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Investigating the Impact of Spatial Variation of Seismic Ground Motions on Reactor Containment Building Response

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ABSTRACT

During seismic events, structural supports experience ground motions that are not coherent, a phenomenon referred to as the spatial variability of ground motion. Accounting for this phenomenon may lead to a reduction in inertial forces acting on the system, a particularly noteworthy occurrence for structures characterized by high frequencies. This study focuses on investigating the effect of the spatial variability of ground motion on the containment building of a nuclear power plant (NPP) including the soil-structure interaction (SSI). In this study, various incoherency models available in literature are used and compared with each other to incorporate the effects of spatial variation of seismic ground motion using the open-source software Code_Aster. The findings of this study show that the incoherence effect mainly decreases the spectral amplitudes after 10 Hz. Therefore, it can be underlined that the effect of the incoherency will be remarkable in the secondary systems which are sensitive to frequencies larger than 10 Hz.

INTRODUCTION

During seismic events, variations in the location of structural supports or foundations lead to differences in the amplitude and phase of recorded seismic motions, a phenomenon known as the spatial variation of seismic ground motion. This observation was experimentally confirmed through data obtained from the Strong Motion Array in Taiwan-Phase 1 (SMART-1), where a network of recorders was strategically placed across an extensive area. Accounting for this phenomenon in structural response analysis may yield a considerable reduction in inertial forces (EPRI, 2005). In EPRI (2005), it was emphasized that the incoherence effect is particularly important for high-frequency ground motions and high-frequency structural responses, especially after 10 Hz.

This spatial variability of ground motion is particularly significant for structures characterized by long spans, such as pipelines, tunnels, dams, and bridges, where different supports experience diverse excitations during earthquakes. Previous studies have also explored the seismic responses of Nuclear Power Plant (NPP) systems under spatially varying ground motions (Hanamura et al., 1996; Ghiocel, 2009; Xu and Samaddar, 2009; Nour et al., 2012; Ding and Xia, 2014; Sayed et al., 2015; Zin et al., 2017; Ghiocel et al., 2017; Johnson and Maslenikov, 2018). In these studies, it is generally indicated that the spatial variation of ground motion reduces the responses of secondary systems which are sensitive to higher frequencies. It was also underlined that the ground motion incoherency has small effects on seismic responses in frequency ranges less than 10Hz. However, there is a need to comprehensively investigate the effects of spatially varying ground motions on NPP responses.

This paper aims to investigate the effect of the spatial variability of ground motion on the reactor containment building of a nuclear power plant (NPP) including the soil-structure interaction (SSI). For this purpose, various incoherency models available in literature are used and compared with each other to incorporate the effects of spatial variation of seismic ground motion using the open-source software Code_Aster.

THEORETICAL FORMULATION

In this study the open-source software Code_Aster is used to carry out the required computations. To perform the seismic dynamic analysis considering the space variability, the operator DYNA_ISS_VARI available in Code_Aster is used. This operator is used to deal with soil-structure interaction (SSI) problems in seismic analysis, where the spatial variability of ground motion needs to be taken into account. The open-source finite element software Code Aster uses a methodology which is based on the spectral decomposition of the coherency matrix, that allows to introduce free field ground motion incoherency in the common SSI analysis (Zentner and Devesa, 2011). Since the related theory already is given by Zentner and Devesa (2011), in this study only the resulting equations are presented.

This study is based on the deterministic approach where an acceleration time history record representing the design motion is simulated. When the structural response to a particular earthquake has to be assessed, the structural response can be obtained by classical linear filtering in the frequency domain. In this case a supplementary deterministic filter $\Phi(\mathrm{w})\Lambda(\mathrm{w})^{1/2}$ is added to model the effect of spatial incoherence. In the frequency domain, this yields the expression,

$$q(w) = \sum_k H(\mathrm{w})\mathrm{G}(\mathrm{w})\phi_k(\mathrm{w})\sqrt{\lambda_k(w)}\,u_0(w) \tag{1}$$

where H(w) is the complex transfer function linking the structural response to the seismic load, u_0(w) is the Fourier transform of the given accelerogram u_0(t), Φ(w) is the matrix containing the eigenvectors ϕ_k of the coherency matrix γ(w) and Λ(w) is a diagonal matrix containing the respective eigenvalues $\Lambda=\mathrm{diag}(\lambda_k)$, and G(w) is the transfer function. The time-domain response is obtained by the inverse Fourier transform (Zentner and Devesa, 2011).

INCOHERENCY MODELS

In this study, the following incoherence models are considered.

Harichandran and Vanmarcke's Model

The model proposed by Harichandran and Vanmarcke (1986) was developed by considering the acceleration records of the SMART-1 database. The developed model has the following regression equation based on the sum of two exponentials.

$$\left|\gamma_{ij}(w)\right|^{i} = A\ e^{\frac{-2d_{ij}}{\alpha\theta(w)}\,(1-A+\alpha A)} + (1-A)\ e^{\frac{-2d_{ij}}{\theta(w)}\,(1-A+\alpha A)} \tag{2}$$

where,

$$\theta(w) = k\left[1+\left(\frac{w}{w_0}\right)^{b}\right]^{-\frac{1}{2}} \tag{3}$$

d_{ij} is the distance between support points l and m and A, α, k, f_0 and b are model parameters determined by regression analysis. In this study the model parameters are obtained from Harichandran and Wang (1996) as: A=0.736, α=0.147, k=5210, f_0=1.09 Hz, b=2.78.

Hindy and Novak's Model

Hindy and Novak (1980) developed a simple exponential coherency model. This coherency model is used with the parameters of α = 0.0003007 and β = 0.9 as given by Chen and Harichandran (2001).

$$\gamma_{ij}(w, d_{ij}) = \exp\left[-\alpha\left(wd_{ij}\right)^{\beta}\right] \quad (4)$$

Luco and Wong's Model

The model developed by Luco and Wong (1986) is also defined by the acceleration records of the SMART-1 seismic network.

$$\left|\gamma_{ij}(w, d_{ij})\right|^{i} = exp\left(-(\alpha d_{ij} w/v_s)^2\right) \quad (5)$$

where α is a dimensionless spatial incoherence parameter and v_s is the shear wave velocity. This coherency model is used with the parameters of α=0.5, v_s=250 m/s (soil site) and v_s=600 m/s (rock site).

Loh and Yeh's Model

Loh and Yeh (1988) also developed the following coherency model by considering the acceleration records of SMART-1 seismic network.

$$\gamma_{ij}(w, d_{ij}) = \exp\left[-\alpha\frac{wd_{ij}}{2\pi V_{app}}\right] \quad (6)$$

where α and v_{app} are the incoherence factor and the apparent wave velocity of the seismic ground motion, respectively. In this study the parameters are considered as α=0.125, v_{app}=250 m/s (soil site) and v_{app}=600 m/s (rock site).

Hao et al.'s Model

Based on data collected during two different earthquakes in SMART-1 seismic network array, a coherence function was determined by Hao et al. (1989) as a function of the frequency and the projected separation distances of d_{ij}^{l} and d_{ij}^{t} in the longitudinal and transverse directions of preferential wave propagation, respectively. The model parameters were determined by using the SMART-1 Event 45.

$$\gamma_{ij}(w, d_{ij}^{l} d_{ij}^{t}) = \exp\left(-\beta_1\left|d_{ij}^{l}\right| - \beta_2\left|d_{ij}^{t}\right|\right) exp\left\{-\left[\alpha_1(w)\sqrt{\left|d_{ij}^{l}\right|} + \alpha_2(w)\sqrt{\left|d_{ij}^{t}\right|}\right]\left(\frac{w}{2\pi}\right)^2\right\} \quad (7)$$

Parameters β_1 and β_2 are constants which control the coherency values at zero frequency while α_1 and α_2 are two frequency dependent parameters which control the loss of coherency with respect to frequency. All these parameters (β_1, β_2, α_1(w) and α_2(w)) were determined by fitting Eq. (7) to the coherency data using the least squares method.

$$\alpha_1(w) = \frac{2\pi a}{w} + \frac{bw}{2\pi} + c \qquad 0.314 \le w \le 62.83 \quad (8)$$

$$\alpha_2(w) = \frac{2\pi d}{w} + \frac{ew}{2\pi} + g \quad (9)$$

In this study, the spatial variation is modelled by the coherency loss based on Event 45 (Table 2).

Table 1. Parameters in the coherency loss function

Event	β_1 (10^{-4})	β_2 (10^{-4})	a (10^{-4})	b (10^{-4})	c (10^{-4})	d (10^{-4})	e (10^{-4})	g (10^{-4})
45	1.109	0.673	38.53	-0.1811	1.177	51.63	-0.0758	-1.905

Abrahamson's Model

The coherency function model proposed by Abrahamson formulating the relationship between seismic ground motions at separate locations as a function of the separation distance d_{ij} and the ground motion frequency f (Abrahamson, 2005). Abrahamson empirical coefficients for horizontal ground motion are given in Table 3.

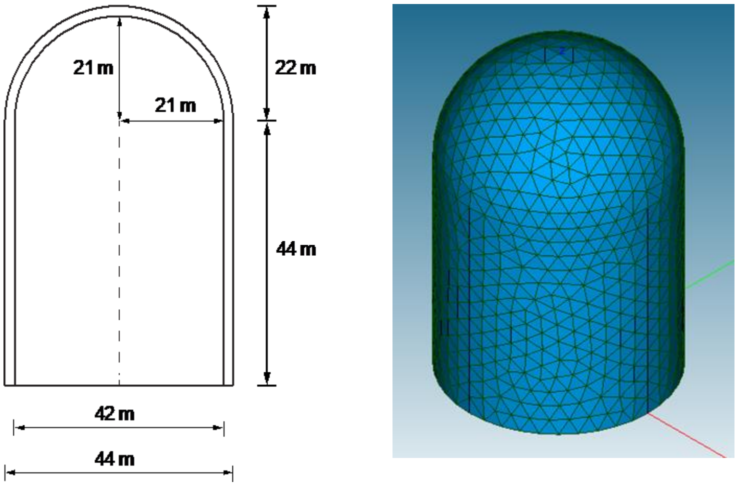
$$\gamma_{ij}(f,d_{ij}) = \left[1+\left(\frac{f\tanh(a_3 d_{ij})}{a_1 f_c}\right)^{n_1}\right]^{-1/2}\left[1+\left(\frac{f\tanh(a_3 d_{ij})}{a_2 f_c}\right)^{n_2}\right]^{-1/2} \tag{10}$$

Table 2. Coherency function coefficients (Abrahamson, 2005)

Coefficient	Abrahamson
a_1	1.647
a_2	1.01
a_3	0.4
n_1	7.02
n_2	5.1-0.51 ln(d_{ij}+10)
f_c	-1.886+2.221ln(4000/(d_{ij}+1)+1.5)

NUCLEAR POWER PLANT (NPP) REACTOR CONTAINMENT BUILDING

The nuclear power plant (NPP) containment building considered in this study is a typical containment building with a cylindrical wall connected to a spherical dome. The dome is monolithic with a thickness equivalent to that of the cylinder. The radius of the cylinder and hemispherical shell is 22 m, while the height of the cylinder is 44 m (Lu et al., 2015). The geometry of the containment building is shown in Figure 1a.



(a) (b)

Figure 1. (a) Cross-sectional view and (b) FE model of the containment building

Mechanical properties of the concrete used in this study are given in Table 3. FE model of the reactor containment building is meshed using 1716 2D triangle elements available in Code_Aster. Figure 1b shows the 3D finite element model of the containment building.

Table 3. Materials properties of the reactor containment building

Material	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's Ratio	Comp/Tensile Stress (MPa)
Concrete B50	2400	33.4	0.2	50
Reinforcement	7850	210	0.3	603.43

It is noteworthy to highlight that the stiffness inputs specified in Table 3 were initially employed to ascertain the frequencies of the structural response. Subsequently, these stiffness inputs underwent calibration to align with the actual and realistic structural response.

GROUND MOTION

To determine the structural responses due to the seismic wave incoherency, a spectrum compatible time history is generated for the rock and soil site conditions. The ground motions are simulated with Code_Aster by using the operator GENE_ACCE_SEISME. To investigate the effect of the coherency function, the site-specific response spectra used in EPRI (2005) for rock and soil sites with 5% damping ratio are used (Figure 2). For the modulation function, which determines the temporal evolution of the seismic signals, the modulation function of Jennings & Housner is used with the parameters of t_1=2.0 sec and T_{SM}=8.00 sec. The acceleration time-history plots simulated for the considered target response spectra are shown in Figure 3.

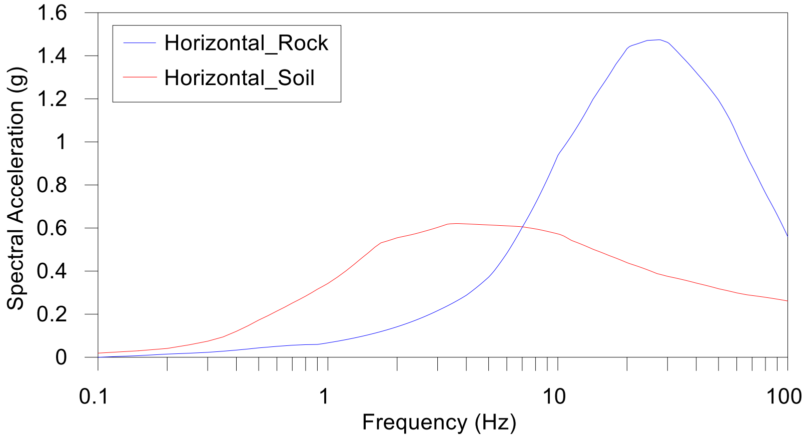


Figure 2. Free field response spectra for rock and soil site (EPRI, 2005)

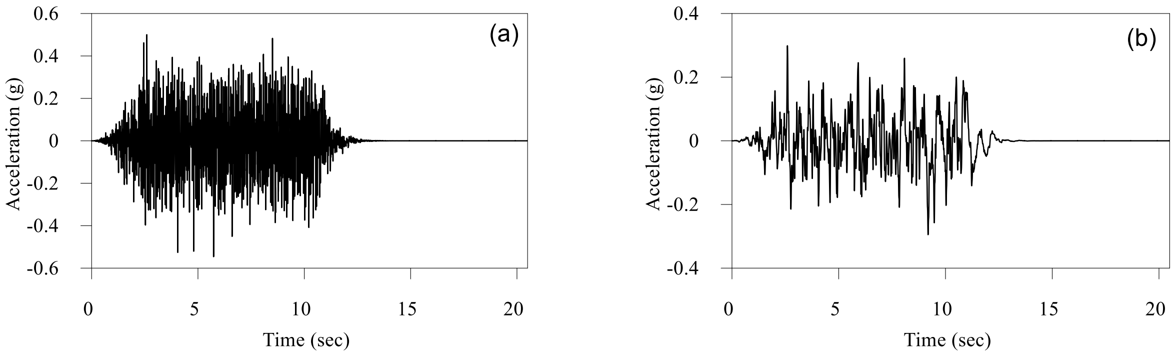
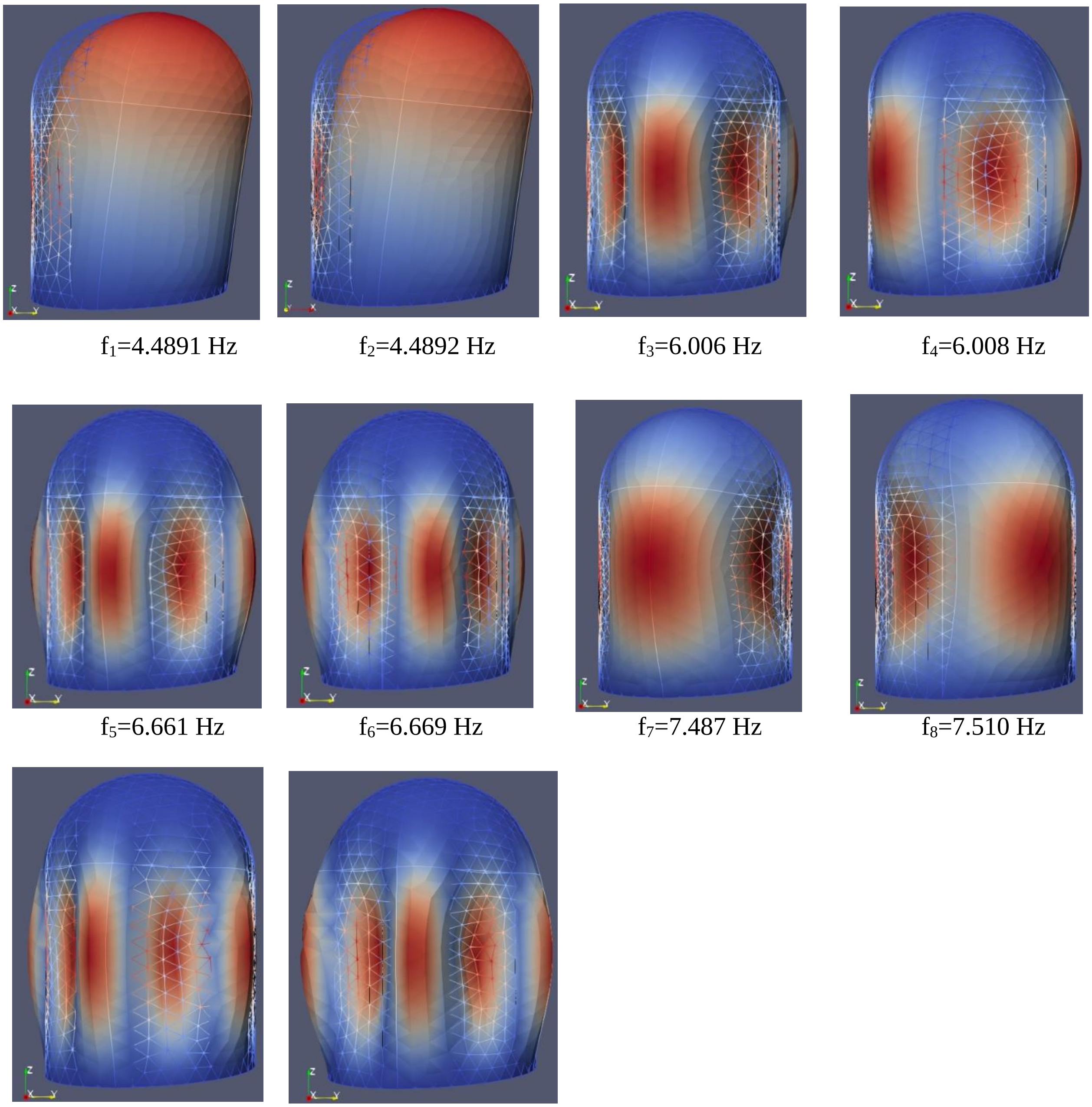


Figure 3. Spectrum compatible generated acceleration time-history plots for; a) rock site b) soil site

NUMERICAL COMPUTATIONS

Modal Characteristics

Prior to spatially varying ground motion analysis of the reactor containment building, eigenvalue analysis of structure is performed to obtain its modal characteristics. Figure 4 presents the first ten vibration mode shapes and the corresponding natural frequencies of the FEM model. It can be noticed that the first two modes are both translational modes y, x with low to medium frequencies, while the remaining have some rotational contribution.



f_1=4.4891 Hz f_2=4.4892 Hz f_3=6.006 Hz f_4=6.008 Hz

f_5=6.661 Hz f_6=6.669 Hz f_7=7.487 Hz f_8=7.510 Hz

f_9=9.054 Hz f_{10}=9.057 Hz

Figure 4. Mode shapes and natural frequencies of the reactor containment building

Structural Responses due to the Incoherence

The simulated ground motion records are applied to the considered nuclear power plant reactor containment building as acceleration-time history plots along the horizontal (x) direction of the system in order to determine the individual effect of each coherency model. The resulting acceleration spectra obtained for 5% damping ratio at the height of 13.5 m and top of the containment building are shown in Figure 5 for rock site. It is already shown that the incoherency effect tends to decrease with increasing frequencies and separation distances and the effect of the incoherency is mostly apparent after 10 Hz. As can be observed in Figure 5, the incoherence effect mainly decreases the spectral amplitudes after 10 Hz. Although the spectral amplitudes even decrease for low-frequency responses, this decrement is not remarkable as in the high-frequency range. Therefore, it can be underlined that the incoherence effect will be mostly effective on the equipment which are sensitive to high frequencies. From the acceleration spectra it is to be noted that the most remarkable decrements are obtained for the empirical coherency models of Abrahamson; Harichandran and Vanmarcke; and Hao et al. The other coherency models of Luco and Wong; Loh and Yeh; and Hindy and Novak which are based on simple exponential functions resulted relatively closer spectral amplitudes to those obtained for the coherent ground motion case.

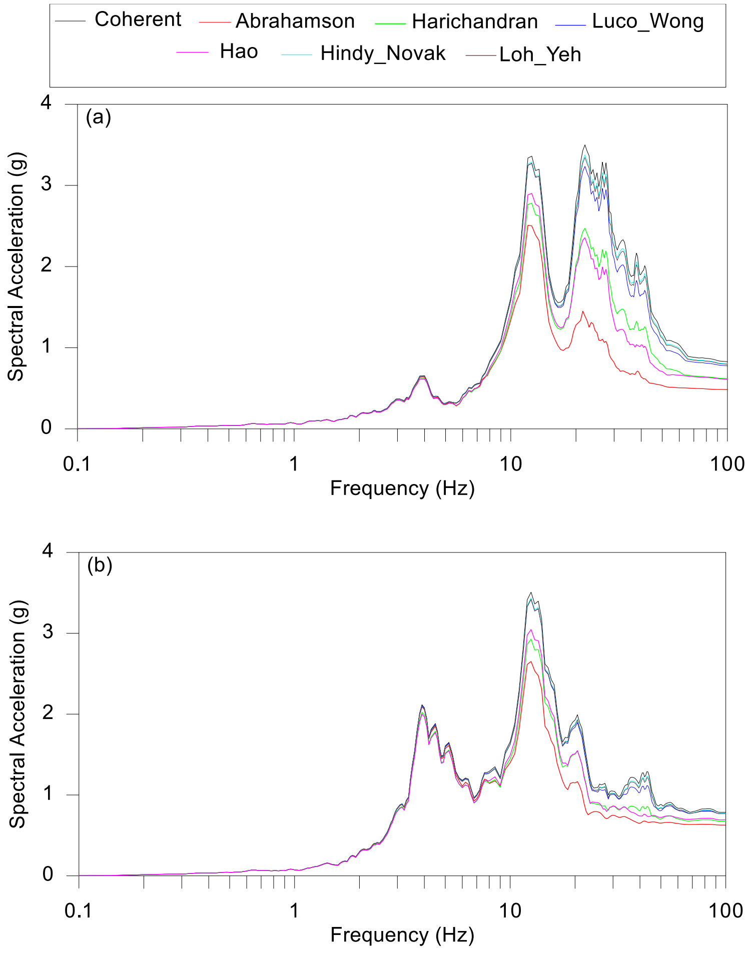


Figure 5. Acceleration spectra at the a) elevation of 13.5m b) top of the containment building for rock site

The acceleration response spectra at a height of 13.5 m and at the top of the reactor containment building are also determined for soil site condition and given in Figure 6. As can be observed, the effect of the incoherence is not remarkable as it was for the rock site. If the acceleration spectra obtained for different coherency models are compared at the at the given points of the containment building, it can be noticed the difference between the coherency models are very small. As the empirical coherency models developed by Abrahamson; Harichandran and Vanmarcke; and Hao et al. cause the largest reductions in the response spectra, the simple exponential coherency models proposed by Luco and Wong; Loh and Yeh; and Hindy and Novak cause the closest spectral amplitudes to the coherent ground motion case.

From Figures 5-6, it can be noticed that the effect of the incoherence is especially apparent at the lower levels of the containment building for both soil conditions. With the increasing height, the difference between coherent and incoherent ground motions decreases.

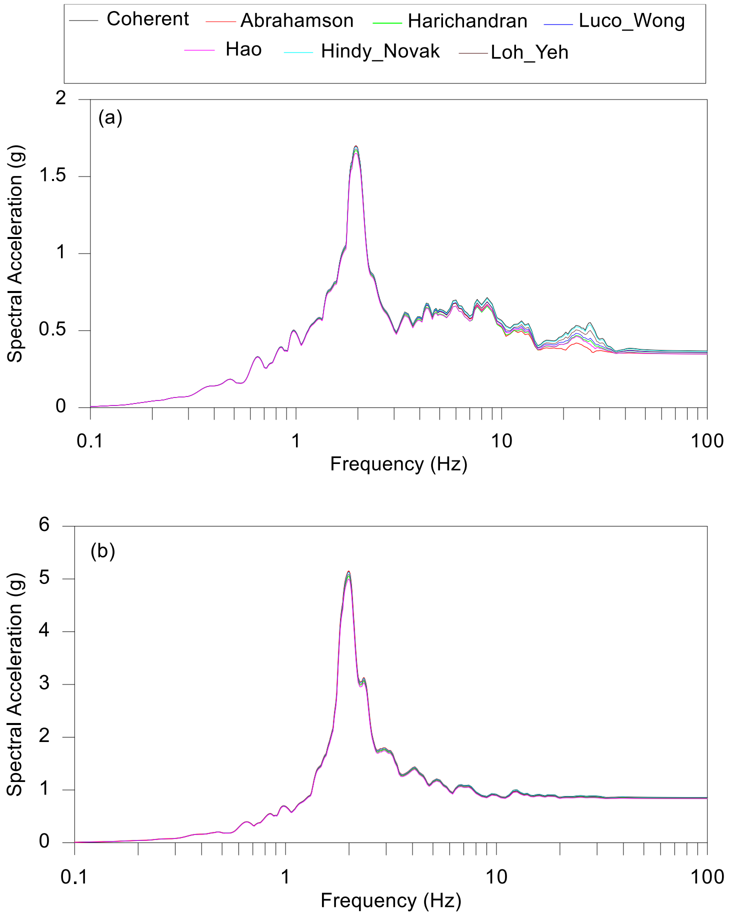


Figure 6. Acceleration spectra at the a) elevation of 13.5 m b) top of the containment building for soil site

The absolute maximum relative horizontal displacements obtained at the top of the reactor containment building is given in Table 4 for the considered coherency models. As can be observed, the incoherence effect decreases the displacements if compared with the coherent ground motion case. It can also be noticed the maximum displacements obtained due to the incoherency models are rather close to the displacement obtained due to the coherent motion for both site conditions. For the coherency models of Luco and Wong; Loh and Yeh; and Hindy and Novak, the differences are even smaller than 1.0%. On the other hand, the difference rises up to 3.53% for the coherency model of Abrahamson, 6.09% for the coherency model of Hao et al. and to 5.60% for the coherency model of Harichandran and Vanmarcke in rock site. This can be attributed to the reduction of the spectral amplitudes corresponding to the fundamental frequencies of the reactor containment building (4-6 Hz) due to these three coherency models as can be observed in Figure 5b.

Table 4. Comparison of max displacements at the top of the containment building

		Rock Site		**Soil Site**	
		u_{max} (mm)	**%**	**u_{max} (mm)**	**%**
Coherent		6.24	-	45.98	-
Incoherent	Abrahamson	6.02	3.53	45.92	1.30
	Harichandran	5.89	5.60	45.11	1.89
	Luco_Wong	6.20	0.64	45.79	0.41
	Hao et al.	5.86	6.09	44.67	2.85
	Loh_Yeh	6.18	0.96	45.42	1.22
	Hindy_Novak	6.18	0.96	45.79	0.41

CONCLUSIONS

The primary findings derived from this study can be given as follows:

The incoherence effect mainly decreases the spectral amplitudes after 10 Hz. Although the spectral amplitudes even decrease for low-frequency responses, this decrement is not remarkable as in the high-frequency range. Therefore, the effect of the incoherency will be remarkable in the secondary systems which are sensitive to frequencies larger than 10 Hz. It can also be noted that the most remarkable decrements are obtained for the empirical models of Abrahamson; Harichandran and Vanmarcke; and Hao et al. On the other hand, the decremental effect of the incoherency seems to diminish for the soil site condition. It can also be underlined that the effect of the incoherence is especially apparent at the lower levels of the reactor containment building for both soil conditions. With the increasing height, the difference between coherent and incoherent ground motions decreases.

The incoherence effect decreases the structural displacements if compared with the coherent ground motion case. However, the displacements obtained due to the incoherency are rather close to the displacements obtained due to the coherent ground motion. On the other hand, a remarkable difference (around 6%) can be observed for the coherency models of Abrahamson; Harichandran and Vanmarcke; and Hao et al. due to the reduction of the spectral amplitudes corresponding to the fundamental frequencies of the reactor building (4-6 Hz).

Because each coherency model is based on a different approximation and has its own characteristics and deficiencies, selection a single coherency model can be misleading while taking into account the incoherency in the dynamic analysis of NPPs. Therefore, it is important to use a coherence model that represents site-specific seismic wave incoherence characteristics whenever possible.

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