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Division V

DEVELOPING SITE-SPECIFIC COHERENCY FUNCTION IN KORI NUCLEAR POWER PLANT SITE OF SOUTH KOREA

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ABSTRACT

In South Korea, Gyeongju earthquake, M5.8 and Pohang earthquake M5.4 occurred on 2017 and 2018, respectively. After experiencing medium-large earthquake, the Korean government and people began to demand more seismic safety on nuclear power plants. To satisfy the seismic demand, Korea Hydro & Nuclear Power (KHNP) considered to secure more seismic margin for operating nuclear power plants. As one of the option for more seismic margin, KHNP began to research coherency function and incoherency Soil-Structure Interaction (SSI) analysis which are used in seismic analysis on operating NPPs in the US. In addition, the Korea nuclear safety authority recommended to use site-specific coherency function. In 2021, horizontal dense array had been installed on Kori NPP site and earthquake data has been collected since July 2021. This study is to explain the process of the development of Korean coherence function and current state of development.

INTRODUCTION

A standard way to evaluate a structure's response to earthquake motion is to assume that the same input ground motion is applied over the entire foundation area. However, short-distance ground motion records show that there can be significant variability in the phasing of ground motion from tens to hundreds of meters. In particular, the phase variability in high frequency range leads to the peaks of ground motion at different times.

In “Spatial Variation of Seismic Ground Motions: Modeling and Engineering Applications” by Zerva (2009), the four causes of spatial variation of ground motion passing through short distances under similar site conditions are presented. The four causes are the wave passage effect, scattering effect, attenuation effect, and extended source effect. A detailed theoretical explanation of these four effects is difficult to include here. Further details are included in the reference, Zerva (2009).

In the United States, the incoherency effect of ground motion was concentrated in order to calculate the actual seismic response to such high-frequency ground motion. A coherency function was developed by analyzing the ground motion measured from the dense array of seismometers installed in Pinyon Plat, California, USA, and applied to the SSI analysis to effectively reduce the high-frequency seismic response. The coherency function of hard rock ground developed by Prof. Abrahamson (2007) has been considered to be used in SSI analysis under similar site conditions in Korea.

A coherency function is developed based on a sufficient number of actual seismic records observed from a dense array created by installing a large number of seismometers in a small area. However, there was no dense array in South Korea. In particular, before the 2016 Gyeongju earthquake, the frequency of earthquakes was very low, so there was no research or technology development attempt to develop a correlation function through seismic measurement.

Since the late 1990s, it has been proven that the effect of reducing earthquake response to a high-frequency input earthquake can be obtained through the development of a coherency function. After then, The incoherency SSI analysis technology began to attract attention from the US nuclear industry and the coherency function of Abrahamson's hard rock model was approved by NRC in 2007. In the EPRI 1015110 report "Effects of Spatial Incoherence on Seismic Ground Motions" published in 2007 by the US Electric Power Research Institute (EPRI), 7 cases of dense array were investigated. Among them, three dense array examples of Pinyon Flat Array in the United States, Lotung LSST Array in Taiwan, and Chiba Array in Japan are introduced in this study.

Pinyon Flat Array is located in Southern California between San Jacinto and San andreas Faults. This array was deployed as part of a PASSCAL experiment to study wave propagation, scattering and spatial variability. The Pinyon Flat area consists of granite. The upper layer was removed due to severe weathering, and the instrument was installed in the rock at a depth of 1 to 3 m from the surface. A solid rock with a shear velocity of 880 m/s is at a depth of 5 m (3 m below the instrument), and the shear velocity increases to 1600 m/s at a depth of 13 m. The average shear wave velocity below 30 m depth of the instrument is 1030 m/s. This site is classified as a hard rock site. Total 58 seismometers were located in Pinyon Flat Array. Since 1990, there have been 287 earthquake records, all of which have a magnitude of less than 4, most of which are less than 2. Among the 287 earthquakes, 78 earthquakes in the range of 10 to 40 Hz, the main frequency range of interest, were selected when the coherency model of nuclear power plants was applied. Based on the 287 earthquake sets, the coherency function model of hard rock site for nuclear power plant was developed and approved by the U.S. NRC and the EPRI 1015110 report "Effects of Spatial Incoherence on Seismic Ground Motions" was published.

Lotung LSST Array is located near Lotung at the southern end of the Lanyang River Plain in northeast Taiwan. The Array operated from 1985 to 1991 as part of a joint program between EPRI and Taipower. The measured shear wave velocity at the upper 50 m is 100 m/s near the surface, and increases to 250 m/s at a depth of 18 m. At a depth of 50 m, it is maintained at 250 m/s. The average shear wave velocity of the upper 30 m is 210 m/s, and the site is classified as a soil site. Total 15 seismometers were located in this array. During operation of Lotung LSST Array, 30 earthquakes were observed.

Chiba Array is located at the Chiba laboratory about 30 km east of Tokyo. This Array was operated from April 1982 to the early 1990s. The average shear wave velocity of the upper 30 m of the Chiba Array is 290 m/s. This site is classified as a soil site. Total 15 seismometers were located in Chiba array. From 1982 to early 1990 through the Chiba Array, more than 160 large-scale seismic measurements have been accumulated. Summary of information of these 3 arrays is shown in Table 1.

Table 1: Summery of Pinyon Flat Array, LSST Array, and Chiba Array.

Array	Loca.	Site condition	N. of seismometer	Distance	N. of event	Magnitude	Distance	Max. PGA
Pinyon Flat	US	Rock	58	7 ~ 340	78	2.0 ~ 3.6	14 ~ 39	0.03
EPRI LSST	Taiwan	Soil	15	3 ~ 85	13	3.0 ~ 7.8	5 ~ 113	0.26
Chiba	Japan	Soil	15	5 ~ 319	9	4.8 ~ 6.7	61 ~ 105	0.41

INSTALLING DENSE ARRAY ON KORI SITE

KHNP decided to install dense array in Kori site in order to develop a site-specific coherency function. in order to more accurately evaluate the response of the structure. It is expected that it will be possible to accurately evaluate the seismic margin by evaluating the response of the structure more closely to reality.

Several ground investigations were carried out, such as refraction seismic surveying, density detection layer, SPS detection layer, and drilling survey for instrument installation. As a result of the refraction seismic survey, it was confirmed that the soil layer and weathering zone were hardly distributed throughout the site, and the bedrock appeared quickly.

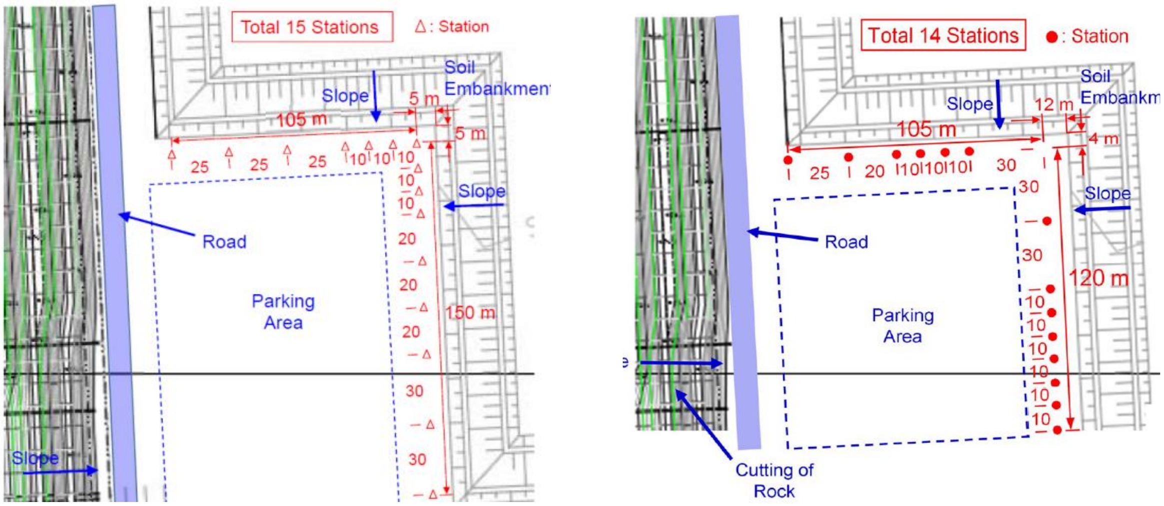
As a result of the drilling survey, the overall bedrock condition is mainly good that is higher than normal rock, and the depth of bedrock appearance for each borehole can be seen in Table 2. The SPS layer was measured from a depth of 3 m, and it was confirmed that the shear wave velocity of soft rock exceeded the required shear wave velocity of 3,500 ft/s. Rocks above soft rock were investigated to be sufficient as bedrock.

Table 2: Depth of rock formation by borehole test (m)

	BH-1	BH-2	BH-3	BH-4	BH-5
Buried layer	0.0~0.6	0.0~1.2	0.0~1.8	0.0~1.1	0.0~1.4
Weathered rocks			27.1~33.3		
Soft rock		1.2~3.1 8.5~11.5	1.8~4.6 23.5~25.2	18.7~20.7 32.0~34.1	1.4~6.4 39.2~40.6 42.3~43.6 46.6~48.2
Normal rock	0.6~3.8 17.8~20.0	3.1~8.5 18.9~20.4	4.6~7.1 25.2~27.1 33.3~34.4	20.7~24.1 30.2~32.0	6.4~13.6 34.0~39.2 40.6~42.3 43.6~46.6 48.2~50.0
Hard rock	3.8~17.8 20.0~50.0	11.5~18.9 20.4~50.0	7.1~23.5 34.4~50.0	1.1~18.7 24.1~30.2 34.1~50.0	13.6~34.0

In order to install the seismic dense array, considering the total area of nuclear island, which has the largest area as a single foundation among major nuclear power plants in Korea, a flat area with at least 105 m x 120 m and free from surrounding interference is needed.

As a result of a comprehensive review, it was confirmed that a part of the parking area within the site of the Kori power plant could be used for the installation of seismometers for this service. Based on the this results, L-shaped horizontal dense array was installed on the site as shown in Fig.1. The length and width of dense array are 120m and 105m, respectively. Total 14 stations are constructed and 14 short period seismometers are installed on July 2021.



(a) (b)

Figure 1. Dense array installed in Kori site of South Korea : (a) initial design (b) final design

As shown in Fig. 1, the initial design (a) and the final design (b) are different. Initially, seismometers were also placed in the upper right corner. However, it was changed to the final design because construction was not possible in the relevant part depending on the situation at the site.

DERIVING COHERENCY FUNCTION OF KORI SITE

According to EPRI 1015110 report, “Program on Technology Innovation: Effects of Spatial Incoherence on Seismic Ground Motions”, experience based spatial incoherency model applying to nuclear power plant was developed using data from dense array in the Taiwan and California. The empirical methodology developing incoherency function is based on earlier study in the US. Detailed theory and process are described in EPRI 1015110 and TR-100463. Practical process and results will be dealt with in this chapter.

The steps for developing an empirical coherency model are described in detail. The purpose of this section is to provide the information needed to calculate correlations from ground motions recorded from installed dense arrays and to develop site-specific empirical coherency models. This section includes data processing, time window selection, cross-spectral smoothing, coherency calculations, and statistical modeling of coherent data for plane wave coherency.

The process of deriving coherency function is described as below :

a) Time windows are selected based on the duration of the normalized Arias intensity of the two horizontal components of velocity from earthquake data.
b) A subset is selected based on the signal in the frequency range of 10 to 40 Hz which is a key frequency range of the application of the coherency model for NPPs.
c) The spatial variability of the ground motion waveforms can be quantified by the spatial coherency.
d) The wave speeds are computed using the coherencies in the frequency band of 5-25 Hz to use plane wave coherency.

e) Using the selected earthquakes, the regression analysis is conducted to develop site-specific coherency model.

In general, the time window is selected in order to capture the strongest oscillations in the horizontal component. If the number of seismic records is small, the time window can be selected manually. For large data sets, such as earthquakes of small magnitude obtained from the Pinyon Flat Array, an automatic time window selection process can be used. In the EPRI study, the automated approach was developed and it uses Arias Intensity to find the time domain in which strong shaking occurs. Arias Intensity can be calculated as

$$I(\tau) = \frac{\int_{T_p-10}^{\tau}\left(V_{H1}^2(t)+V_{H2}^2(t)\right)dt}{\int_{T_p-10}^{T_p+10}\left(V_{H1}^2(t)+V_{H2}^2(t)\right)dt} \tag{1}$$

where $\mathrm{T_p}$ is the time of maximum velocity. The time for $I(\tau)$ to reach 0.1 and 0.75 is denoted by $\mathrm{T}_{0.1}$ and $\mathrm{T}_{0.75}$. The Time Window is selected from $\mathrm{T}_{0.1} - 0.5$ sec to $\mathrm{T}_{0.75} + 1.0$ sec. Either this automated approach or a manual approach can be used to select the time window. Minimum and maximum times are used across all observation points so that the same time window is used for all records from a single earthquake.

After time window selected, a complex fourier transform is computed for each of the two horizontal components per observation point and a cross spectrum is computed and smoothed in the frequency band for each pair of observation points using a complex fourier spectrum. In the next step, delayed coherency, plane wave coherency, and undelayed coherency for pairs and frequencies at each observation point are calculated. This data can be used for regression analysis to develop empirical correlation models.

Although the complex calculation process cannot be fully expressed here, the coherency function calculated through regression analysis is expressed in the following equation. This equation was suggested in EPRI 1015110 report.

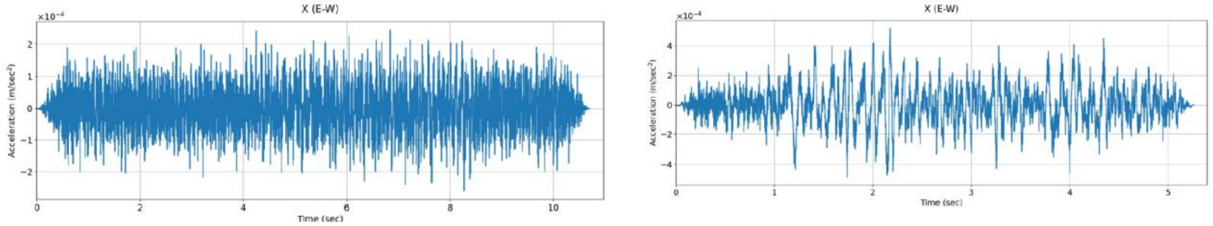
$$\mathrm{Tanh}^{-1}\left(\gamma_{pw}(f,\xi)\right) = \mathrm{Tanh}^{-1}(\left[1+\left(\frac{f\tanh a_3\xi}{f_{c1}}\right)^{N_1}\right]^{-0.5}\left[1+\left(\frac{f\tanh a_3\xi}{f_{c2}}\right)^{N_2}\right]^{-0.5}) \tag{2}$$

Where f and ξ is frequency in Hz and distance between two observation spots, respectively. The separation distance dependence of the corner frequency of the filters is expressed as f_c , and the number of poles are N_1 and N_2.

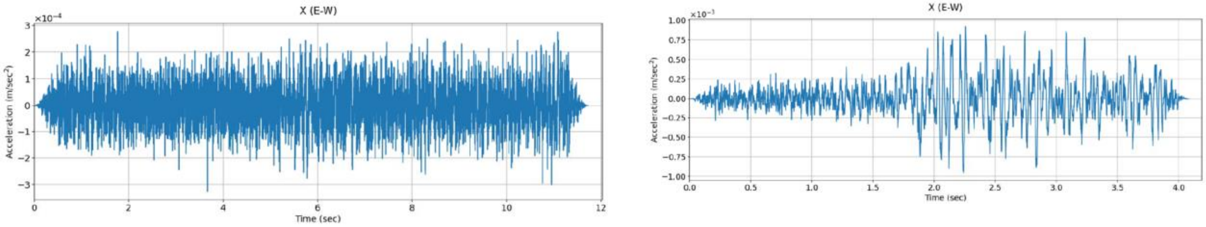
COLLECTED EARTHQUAKE DATA

Since July 2021, detected earthquake data has been used as input data for coherency function development, and the total number of used earthquake events are just 10. It should be noted that targeted number (about 30) of earthquake is not collected because there are few earthquake events in South Korea, neither big earthquake nor small one. It will be constantly updated until the targeted number of earthquakes are collected.

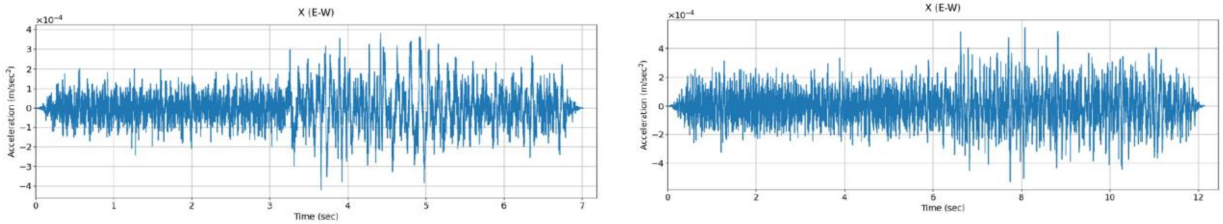
As a result of analyzing the measurement data accumulated for 6 months from July 2021 to December 2021, there were 10 earthquakes with a magnitude of 2.0 or greater that could be used to develop a coherency function of the site. Fig. 2 shows the acceleration time histories of 7 cases analyzed up to October 2021.



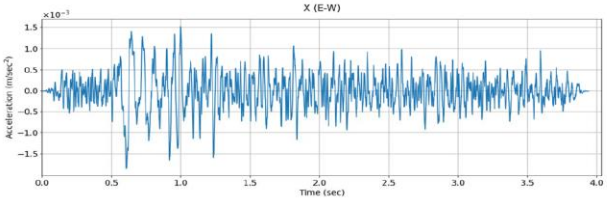
(a) 2021.07.25 / M2.2 / Distance 148 km
(b) 2021.07.30 / M2.5 / Distance 89 km



(c) 2021.08.01 / M2.2 / Distance 41 km
(d) 2021.09.13 / M2.2 / Distance 48 km



(e) 2021.09.23 / M2.6 / Distance 74 km
(f) 2021.08.29 / M2.2 / Distance 74 km



(g) 2021.10.19 / M2.2 / Distance 75 km

Figure 2. Acceleration time history of collected 7 earthquakes until October 2021.

CONCLUSION

The development of site-specific coherency model in Kori site was introduced in this paper. KHNP, the Korean company operating nuclear power plant in South Korea, installed a dense array at the Kori site to accumulate seismic data for the development of coherency function, and has been collecting data since July 2021. Appropriateness and validity were confirmed through the review of experts with experience in coherency function development. In the case of the Kori nuclear power plant, the site condition is classified as hard rock and the methodology developing coherency function by EPRI was adopted.

Although the results have not been completed because a lot of seismic data has not yet been collected, the data analysis of 7 cases accumulated since the July 2021 is being performed. After a significant amount of data is collected and site-specific coherency function is derived, it is expected that the incoherency SSI analysis can be performed.

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