model

Physical Quantity	Actual System	Scale Model
Outside diameter	ϕ1000	ϕ130
Period of coned disk spring	1.1 Hz	2.8 Hz
Support load	2.8MN (5 in parallel)	18.6kN (2 in parallel)

The test model is shown in Fig.3 and Photo 1. The dimension of the common deck model is 1.7m×2.2m. The cylindrical mass, which is modeled a reactor vessel, is in the center of the common deck. The sum total weight of the common deck model and the cylindrical mass is 76.2kN.

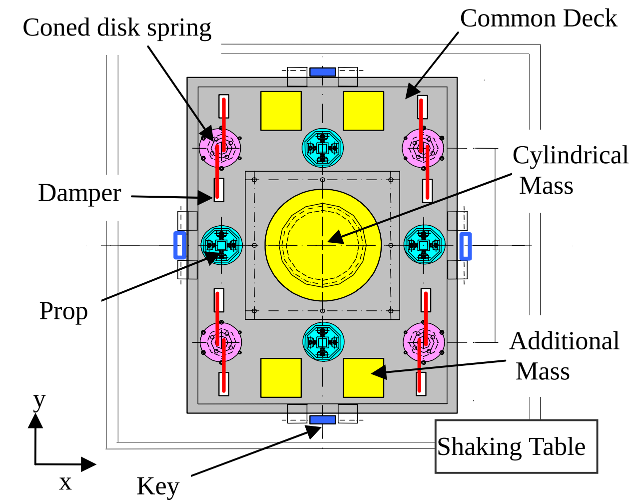


Fig. 3 Model System of This Examination

3.2 Isolation Device

The geometry of single coned disk spring specimen is shown in Fig.4. The coned spring is standard product by press forming. The combination of coned disk springs for the vertical isolation device model is designed to be 2 in parallel and 14 in series, and then one device model consists of 28 disk springs in total. A preassembled disk spring stack is shown in Photo 2. The supporting load per one device is about 20kN.

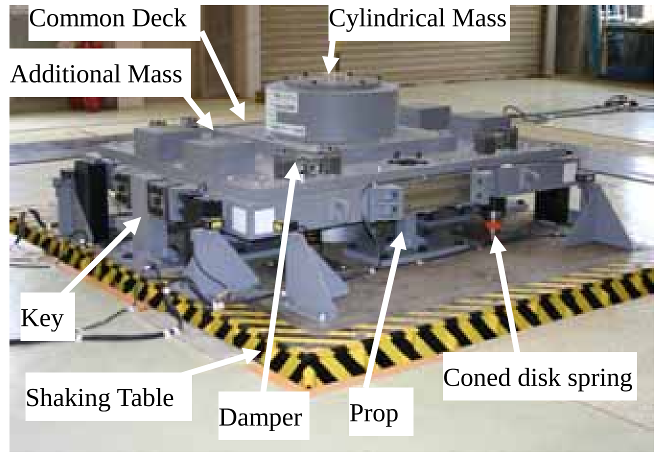


Photo 1 Model system of this examination

The vertical isolation frequency of the devise around the supporting load is set to be 2.8Hz without dampers.

The restoring force characteristics of the devices obtained by static loading tests are shown in Fig.5. The characteristics curve of each device and sum total of four devices are shown in this figure. It was confirmed that there was no variation in characteristics curve of each device. The characteristics curve estimated by design equations is also shown. It was possible to ensure the sufficient design accuracy in the coned springs by press forming.

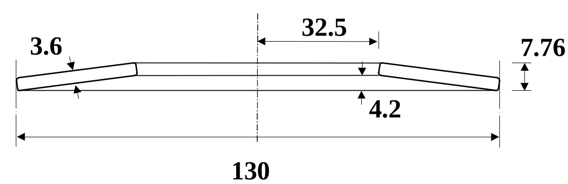


Fig. 4 Geometry of coned disk spring in mm

Photo 2 Coned disk spring

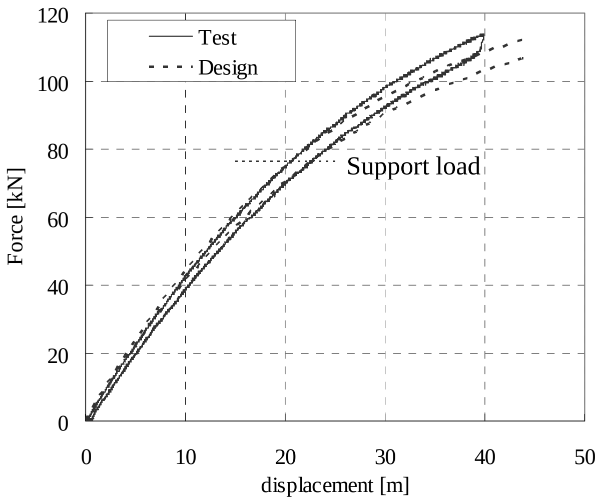


Fig. 5 The characteristics of vertical isolation device

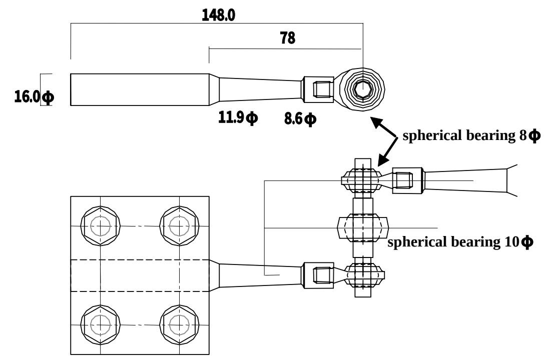


Fig. 6 Geometry of damper

3.3 Damper

The geometry of the damper model is shown in Fig.6. The damper is made of general steel, and it has taper so that stress may become uniform. Photo 3 shows the installation view of the damper. Two dampers are installed in one device. One end of the damper is fixed on the common deck, and the other end is connected to the center guide using a spherical bearing. Two spherical bearings are attached to both end of the guide. As shown in Photo 3, 3 spherical releases the rotation that results form the reducing axial length when the damper deforms.

The damping force was designed considering the law of similarity and parallel number of coned disk spring. The restoring force characteristics of two dampers are shown in Fig.7. From the results of a design analysis, the vertical frequency of the test model increased to 4.5Hz by the stiffness of the damper.

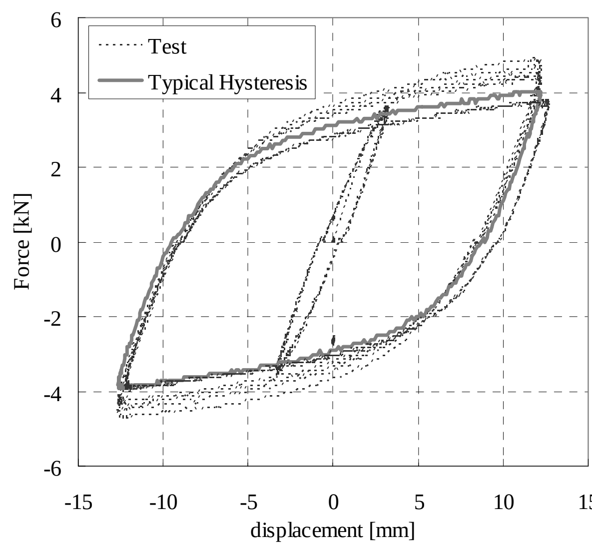


Fig. 7 The characteristics of damper (one unit)

Photo 3 Steel beam damper

3.4 Test Cases

The frequency response characteristics in horizontal and vertical directions of the test model were measured by sine sweep tests. In order to confirm the isolation performance of the isolation system during the earthquake, a series of seismic wave tests was carried out. Test cases are shown in Table 3.

The input seismic wave was set in the following procedures.

1) The design earthquake, named “Case Study S2”, was set for the isolation device development by “The three-dimensional isolation development project in Japan” [6].
2) Response acceleration at the isolation device installation level was evaluated by seismic response analysis of a typical FBR building (Fig.8) for the design earthquake.
3) Time axis of the response acceleration was reduced to 1/2.8 according to the law of similarity. Floor response spectrums are compared in Fig. 9.

Table.3 Test Case

Test Case	direction	Input wave		
Sine Sweep Test	horizontal	Sine	2-60[Hz]	0.45 [m/s^2]
	vertical		2-20[Hz]	0.60 [m/s^2]
				1.20 [m/s^2]
				2.40 [m/s^2]
Seismic Wave Test	horizontal and vertical	0.67 times seismic wave		
		seismic wave		
		1.5 times seismic wave		

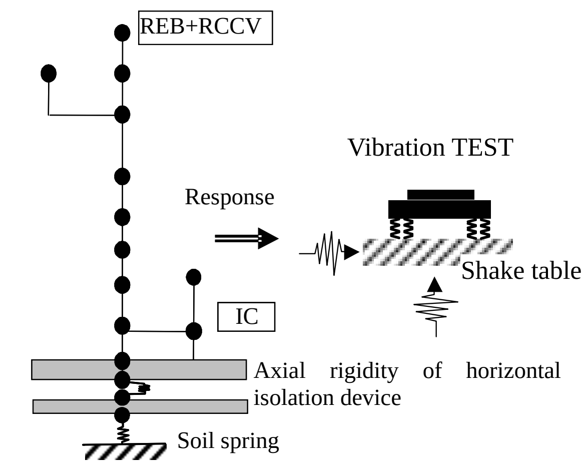
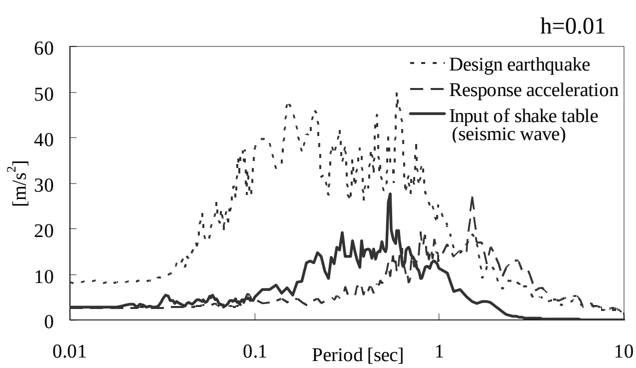
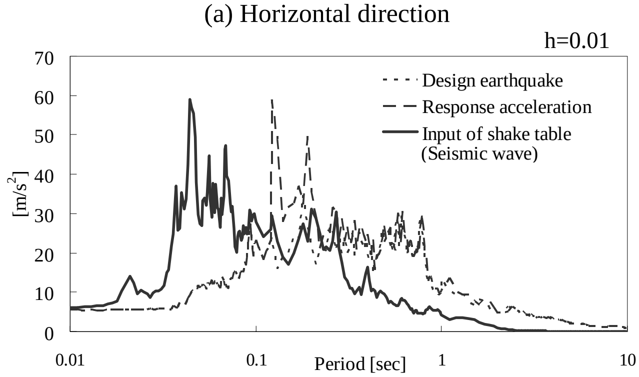


Fig.8 Analysis model of FBR building



(a) Horizontal direction

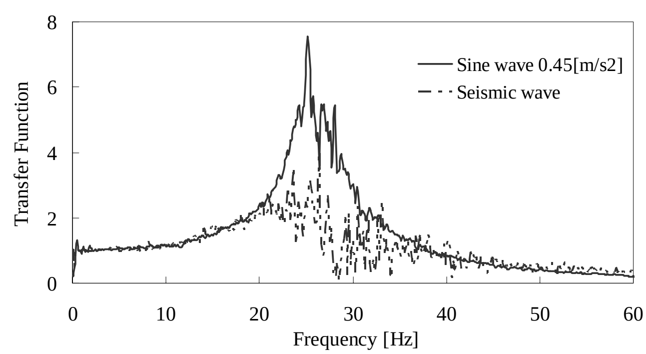


(b) Vertical direction

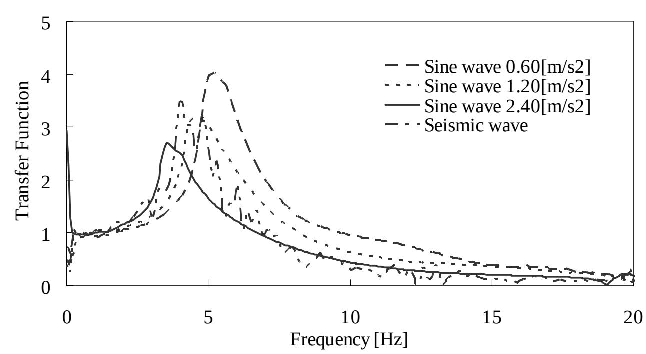
Fig.9 Floor response spectrum of input wave.

3.5 Frequency Response Performance

The transfer functions obtained by the sine sweep tests are shown in Fig.10. The horizontal dominant frequency of the test model is about 25Hz, which is determined by the total stiffness of the horizontal load support structures. The vertical resonance frequency is about 3.5Hz, 4.5Hz, 5.0Hz at input level 0.60m/s^2, 1.20m/s^2, 2.40m/s^2 respectively. As the input level increases, the vertical frequency increases, because the characteristic of the isolation device which consists coned disk springs and steel dampers have the softening property. In Fig.10, frequency response performance curve obtained by the seismic wave test is also plotted. In this case, vertical resonance frequency becomes about 4.8Hz, and almost the same as the design value 4.5Hz. Damping ratio obtained by the curve fitting method using the transfer function of the seismic wave test is about 20%, which is well consistent with the design value. Therefore, it can be judged that the design method of the vertical isolation device was appropriate.



(a) Horizontal direction

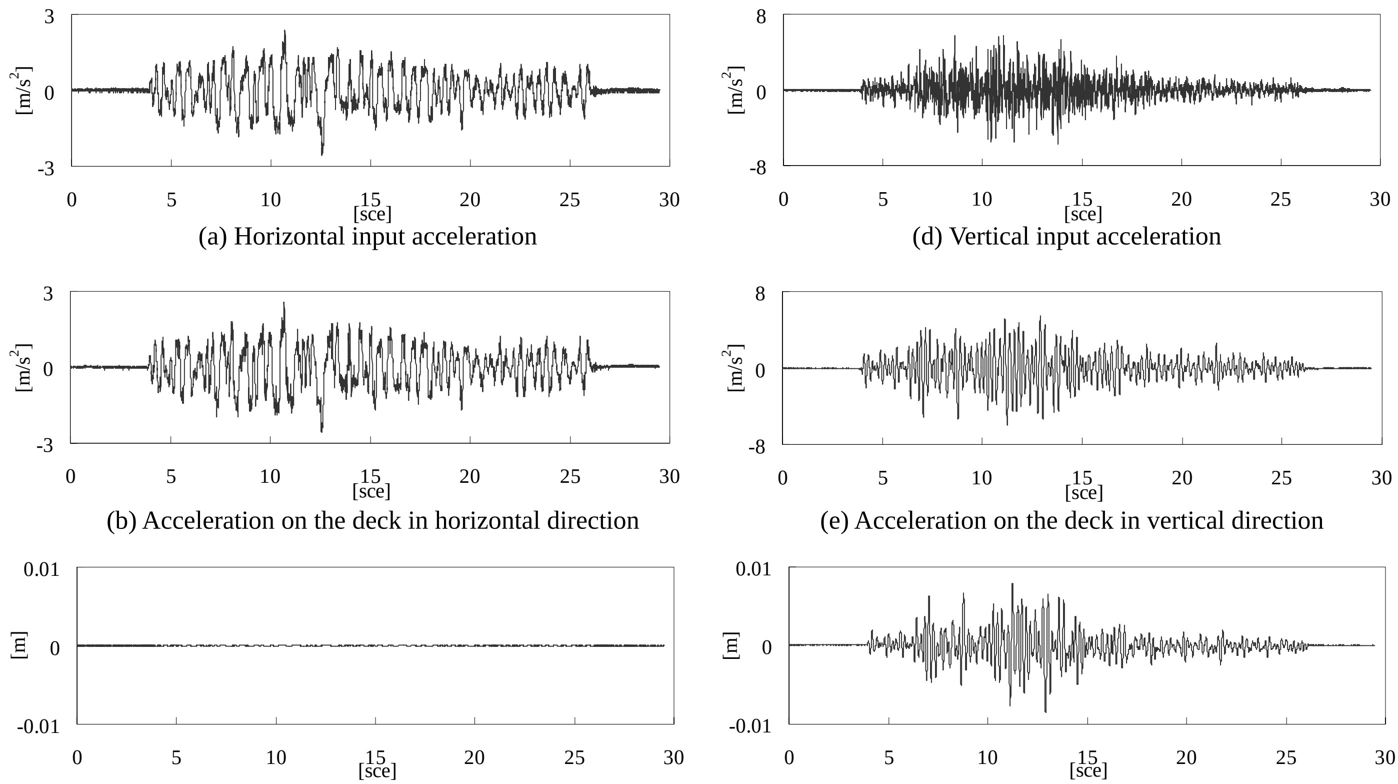


(b) Vertical direction

Fig.10 Transfer functions in Sweep Test

3.6 Seismic Wave Test

Seismic wave tests were carried out using the seismic wave in several times, it was confirmed that the system smoothly responded. The typical results of the seismic wave test are shown in Fig.11. In the figure, the acceleration of the



(a) Horizontal input acceleration

(d) Vertical input acceleration

(b) Acceleration on the deck in horizontal direction

(e) Acceleration on the deck in vertical direction

(c) Relative displacement of the deck in horizontal direction

(f) Relative displacement of the deck in vertical direction

Fig. 11 Time histories of seismic wave test

center of common deck, the displacements of common deck in horizontal and vertical directions are shown.

In horizontal direction, there is no difference between the input and the response acceleration. Relative displacement between the common deck and the shaking table is very small. Therefore, it was confirmed that the horizontal load supporting systems sufficiently supported the horizontal seismic load.

In vertical direction, we can see the high frequency component has faded away from the waveform of the response acceleration. Maximum value of the response acceleration is almost the same as that of the input. Maximum value of the response displacement is about 9mm.

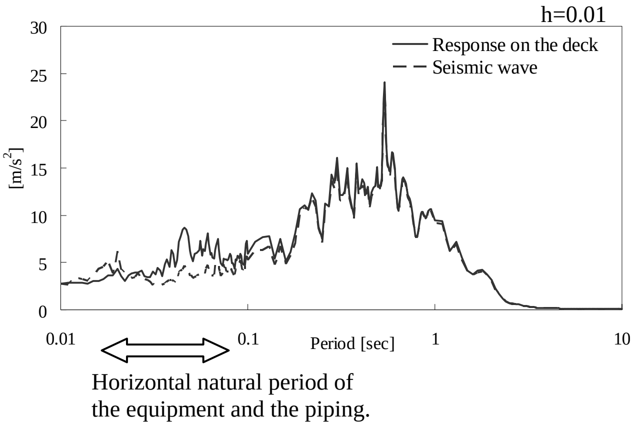
Fig. 12 shows the Floor Response Spectra (FRS) at the center of common deck for each input level, comparing with the seismic wave. The parts of the arrow in these figures are natural period band, reduced by the law of similarity, of the main equipment and piping. Though the FRS in horizontal direction is amplified a little near 0.04sec of the natural period of horizontal support systems, the FRS of the seismic wave test is less than the value of acceleration criteria on equipment design of 9.8m/s^2.

The vertical isolation performance was confirmed, because the FRS around natural period band of the main equipment and piping was sufficiently reduced.

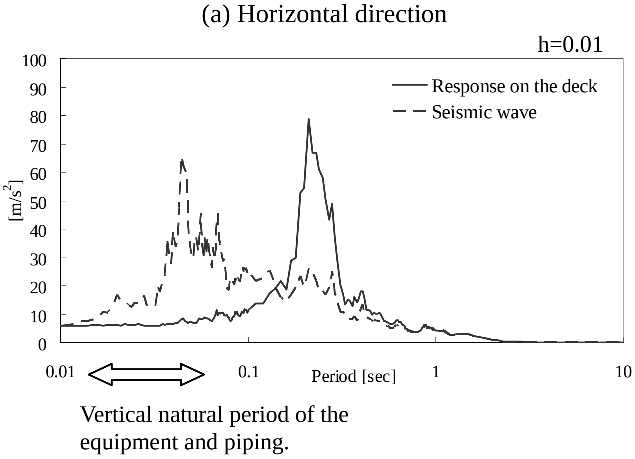
4. SIMULATION ANALYSIS

4.1 Analysis Model

Simulation analysis of the test model was conducted. The analysis model is shown the Fig.13. In horizontal direction, analysis model is two-degrees-of-freedom with two-mass model which consists of the common deck and the cylindrical mass. Two nodes are connected by the beam element which has equivalent bending stiffness of the cylindrical mass. The stiffness of the horizontal supporting system is considered. In vertical direction, analysis model is single-degree-of-freedom model. The restoring force characteristics of the coned disk spring and the damper were used the measured results of Fig.3 and Fig.5, respectively.

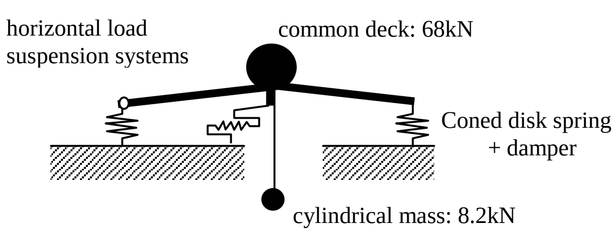


(a) Horizontal direction

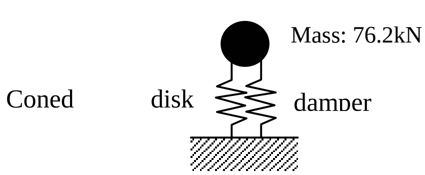


(b) Vertical direction

Fig.12 Floor response spectra of seismic wave test

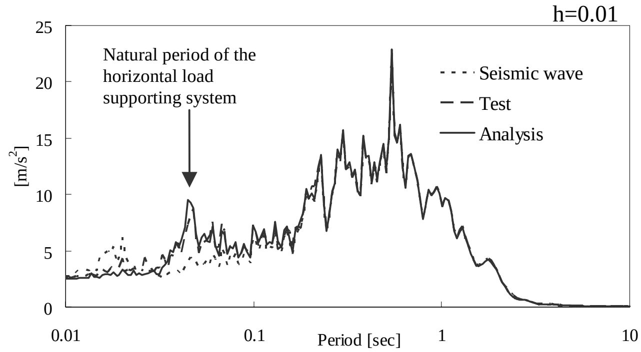


(a) Horizontal analysis model

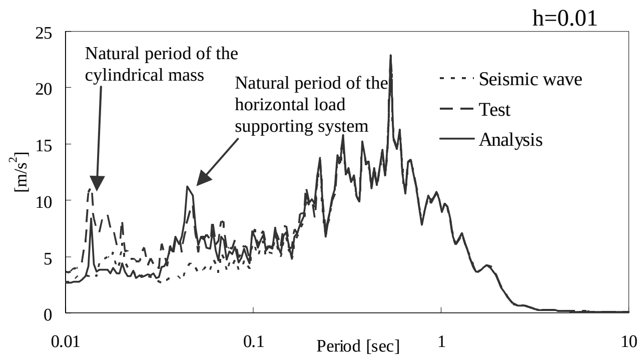


(b) Vertical analysis model

Fig.13 Analysis model



(a) Center of common deck



(b) Cylindrical mass

Fig.14 Comparison of floor response spectra in horizontal direction

4.2 Result of Analysis

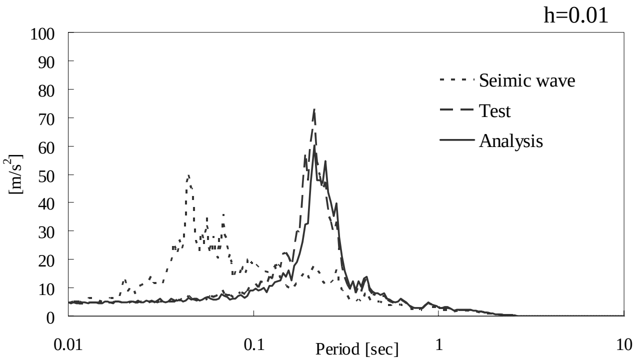
Fig.14 and Fig.15 show the comparison of FRS between analysis and tests results in horizontal and vertical directions, respectively. In horizontal direction, FRS increases at about 0.04sec (25Hz) which is a natural period of the horizontal load supporting system in comparison with the seismic wave. In FRS of cylindrical mass, FRS increases at about 0.014sec (71.4Hz) which is a natural period of the cylindrical mass.

The analysis is similar to the test results in both directions. Therefore, it was confirmed that this analysis method is applicable to the response estimation for the common deck isolation system.

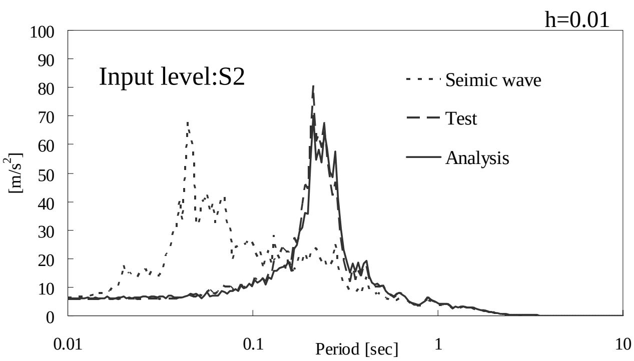
The comparison of load-displacement relationships of the vertical isolation device for the seismic wave is shown in Fig.16. In this figure, the load is sum total of four isolation devices.

5. CONCLUSION

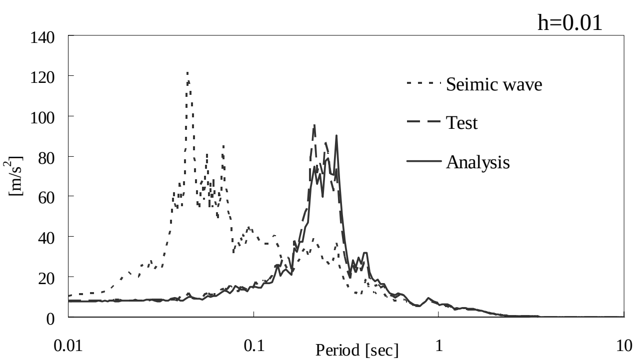
The shaking table test using 1/8 scale model of the common deck isolation system was carried out. The characteristics in horizontal and vertical direction of the test model were grasped, and it was confirmed that isolation performance of the proposed isolation system during the earthquakes. As the result, the prospect that the vertical component isolation system applied to the FBR plant could technically realize was obtained.



(a) The 0.67 times the seismic wave input



(b) The seismic wave input



(c) The 1.5 times the seismic wave input

Fig.15 Comparison of floor response spectra in vertical direction

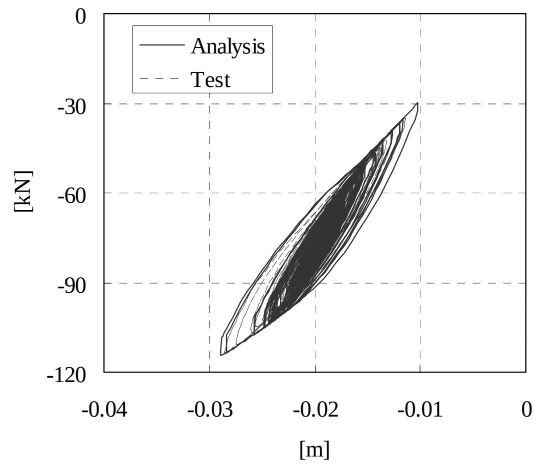


Fig.16 Load-displacement curve at input seismic wave

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