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# A study of vertical seismic responses for base isolated PWR using high damping rubber bearing

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## ABSTRACT

Time history analyses of a base isolated Pressurized Water Reactor(PWR) building with high damping rubber bearings as isolator are performed to evaluate seismic responses for two earthquakes. While the horizontal acceleration responses in base isolated superstructure are much smaller than those in fixed base structure, the vertical accelerations of the superstructure are amplified to some extent. Sensitivity study to reduce vertical responses at superstructure is carried out by manipulating the vertical stiffness and damping of isolation system.

## 1. INTRODUCTION

The seismic isolation systems used for the reduction of the seismic response of the structures are now practically applied in Japan, USA, New Zealand, Italy, China, etc. where large earthquakes are occurred. In Korea a seismic isolation system was applied for LNG tanks, and authors have studied to establish the seismic isolation design for nuclear facilities[1,2]. Horizontal seismic base isolation system is excellent to reduce the horizontal seismic responses but likely tends to amplify the vertical responses[3]. To resolve the problem some ideas for vertical isolation systems[4,5,6] have been suggested such as helical springs and viscodampers, air springs and horizontal rubber bearings, multicomponent low frequency system. Since high damping laminated rubber bearing(HLRB) has a comparably large damping, the accelerations in superstructure are remarkably reduced in horizontal direction[1,2,3]. However the vertical stiffness of HLRB to transmit vertical load is relatively larger than horizontal one, the seismic responses in vertical direction are likely to be amplified. Thus vertical behavior of HLRB on seismic responses of superstructure should be evaluated.

In this paper, simplified linear two DOF isolation system are studied and time history analyses for a typical PWR superstructure with a HLRB isolation system are performed to understand the effects on the seismic responses in superstructures and the results are compared to fixed base model. Sensitivity study to reduce the vertical responses at the superstructure is carried out by manipulating the vertical stiffness and damping of isolation system. Vertical isolation system with soft stiffness and high damping may meet the tentatively proposed vertical isolation criteria that requires the vertical acceleration response at the critical support of the superstructure be not larger than zero period acceleration(ZPA) of input motion.

## 2. STRUCTURAL MODEL

The model for isolated PWR containment structure used in the analysis is shown in Fig.1. The isolated system considered in this paper consists of the isolator, base mat and the superstructure (containment vessel part and internal structure part). The computer program used in analysis is ABAQUS version 5.5[7].

In the model, the nodes from 1 to 10 represent the containment part and the nodes from 11 to 17 represent internal structure part. The nodes 18, 7 and 11 represent the base mat, the polar crane support and the reactor vessel support respectively. The total weight of the superstructure is about 68,000 tons. The structural damping of the superstructure is assumed to be material damping with 5% damping ratio for all modes.

Fig.2 shows the shear cycle test results of the HLRB, which is scaled down 1/8 size. In modeling of the isolator which has severe hardening characteristics in large strain region, a non-linear spring model with an equivalent viscous damping should be applied. However, the shear deformation predicted in the analysis is much smaller than 150% shear strain up to which is assumed to be linear, we can use an equivalent linear spring model for horizontal direction as follow:

Kh = 0.6887 x 10E6 Kgf/cm.

The Kh is determined by an equivalent stiffness that is resonated at 0.5Hz in horizontal direction. The vertical stiffness of isolator is designed to resonate at 21 Hz as follow:

Kv = 1214.9 x 10E6 Kgf/cm.

The vertical stiffness is assumed to be in compression state because it always resists total structure weight. The viscous damping values of the isolator used for the numerical simulations are 12% for horizontal direction, and 12%, 5%, and 0% for vertical one.

## 3. DYNAMIC CHARACTERISTICS OF SUPERSTRUCTURE

In horizontal direction, the fundamental frequencies of the containment building and internal structures for fixed base are 5.39 Hz and 15.73 Hz respectively, and for base isolated system are 5.94 Hz and 16.17 Hz respectively. The horizontal isolated frequency of the isolation system is 0.5 Hz. Fig.3 shows the first seven modes of the base isolated model in horizontal and vertical directions.

In vertical direction, the fundamental frequencies of the containment vessel and internal structures for fixed base are 12.15 Hz and 26.8 Hz respectively, and for base isolated system are 11.42 Hz and 27.95 Hz respectively, and the vertical natural frequency of the isolation system is 21Hz. Table 1 and Table 2 show the several frequencies of the models.

## 4. EFFECTS OF ISOLATOR ON STRUCTURAL RESPONSES UNDER EARTHQUAKES

### *4.1 Linear Two DOF Isolation System Study*

To investigate the role of isolation frequency and damping on the seismic responses, we introduced 2 degrees of freedom system simulating the PWR superstructure that is isolated and applied white noise input, and two structural frequencies, 5Hz and 15Hz are considered. Several mass ratios that are effective masses of each mode divided by the effective isolation mass are taken into account in this analysis. As increasing of isolation frequency as shown in Fig. 4, the acceleration response ratios between isolated and fixed base structure of this 2 DOF structure with 12% isolation viscous damping are increased monotonously, but the relative displacement response ratio is decreased asymptotically. The acceleration response ratios of 2 DOF structure isolated with 0.5Hz are reduced as increase of the isolation damping values as shown in Fig. 5.

### *4.2 Effects of Isolators on PWR Seismic Responses*

The isolated system is assumed to be subjected to horizontal and vertical component of 1940 El Centro earthquake and artificial one compatible to USNRC RG1.60 design response spectra as shown in Fig. 6. The effects of the isolator on the superstructure responses are investigated by using the numerical simulations.

In Table 3 the horizontal ZPAs at the superstructure for the isolated system, which represents rigid body motion, are remarkably reduced to 0.125g at reactor support and 0.13g at polar crane support when it is subjected to peak ground acceleration(PGA) of 0.34g horizontal El Centro earthquake(NS). It is noteworthy that the acceleration at the crane support for the fixed base system is 0.97g and that at reactor support is 0.34g respectively. In case of SSE 0.3g artificial one the horizontal ZPAs at the superstructure for the isolated system are also reduced to 0.172g at reactor support and 0.179g at polar crane support from 0.38g and 1.24g in fixed base model.

The vertical seismic responses of superstructure with horizontal isolator subjected to PGA of 0.2g vertical El Centro earthquake and SSE of 0.21g vertical artificial one are represented in Table 4. The vertical ZPAs at the superstructure for the isolated system without vertical isolator are increased to 1.0g and 0.7g at polar crane support while those for the fixed base system are 0.81g and 0.61g respectively. Since high vertical stiffness of horizontal isolator has vertical natural frequency as 21 Hz which cannot make the participation factor of the first superstructure mode lower. Hence the vertical response of the structure cannot be reduced but amplified with this high vertical stiffness of isolator because the first vertical superstructure mode corresponds to the high spectral value of the vertical input motions.

In order to reduce the vertical response of the superstructure, the several analyses are performed by changing the vertical stiffnesses for the natural frequency of the vertical isolation system to be in the frequency range of 5 Hz to 1 Hz. The results are summarized in Table 5 & 6, and Fig. 7 & 8. Under these softer stiffnesses the vertical ZPA varies depending on the seismic input types, isolator damping values and superstructure dynamic characteristic features. The higher damping is effective to reduce the acceleration and displacement responses, but the vertical damping device is not easily available. So the soft stiffness is another choice to reduce the acceleration, but it is important to consider the seismic input spectrum and the first frequency of superstructure because the vertical isolation frequency around of 5Hz under the artificial seismic input amplifies their vertical responses as shown in Fig. 8. On the contrary softening of vertical isolation frequency, lower than fundamental frequency of structure, always reduces the acceleration responses as verified in two DOF isolation system study.

We suggest the isolation criteria that the acceleration response at the critical support of superstructure be at least not larger than ZPA of input motion. Horizontal isolation system with high damping rubber bearing currently developed is effective in reducing horizontal seismic responses but amplifies vertical seismic responses. Based upon the results of sensitivity study as shown in the Table 5 & 6, as the vertical isolation frequency is lowered to 5 Hz from 21 Hz which is the vertical natural frequency of horizontal isolation system, the acceleration responses at the superstructure are decreased, but are not so sufficiently reduced to satisfy the requirements. If we reduce the isolation frequency less than 1 Hz or 2 Hz and increase the damping of vertical isolation system more than 5%, we may obtain the vertical seismic responses which meet the criteria.

Meanwhile the vertical displacement is increased as we lower the frequency of vertical isolation system and is decreased as we enlarge the damping of vertical isolation system.
Now we are developing 3 dimensional isolation system which can reduce the horizontal acceleration responses as well as the vertical ones under the following considerations for implementation of proper 3D isolation; 1) integral isolator with function of both horizontal and vertical isolation, 2) need to decouple the vertical and horizontal isolation roles, 3) need to be passive system.

## 5. CONCLUSIONS

The acceleration responses in base isolated PWR superstructure with HLRB isolator subjected to 1940 El Centro earthquakes and artificial ones compatible to USNRC RG 1.60 spectra are much smaller than those in fixed base superstructure in horizontal direction. But the vertical acceleration responses are larger than those in fixed base superstructure. Tentative vertical isolation criteria which requires that acceleration responses at the critical support of superstructure in this case at the reactor support be not larger than ZPA of input motion is proposed. Vertical seismic isolation with the reduced vertical stiffness and large damping of isolator is more effective in reducing the vertical seismic responses. In the base isolated system, the seismic acceleration responses at flexible structure are much more reduced than those at stiff structure.

The further researches to implement the vertical isolation design for the reduction of vertical seismic responses, and to study the rocking behavior induced by vertical flexibility are needed.

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Table 1. Horizontal Natural Frequencies of PWR Reference Plant

| | Fixed base | | | Horizontal isolator with 0.5 Hz | | |
|---|---|---|---|---|---|---|
| Mode No | Frequency (Hz) | Parti. factor | Effect. Mass (kg) | Frequency (Hz) | Parti. factor | Effect. Mass (kg) |
| 1 | 5.386 | 1.470 | 15.11E06 | 0.5* | 1.0106 | 68.34E6 |
| 2 | 15.73 | 1.532 | 14.43E06 | 5.94 | -0.0112 | 942.0 |
| 3 | 16.24 | -0.452 | 1.926E06 | 16.17 | -0.0001 | 0.257 |
| 4 | 22.38 | 0.246 | 3.370E06 | 17.77 | -0.0012 | 16.36 |
| 5 | 30.68 | -0.391 | 0.657E06 | 23.76 | -0.0003 | 3.568 |

* : Horizontal Isolation Frequency of Horizontal Isolator

Table 2. Vertical Natural Frequencies of PWR Reference Plant

| | Fixed base | | | Vertical(21Hz)* | | | Vert. Isolator with 5.0Hz | | |
|---|---|---|---|---|---|---|---|---|---|
| Mode No. | Freq. (Hz) | Parti. Factor | Effect. mass | Freq. (Hz) | Parti. factor | Effect. mass | Freq. (Hz) | Parti. factor | Effect. mass |
| 1 | 12.15 | 1.511 | 20.91E6 | 11.42 | 1.778 | 33.23E6 | 4.85** | 1.180 | 67.85E6 |
| 2 | 26.80 | -0.719 | 4.246E6 | 22.0* | -1.227 | 29.39E6 | 14.68 | -0.201 | 0.392E6 |
| 3 | 32.20 | 1.323 | 15.53E6 | 27.95 | 0.382 | 1.766E6 | 27.52 | 0.002 | 2990.0 |

*  : Vertical Frequency of Horizontal Isolator

** : Vertical Isolation Frequency of Vertical Isolator

Table 3. Horizontal Responses under El Centro(0.34g) and Artificial Time History(0.3g)

| Input Motion | El Centro(NS) | | | Artificial time history of USNRC | | |
|---|---|---|---|---|---|---|
| Isolator frequency | Fixed | 0.5 Hz | | Fixed | 0.5 Hz | |
| Viscous damping | - | 12% | 0% | - | 12% | 0% |
| RV support(g) | 0.340 | 0.125 | 0.172 | 0.383 | 0.172 | 0.272 |
| Polar crane(g) | 0.970 | 0.130 | 0.182 | 1.244 | 0.179 | 0.273 |
| Isolator displ.(cm) | - | 12.8 | 17.9 | - | 19.8 | 30.8 |

Table 4. Vertical Responses under El Centro(0.2g) and Artificial Time History(0.21g)

| Input Motion | El Centro(Vertical) | | | | | Artificial time history(Vertical) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Isolator frequency | Fixed | 21 Hz | | | | Fixed | 21 Hz | | | |
| Viscous damping | | 25% | 12% | 5% | 0% | | 25% | 12% | 5% | 0% |
| RV support(g) | 0.328 | 0.387 | 0.462 | 0.511 | 0.551 | 0.216 | 0.260 | 0.287 | 0.304 | 0.319 |
| Polar crane(g) | 0.806 | 0.841 | 0.904 | 0.954 | 1.00 | 0.605 | 0.620 | 0.651 | 0.662 | 0.700 |
| Isolator displ.(cm) | - | 0.025 | 0.027 | 0.028 | 0.030 | - | 0.018 | 0.021 | 0.021 | 0.021 |

Table 5. Vertical Responses of EL Centro Vertical Seismic Input(0.2g)

| | | Vertical isolation frequency | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Isolation frequency | Fixed base | 5 Hz | | | 2Hz | | | 1Hz | | |
| Viscous damping | | 12% | 5% | 0% | 12% | 5% | 0% | 12% | 5% | 0% |
| RV support(g) | 0.328 | 0.216 | 0.292 | 0.444 | 0.132 | 0.151 | 0.228 | 0.036 | 0.050 | 0.084 |
| Polar crane(g) | 0.806 | 0.274 | 0.367 | 0.532 | 0.134 | 0.150 | 0.233 | 0.040 | 0.051 | 0.084 |
| Upper base(g) | 0.210 | 0.209 | 0.287 | 0.438 | 0.132 | 0.151 | 0.227 | 0.036 | 0.050 | 0.084 |
| Isolator displ.(cm) | - | 0.220 | 0.309 | 0.466 | 0.786 | 0.930 | 1.42 | 0.878 | 1.232 | 2.11 |

Table 6. Vertical Seismic Responses of an Artificial Time History USNRC Vertical Input(0.21g)

| | | Vertical isolation frequency | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Isolation frequency | Fixed base | 5 Hz | | | 2Hz | | | 1Hz | | |
| Viscous damping | | 12% | 5% | 0% | 12% | 5% | 0% | 12% | 5% | 0% |
| RV support(g) | 0.216 | 0.383 | 0.543 | 1.322 | 0.270 | 0.399 | 0.625 | 0.150 | 0.191 | 0.303 |
| Polar crane(g) | 0.605 | 0.446 | 0.619 | 1.497 | 0.280 | 0.414 | 0.641 | 0.150 | 0.193 | 0.305 |
| Upper base(g) | 0.208 | 0.379 | 0.536 | 1.303 | 0.269 | 0.398 | 0.624 | 0.150 | 0.191 | 0.303 |
| Isolator displ.(cm) | - | 0.393 | 0.561 | 1.369 | 1.636 | 2.488 | 3.905 | 3.487 | 4.79 | 7.518 |

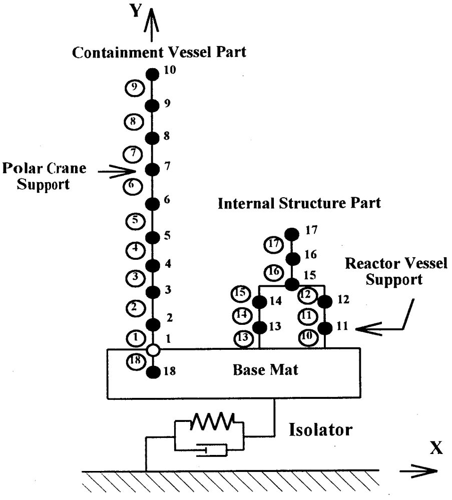

Fig. 1 Model of PWR Reference Plant

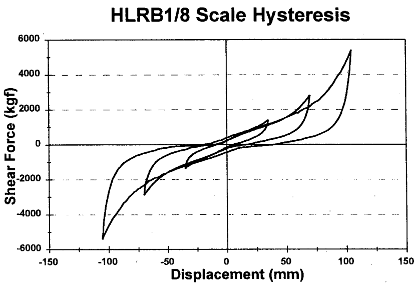

Fig. 2 Hysteretic Curve of 1/8 Scale HLRB

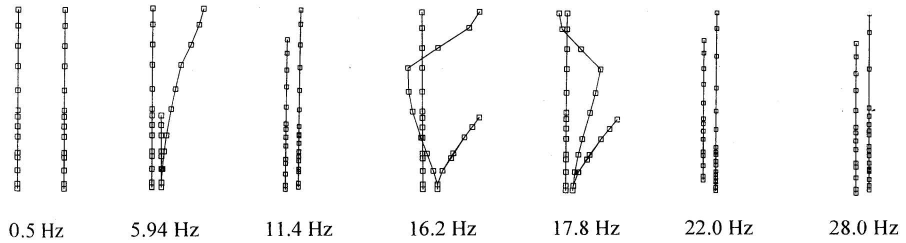

Fig. 3 Mode Shapes of Superstructure Base-Isolated with 0.5 Hz

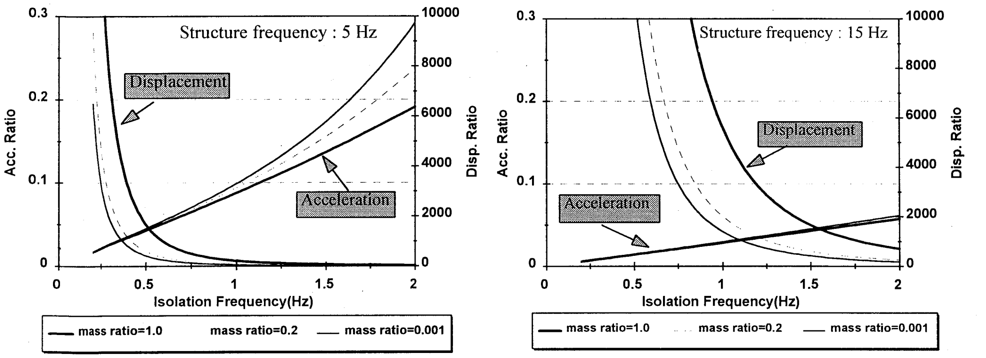

Fig. 4 2 DOF Superstructure Responses with Isolation Frequency
( Isolator Viscous Damping: 12%)

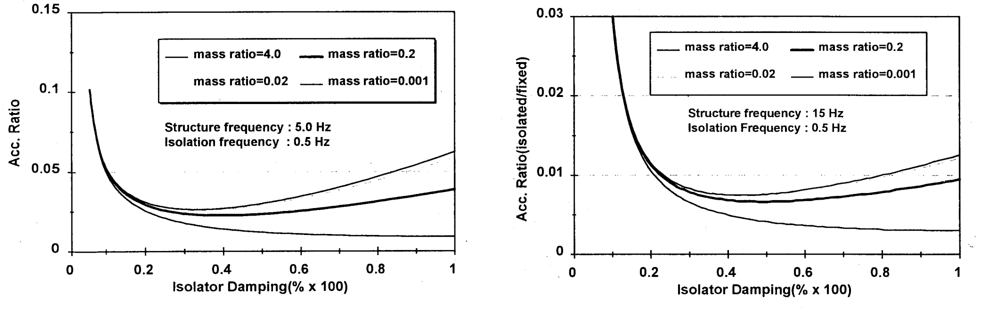

Fig. 5 2 DOF Superstructure Responses with Isolator Damping

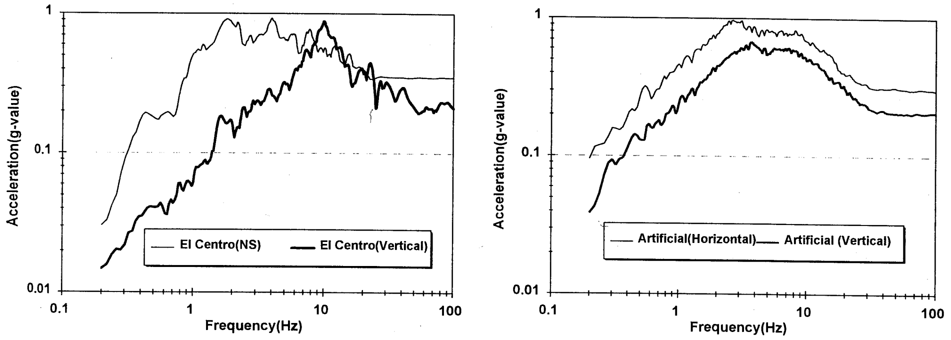

Fig. 6 Acceleration Input Spectra of 1940 El Centro and Artificial Earthquakes

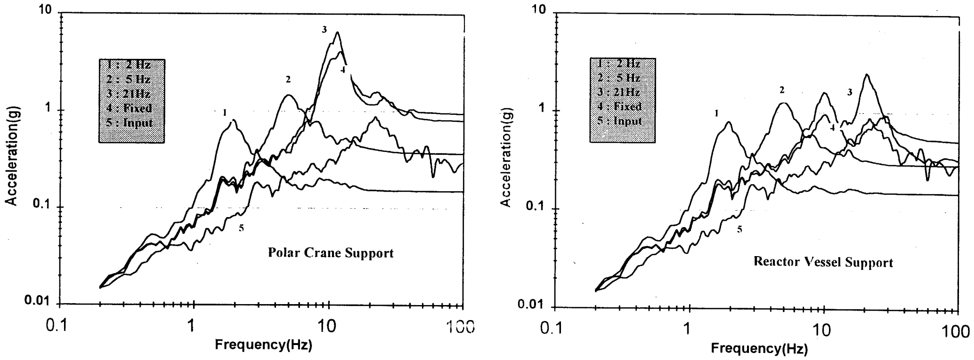

Fig. 7 Vertical Acceleration Response of Superstructure under El Centro Earthquake

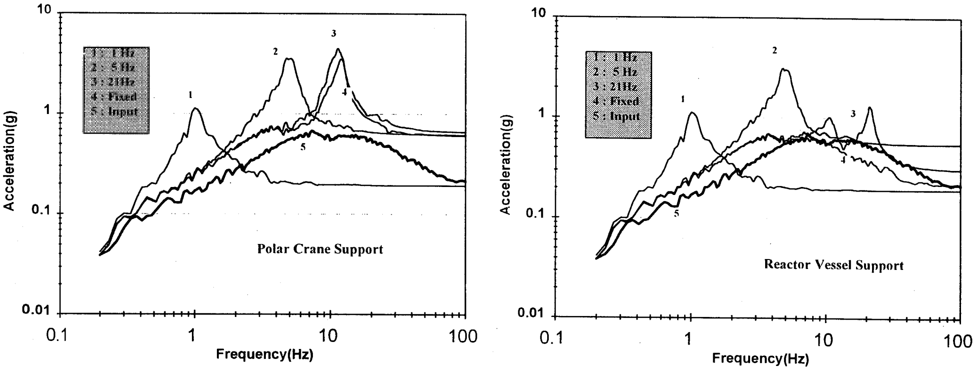

Fig. 8 Vertical Acceleration Response of Superstructure under Artificial Earthquake