Effect of Foundation Embedment of PWR Structures in SSI Analysis considering Spatial Incoherence of Ground Motions

Joo-Hyung Kang[1] and Sang-Hoon Lee[2]

[1] *Junior Engineer, Civil Engineering Department, Korea Power Engineering Co., Inc., Yongin, Korea*
[2] *Senior Engineer, Civil Engineering Department, Korea Power Engineering Co., Inc., Yongin, Korea*
Email: frame365@kopec.co.kr, shljrl@kopec.co.kr

ABSTRACT:

Seismic response at large foundation caused by strong ground motion has tendency to be less intense than the corresponding free-field motion. This phenomenon, called as base-slab averaging effect or wave incoherence effect, can be explained that the spatial variations in the free-field motion are constrained by stiffness of the foundation within its footprint. Several approaches have been developed to consider the incoherence of ground motion as part of soil-structure interaction (SSI) analysis. However, most of them are based on the assumption of massless rigid foundation, or their applications are restricted to the simple surface structures. This paper presents parametric studies on the effect of foundation embedment in SSI analysis to incorporate spatial incoherence of seismic ground motion, and evaluates its feasibility on practical pressurized water reactor (PWR) structures. In addition, engineering application guidelines and further considerations including rocking and torsion are described.

KEYWORDS: Spatial Variation, Wave Incoherence, Coherency Function, Foundation Embedment

1. INTRODUCTION

Many strong earthquake recordings show the response motions at building foundations to be less intense than the corresponding free-field motions. To explain these phenomena as part of soil-structure interaction (SSI) effects, the concept of spatial variation, or wave incoherence was introduced. Approaches ranging from simplified to rigorous - such as spectrum reduction factor, ratio of response spectrum, wave coherency function - have been developed to account for these effects and apply them to practical analysis and design of structures. However, most of these approaches contain site-specific considerations or assumptions of massless rigid foundation. In addition, most of them deal with surface structures, and there are few results related with foundation embedment.

This paper is focused on the embedded pressurized water reactor (PWR) structures, and describes the effect of foundation embedment by parametric case studies. For this purpose, a simple PWR containment building model is developed and it is placed on a typical ground site. Also an earthquake motion set is prepared and used as input motion according to various embedment depths. From SSI analyses ignoring and considering the wave incoherence, this study presents the influence of foundation embedment on the coherence and incoherence behavior. Furthermore, engineering application guidelines and limits are described.

2. COHERENCY FUNCTION

The spatial variation of ground motions can be quantified by spatial coherency. Based on the assumption that the ground motions can be represented by a stationary random process, the coherency function is defined by the ratio of the cross spectrum to the geometric mean of the auto power spectra as shown in equation 2.1.

Mathematically the coherency function is a complex function of frequency ω. Practically, however, empirical real functions are more frequently used for engineering application. The main parameters that control the coherency are the separation distance and frequency. Also the topography has been found to have a significant effect on the coherency. As a result various coherency functions have been proposed by Luco & Wong, Abrahamson and other researchers. For incoherence analysis in this study, the 2006 Abrahamson model is used.

$$\gamma_{ij}(\omega) = \frac{S_{ij}(\omega)}{\sqrt{S_{ii}(\omega)S_{jj}(\omega)}} \tag{2.1}$$

3. ANALYSIS PROCEDURE

Analysis to investigate the effect of foundation embedment on incoherence behavior is performed by two sub steps. First, structure and ground models are established for analysis. They have appropriate size and material properties to represent typical PWR power plants. And then, a set of time histories for input motion is prepared and imposed on the control points of the structure and ground models according to the embedment depths.

3.1. Analysis Model

For SSI analyses, a simple 3-D PWR containment building model is considered as shown in Figure 1. To clarify and identify the spatial embedment effect, i.e., to exclude internal equipment effect, it is composed of only structural shell elements. Their material is concrete for typical PWR power plant that has elastic modulus of 690,000 ksf, Poisson ratio of 0.2, unit weight of 0.15 kcf and damping ratio of 5 %. And the shell thicknesses are 15, 4, 3.5 ft for foundation mat, cylindrical wall, and hemispherical dome, respectively. The radii of foundation mat, cylindrical wall, and hemispherical dome are all the same to 75 ft, and the total height of the containment building is 225 ft.

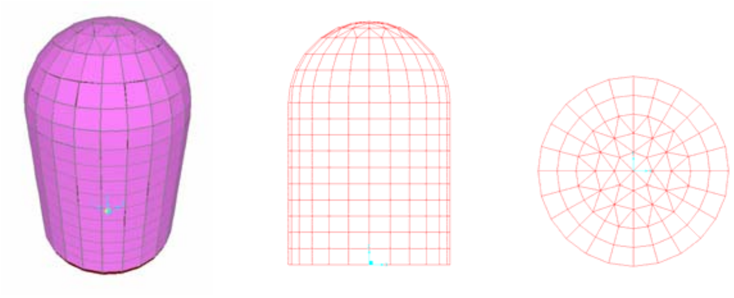
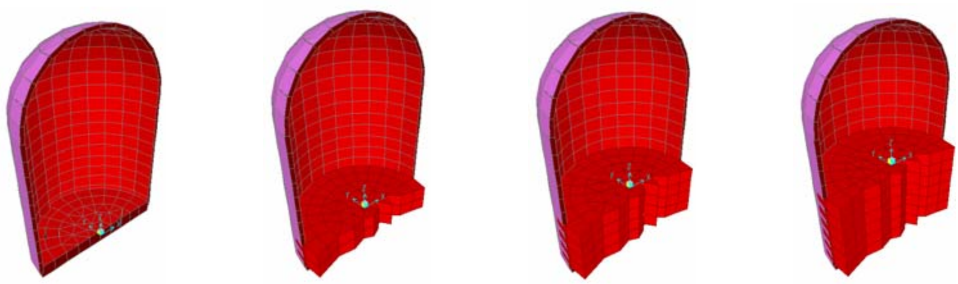


Figure 1 PWR containment building model

The ground that the containment building lies on or embeds into is moderate rock site. It has shear wave velocity of 3,500 ft/s and associated damping ratio of 2 % uniformly. The embedment depths for analyses are 0 (surface structure), 30, 60, 90 (40 % of the total height) ft. The excavated soil is modeled as solid elements as shown in Figure 2. For each depth, coherence and incoherence analyses are performed and compared.



(a) Embedment 0 ft (b) Embedment 30 ft (c) Embedment 60 ft (d) Embedment 90 ft

Figure 2 Excavated soil elements according to embedment depth

3.2. Input Motion

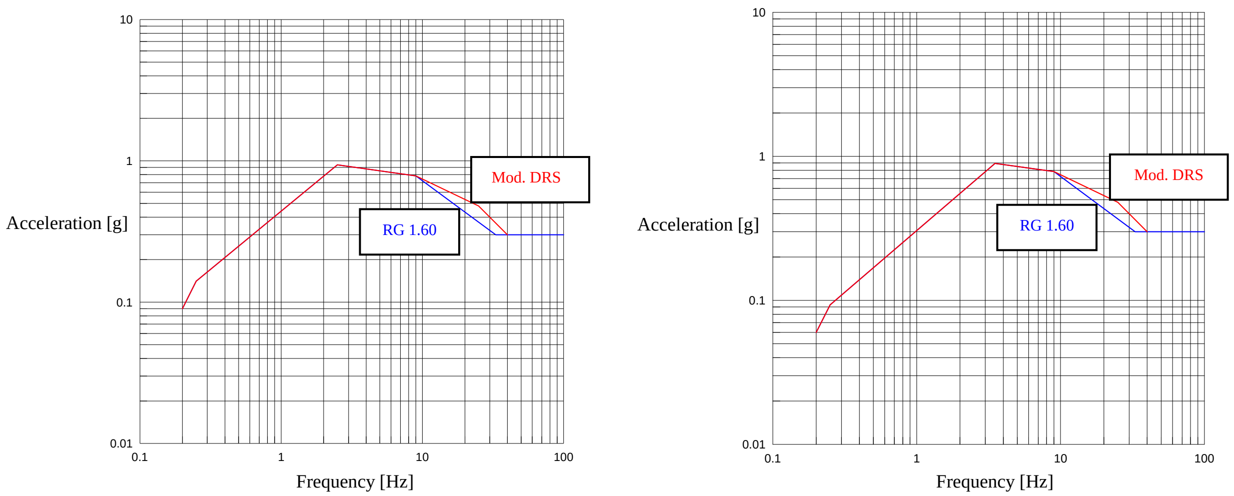
For input motion, a single set of acceleration time histories composed of two horizontal components and one vertical component is artificially generated by a numerical simulation method.[주] The input motion complies with Regulatory Guide (RG) 1.60 spectrum in low frequency range and is enriched in high frequency range as follows. And it is anchored to peak ground acceleration (PGA) of 0.3 g.

(a) Increase the acceleration of the design response spectrum (DRS) in RG 1.60 at 25 Hz by the factor of 1.3.
(b) Vary the DRS linearly on log-log-scale, from 9 Hz to the amplified spectrum at 25 Hz.
(c) Vary the DRS linearly on log-log-scale, from the amplified spectrum at 25 Hz to the PGA at 40 Hz.

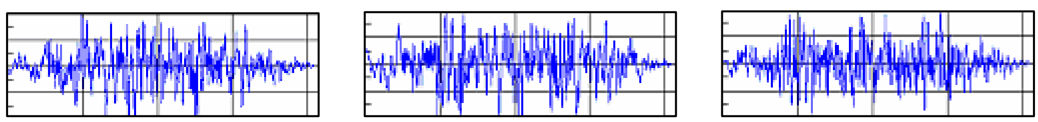
Table 1 shows the spectral amplification values on the modified DRS at the following control frequencies, 0.2, 0.25, 2.5, 3.5, 9, 25 and 40 Hz, and its spectral curves are plotted in Figure 3.

Table 1 Spectral acceleration of modified DRS

Damping ratio	Amplification factor for control motion							Remarks
	0.2 Hz	0.25 Hz	2.5 Hz	3.5 Hz	9 Hz	25 Hz	40 Hz	
5 %	0.090	0.141	0.939	0.895	0.783	0.479	0.300	Horizontal
	0.060	0.094	0.672	0.895	0.783	0.479	0.300	Vertical



(a) Response spectrum for horizontal direction (b) Response spectrum for vertical direction



(c) Time histories for two horizontal and one vertical directions

Figure 3 Spectral curves and time histories of input motion

The design time histories are defined at a time step of 0.005 seconds, and each component has a total duration of 20.48 seconds with approximately 10 second strong motion. The shapes of the acceleration time histories are shown in Figure 3, and they are to be applied as the free-field seismic input motions at the ground surface. For incoherence analysis, the 2006 Abrahamson model is applied. And the wave passage effect is considered by assigning twice the mean shear wave velocity to the apparent wave velocity.

4. ANALYSIS RESULTS

The analysis results are presented in the form of response spectra representing behavior of selected locations. The major points of interest and significance are shown in Figure 4. And damping ratio of all response spectra in analysis results is 5 %.

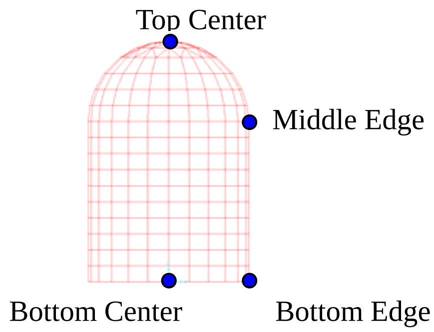
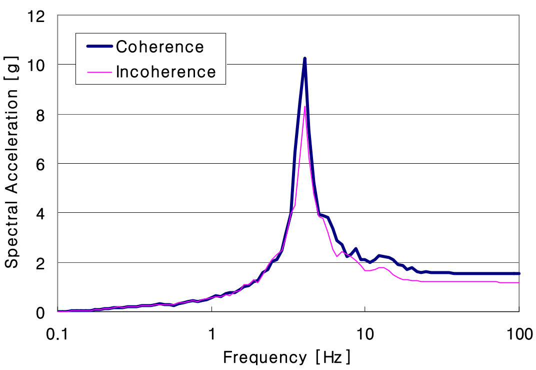


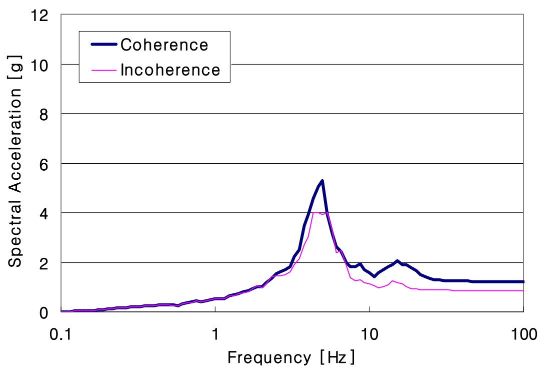
Figure 4 Selected points for response investigation and comparison

4.1. Incoherence Effect

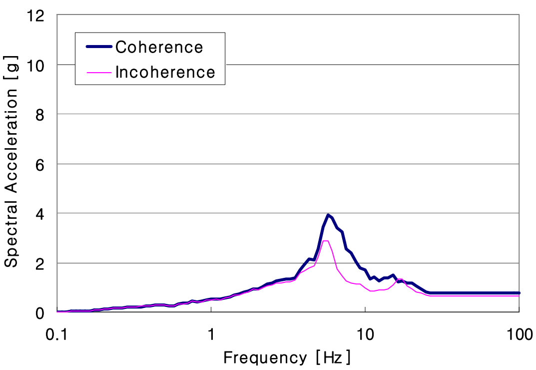
First of all, the SSI analyses show that seismic responses of incoherent earthquake are less intense than those of coherent motion. Such a tendency is clear especially in high frequency range. The response spectra are shown in Figure 5 and 6.



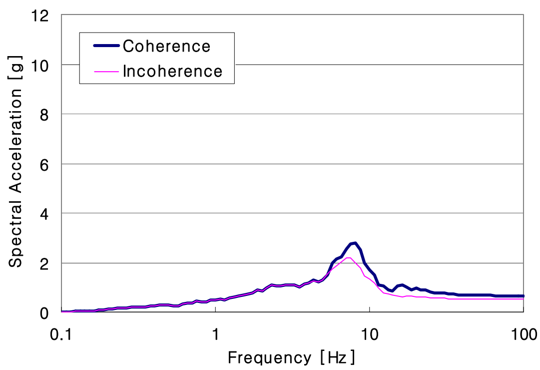
(a) Embed 0



(b) Embed 30

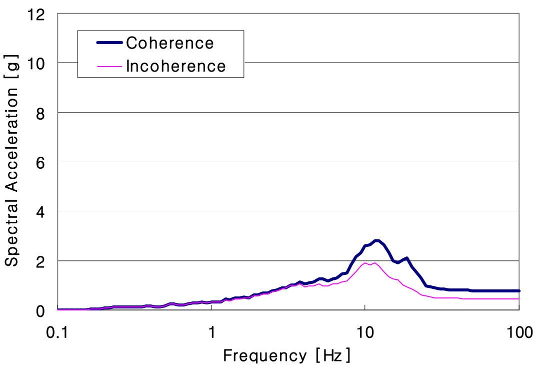


(c) Embed 60

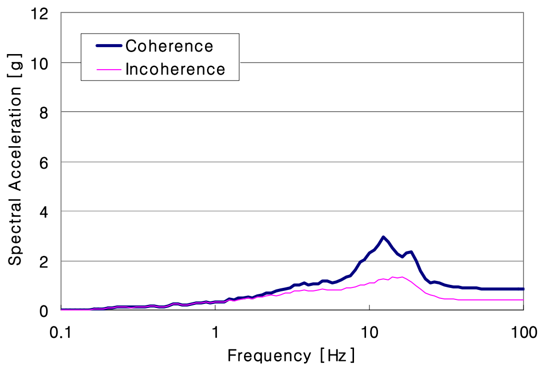


(d) Embed 90

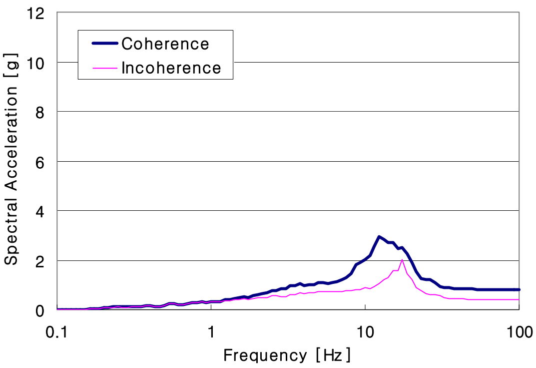
Figure 5 Horizontal response by horizontal excitation at Top Center



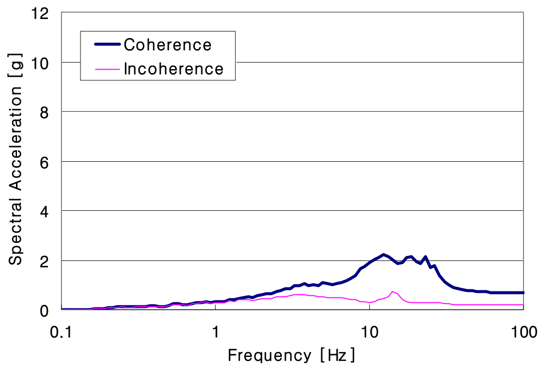
(a) Embed 0



(b) Embed 30



(c) Embed 60

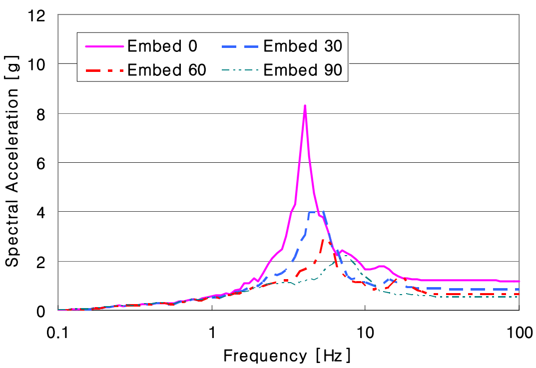


(d) Embed 90

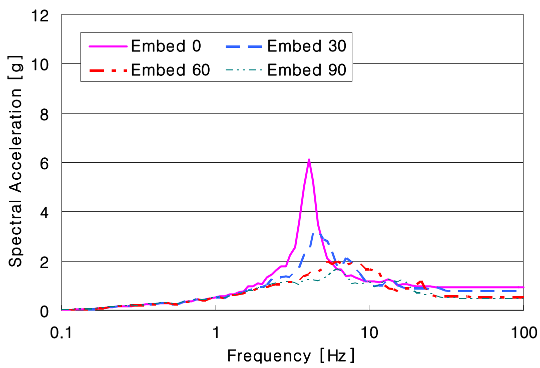
Figure 6 Vertical response by vertical excitation at Top Center

4.2. Embedment Effect

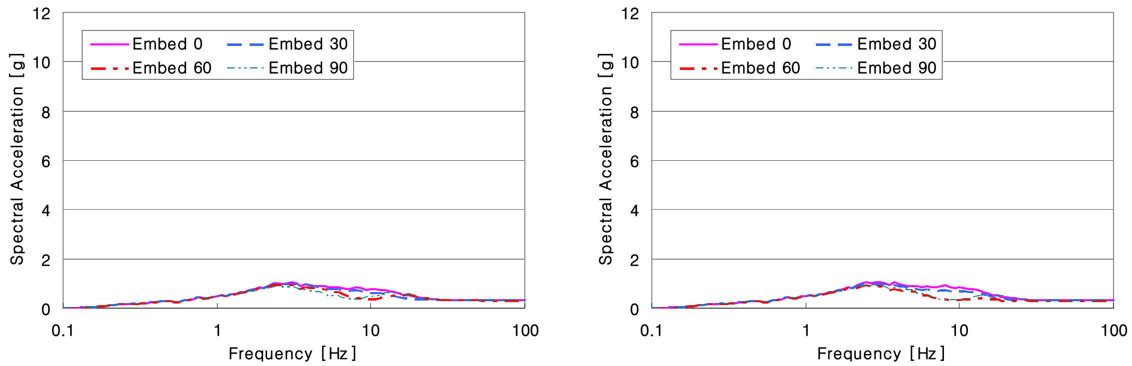
From the SSI analysis considering wave incoherence, it can be confirmed that embedment effect appears, not only from coherent motion but also from incoherent motion. That is, the deeper the embedment is, the lower the peak response is. And the embedment gets the deeper, frequency of the peak response shifts to the higher range. These trends are explicit at high locations and in the horizontal direction as shown in Figure 7.



(a) Top Center



(b) Middle Edge



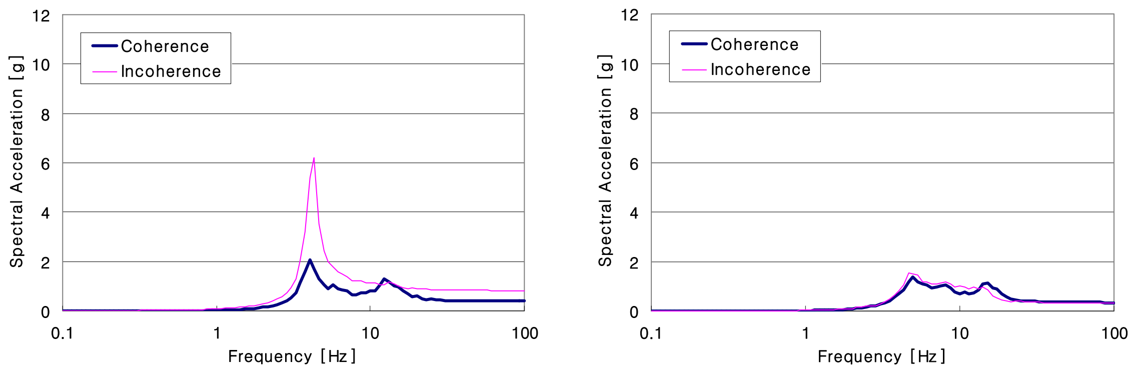
(c) Bottom Center　　　(d) Bottom Edge

Figure 7 Horizontal response by horizontal excitation from incoherence analysis

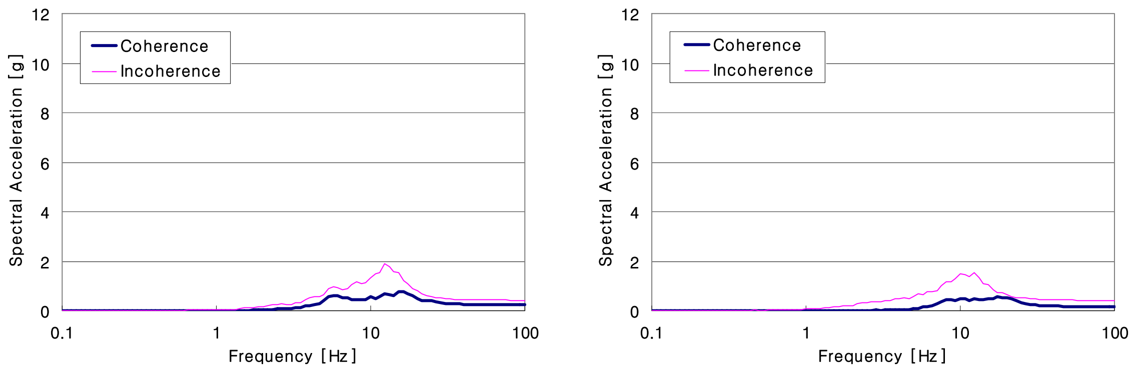
4.3. Rocking Effect

As might be expected, there is no rocking motion at center locations by coherence input motion, and there is relatively weak rocking effect at edge locations. The distance from rotation axis can be thought an important factor of these phenomena.

For incoherence input motion, the rocking effect comes out at the center locations as well as the edge locations. The rocking motions at the edge locations get strengthened and magnified compared to the coherence cases. Embedment can be thought as obstacle to prevent rocking motion as shown as Figure 8. Horizontal response by vertical excitation has similar feature to vertical response by horizontal excitation.



(a) Embed 0　　　(b) Embed 30



(c) Embed 60　　　(d) Embed 90

Figure 8 Vertical response by horizontal excitation at Middle Edge

4.4. Torsion Effect

It is natural that there is no torsion mode at all locations in coherence analysis because the model has axis symmetric features. However, incoherent input motion causes additional torsion behavior as shown in Figure 9. Magnitude of torsion effect is relatively small compared to the rocking effect described in the previous section, but it tends to be stronger according as the location is far from the center. Therefore, in case of irregular structures or outer locations, torsion effect should be considered in SSI analysis. There is no significant difference according to the embedment depth.

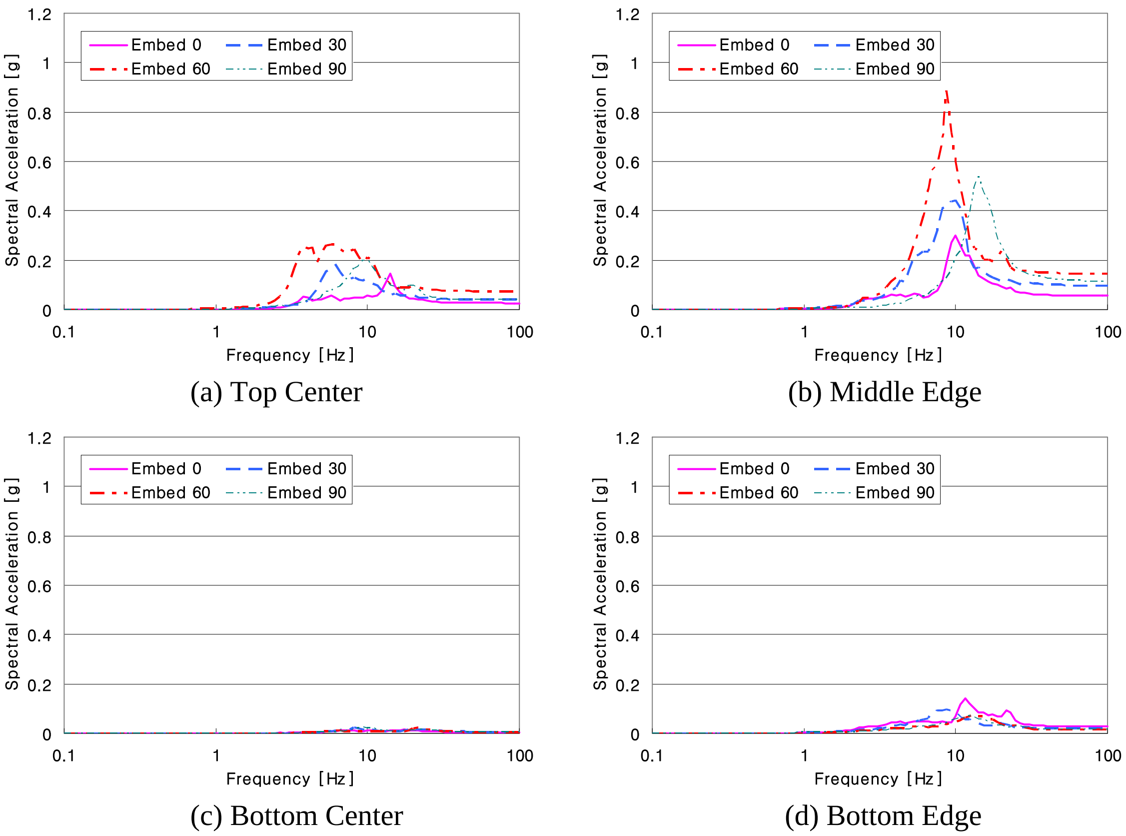


Figure 9 Perpendicular horizontal response by horizontal excitation from incoherence analysis

5. CONCLUSION

To consider spatial variations of ground motion, the seismic analysis incorporating the wave incoherence effect can be performed. From the SSI analyses of typical PWR containment building model with various embedment depths, this paper presents several insight into the behavior of structures. First, incoherent input motion has a tendency to lower the peak level of structural response in high frequency range, and this effect also appears in embedded cases. Secondly, deeper embedment causes lowering peak response and shifting the peak point to higher frequency. Thirdly, incoherence input motion causes stronger rocking motion than coherent one, but embedment can be an obstruction for such an effect. Lastly, for irregular shaped structures or outer locations of regular structures, non-negligible torsion behavior can be induced by incoherent input motion.

In spite of analysis results in this paper, the application for general structures is limited. This is because the coupled effect of wave incoherence and structural embedment has not been fully understood yet, and because sometimes the response of soil-structure system is considerably sensitive to model parameters.

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