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# SEISMIC ANALYSIS OF NUCLEAR POWER PLANT STRUCTURES UNDER BEYOND-DESIGN BASIS EARTHQUAKE EXCITATION

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## ABSTRACT

Seismic analyses of Korean Standard Nuclear Power Plant (KSNP) structures under the beyond design basis earthquake (BDBE) excitation are performed in accordance with the domestic and the Japanese seismic design standards, respectively. The applied peak ground acceleration (PGA) of input motion is 0.4g, which exceeds the PGA of design input of the KSNP, 0.2g.

The seismic analysis based on the code requirements of Korea is performed considering linear behaviour of the structure and its supporting media with the sub-structuring method formulated in the frequency domain. In contrast, with regard to the seismic analysis based on the Japanese standards, JEAG 4601 (2015) and JEAC 4601 (2015), the soil medium is idealized with sway-rocking (SR) springs to simulate dynamic behaviour of the ground, and the superstructures are modelled to implement the flexural yielding and shear failure behaviour. That is, the former method adopts using an appropriate damping ratio based on the condition of linear seismic analysis, whereas the latter directly reflects the nonlinear dynamic behaviour of the soil medium and structures in the seismic analysis. The responses at major locations of the structures are presented for the comparison of seismic analysis results from two different analysis and design approaches. In addition, a currently developed technology for the seismic nonlinear soil-structure interaction (SSI) analysis of the NPPs structures in Korea is applied for seismic analysis of KSNPs' reactor containment building (RCB), and the responses are compared with the results of the SR model analysis.

## INTRODUCTION

Performance goals of Nuclear Power Plant (NPP) for the beyond design basis earthquake (BDBE) can be defined probabilistically or deterministically. For post-Fukushima checks regarding the SSCs for BDBE, France regulatory body requires that the seismic ground motion envelopes 150% of the site specific design basis earthquake (DBE) ground motion and deterministic approach is used to consistent with the hard-core components' functionality. In Japan, the amplified ground motion for BDBE is used to check deterministically the seismic margin of SSCs based on the DBE ground motion Ss.

Nonlinear analysis is currently becoming a popular tool for performance and safety evaluations of structure and pipe systems, and the skill has been adopted to assess the safety of NPPs' structures under the beyond design basis events, such as the severe accidents and a large commercial aircraft impact. In ASCE 4 (2017) and KEPIC STB (2020), the nonlinear seismic analysis methods and their specifications are provided, but the details for the nonlinear analysis and its application to the seismic margin assessment are not defined in those design codes. In Korea, nonlinear seismic soil-structure interaction (SSI) analysis technology for nuclear power plants using the commercial program ABAQUS is being developed, and the results will be applied to supplement the domestic design standard KEPIC STB and to assess the seismic margin of KSNP under the BDBE.

KSNPs' power block consists of a reactor containment building (RCB), an auxiliary building (AB), and a turbine generator building (TGB), and the RCB and AB are physically separated by a seismic gap of 2 inches. In order to evaluate the dynamic behaviours of the KSNPs' structures for BDBE, the conventional frequency-domain SSI analysis, the nonlinear seismic analysis using the SR model, and the nonlinear SSI analysis developed in this study are performed and the responses from these analyses are compared to each other. The first and second analyses are performed in accordance with the domestic and the Japanese seismic design standards, respectively. The nonlinear SSI analysis is a technology which is developed and verified using the ABAQUS program to properly consider the nonlinear behaviours of the ground and structure including the contact nonlinearity between the structure basemat and the adjacent ground. The effect of the nonlinear behaviour of the KSNPs' structures is represented by comparing the responses of the frequency-domain SSI analysis and nonlinear analysis using the SR model. In addition, the developed nonlinear SSI analysis method is preliminary verified by comparing the responses of the nonlinear SSI analysis with those of the nonlinear analysis using SR model.

## DESIGN GROUND MOTIONS

The two sets of acceleration time histories compatible with the design response spectra, which are currently being applied to the seismic design of the Korean NPP, are generated in accordance with the guidelines provided in the SRP 3.7.1 and JEAG 4601 (2015), respectively. Since the design requirements, such as the spectrum-enveloping criteria, etc. of the SRP 3.7.1 and JEAG 4601 (2015) are different from each other, the generated time histories show different signal and spectral shape as shown in Fig. 1 and Fig. 2. These acceleration time histories are used as the input motions of the linear SSI analysis according to the seismic design requirements of Korea and the nonlinear seismic analysis according to the seismic design requirements of Japan, respectively. As mentioned before, the peak ground acceleration (PGA) of 0.4g for the BDBE is applied in these analyses.

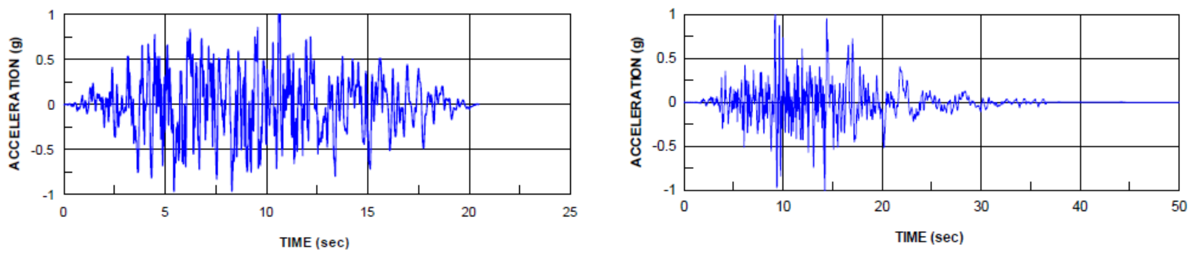


Figure 1. Horizontal acceleration time histories according to design requirements of SRP 3.7.1 and JEAG 4601

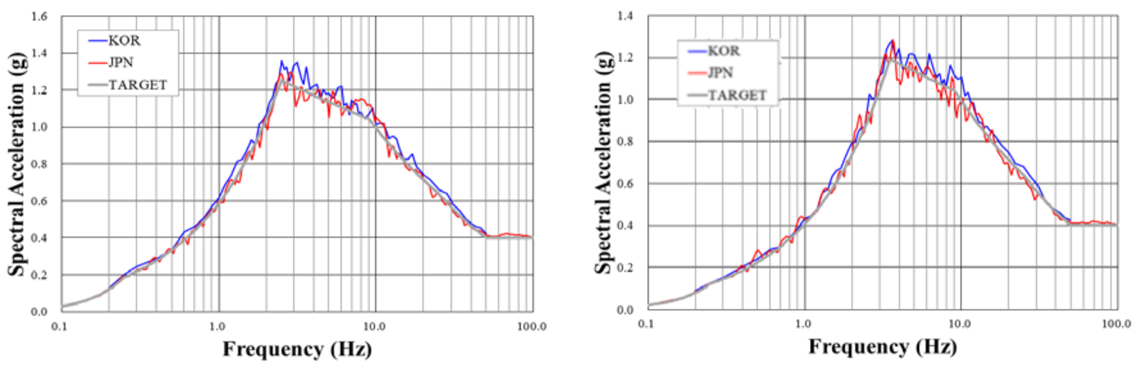


Figure 2. Response spectra of horizontal and vertical directions

## KSNPs' DESIGN CHRACTERISTICS

In the 1000 MWe PWR type KSNP, the prestressed concrete RCB and reinforced concrete AB are regarded as the most important buildings. Because the two buildings are structurally separate from each other with a minimum seismic gap of 2 inches throughout the entire height of the building including the basemat, they behave independently when the earthquake ground motions are applied. The shear-strain-dependent soil/rock modulus degradation and damping value variation curves for the soil/rock materials considered for the low-strain site profiles are shown in Fig. 3. The strain-compatible shear wave velocity profiles obtained from the site response analyses according to the design requirements of Korea and Japan are shown in Fig. 4.

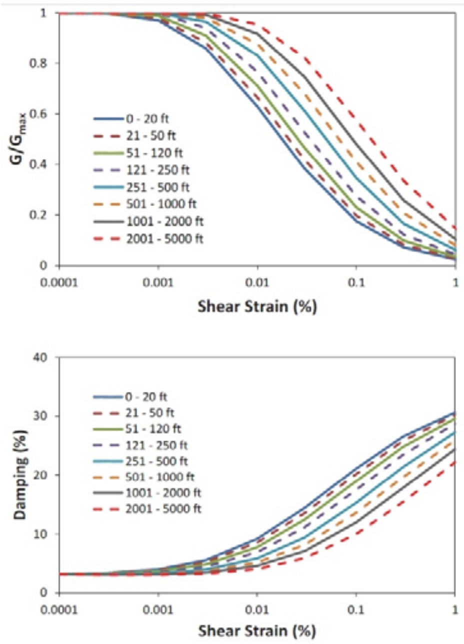


Figure 3. Nonlinear characteristics of rock

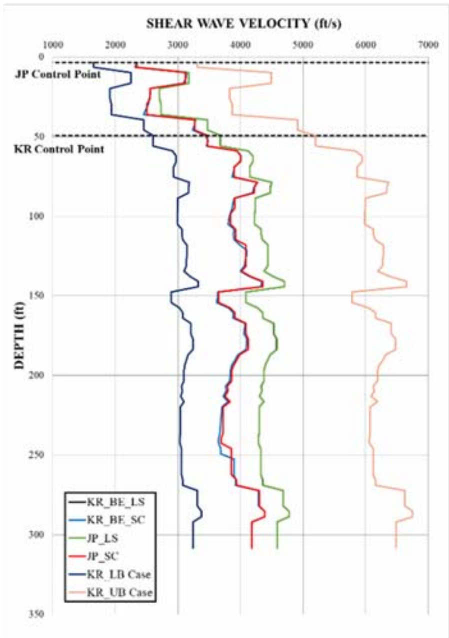


Figure 4. Site response analysis results

## COMPARISION OF LINEAR ANALYSIS AND SR MODEL ANALYSIS RESULTS

For seismic analysis of the KSNP under the BDBE, the analysis models of the RCB and AB are developed in accordance with the seismic analysis procedures of Korea and Japan, respectively. Since the KSNP has a structural characteristic that the RCB and AB are physically separated by a seismic gap, the individual analysis models are also developed for the RCB and the AB, respectively. The final models which satisfy the domestic standards and their seismic analysis procedures consist of the soil medium, RCB and AB, and the SSI analysis is carried out at once by incorporating them. Through the linear SSI analysis using this combined model, the structure-soil-structure interaction (SSSI) effect is also considered indirectly.

In the analysis model based on the seismic design standards and their analysis procedures of Japan, the RCB and AB models are developed for each direction of the structure, and the soil medium is idealized as the SR springs in accordance with the criteria in the design standards. The seismic analyses are carried out individually for the RCB and the AB, and for each direction.

Fig. 5 shows the finite element models of RCB and AB developed for the verification of the lumped mass stick models. Fig. 6 represents the lumped mass stick models for the RCB and the AB developed in accordance with the seismic design standards and their analysis procedures of Korea. In these models, the stiffness and mass properties are calculated and reflected in a single model regardless of the direction, whereas the models based on the seismic design standards and their analysis procedures of Japan are developed separately for each direction of the structures as shown in Fig. 7. For seismic analyses, ACS SASSI is applied to the linear SSI analysis, and the RESP-F3T program that can implement the flexural yield and shear failure behavior is used for the simplified nonlinear SSI analysis.

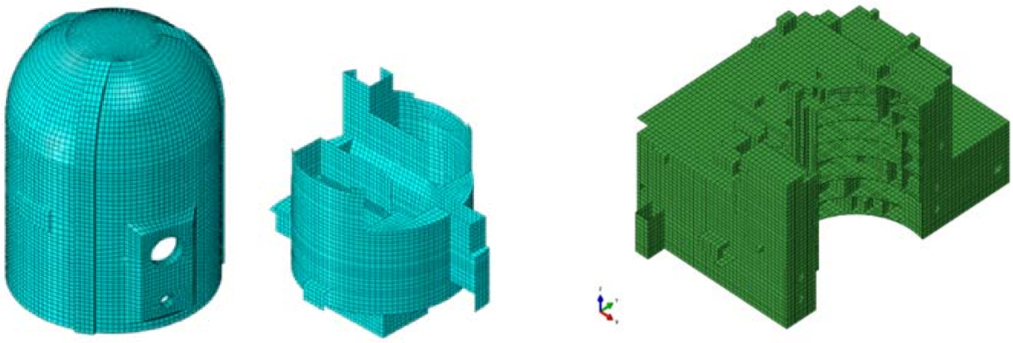

Figure 5. Finite element models of RCB and AB

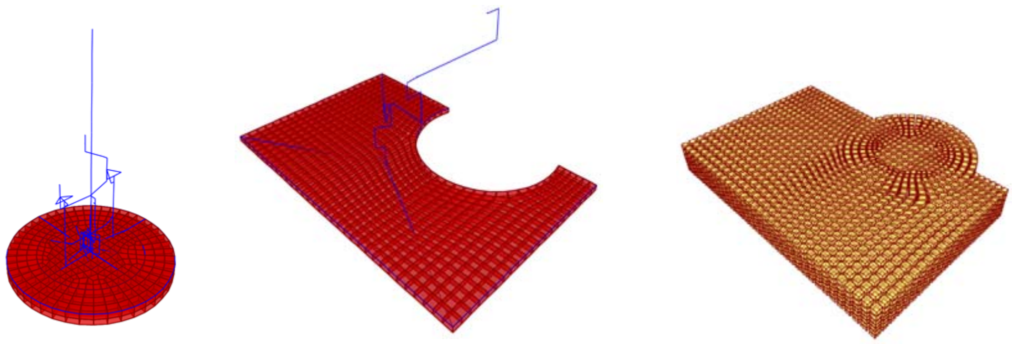

Figure 6. Lumped mass stick models of RCB, AB and soil foundation

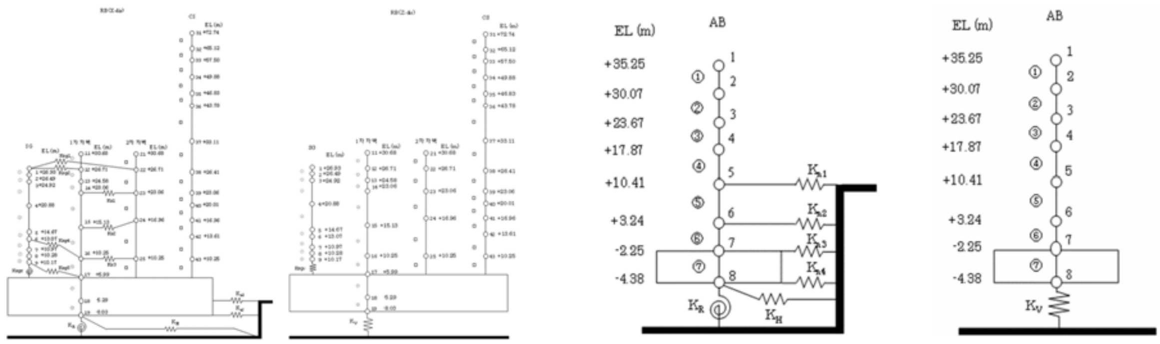


Figure 7. Lumped mass stick models of horizontal and vertical direction for RCB and AB

The floor response spectra (FRS) at the dome apex of RCB are compared as shown in Fig. 8. The comparison result shows that the vertical FRS from the SR model analysis is similar to or slightly exceed the responses by the frequency-domain SSI analysis, while the horizontal FRS from the SR model analysis is overall small, and the domain responses occur at the different frequencies. The shear strain and moment curvature levels from the SR model analysis slightly exceed the concrete cracking strain at the wall part of the wall-to-basemat junction of the wall as shown in Fig. 5. As a result, the responses from the nonlinear seismic analysis using the SR model can be considered as the result of interaction between the nonlinear behaviors of the soil/rock and the structure.

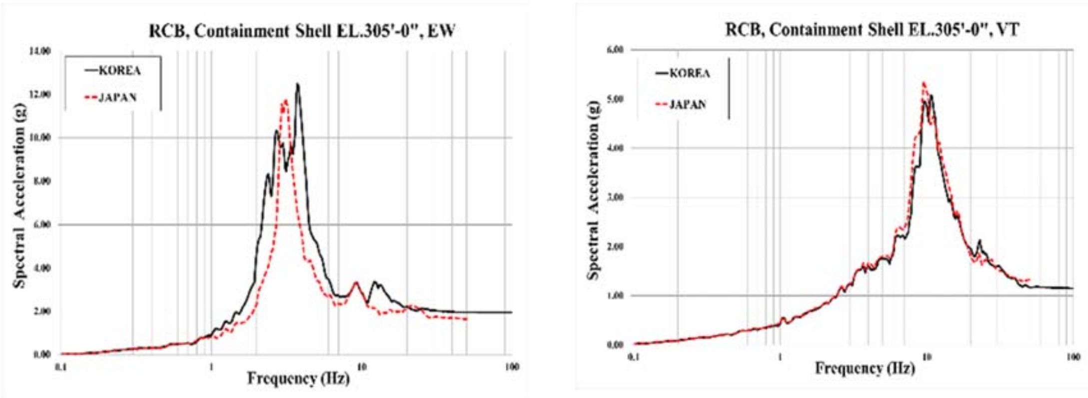


Figure 8. Floor responses spectra in horizontal and vertical directions at RCB dome apex

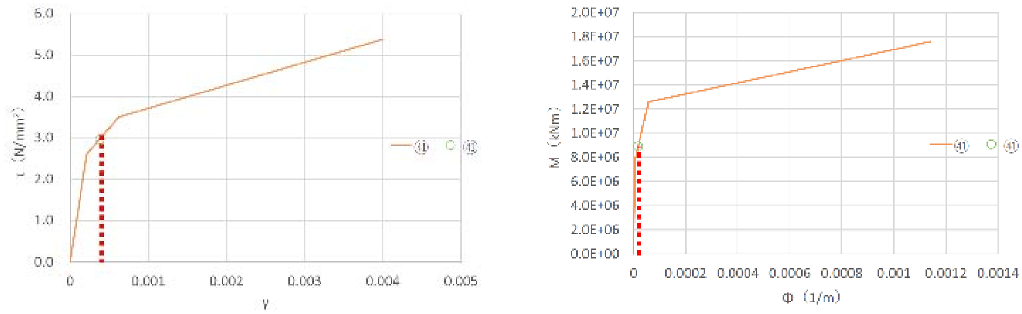


Figure 9. Shear strain and moment curvature levels at RCB wall

Fig. 10 shows the comparison result of the FRS at the roof of the AB which is composed of shear walls and slabs. In case of a horizontal direction, the FRS by the nonlinear SSI analysis using the SR model are overall smaller than the FRS from the frequency-domain SSI analysis. The shear strain levels at the first floor of AB represents a nonlinear behavior of in-plane shear, whereas the moment curvature represents the linear behavior. The FRS of a vertical direction show that there is no significant difference between both analysis results.

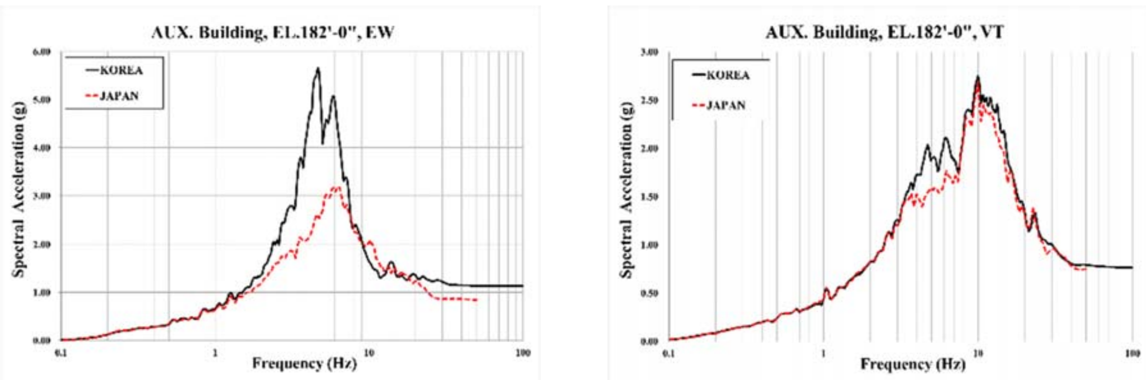


Figure 10. Floor responses spectra in horizontal and vertical directions at AB roof

## COMPARISION OF NONLINEAR ANALYSIS AND SR MODEL ANALYSIS RESULTS

### *Nonlinear Seismic Analysis*

The seismic analysis is to calculate the seismic responses in structure, and the results are applied to the design and assessment for the individual SSCs of NPP. For the BDBE, the structure is expected to represent the nonlinear behaviour due to the combined factors of concrete cracking and steel yielding, and a simplified model for the structure is necessary to reduce the computational time for full nonlinear SSI analysis. The simplified model should be made by an appropriate method which does not include the error of the analysis results. Luckily, JEAC 4601 (2015) provides the details for the simplified model such as skeleton curve and hysteresis model for the nonlinear analysis. The safety criteria for the concrete structure is also defined as the shear strain of $2\times10^{-3}$, and these specifications are already demonstrated through a long time researches. In this study, both of three-dimensional finite element and simplified beam stick models are developed, and the model verification is performed using a large-scale shear wall test results.

Fig. 11 shows the three-dimensional FE model and beam stick model for the RCB, and the comparison results from the analyses with both modelling methods are represented in Fig. 12. As shown in the figures, the displacement and acceleration responses from the analyses with both models show good agreement with an error rate of less than 5%.

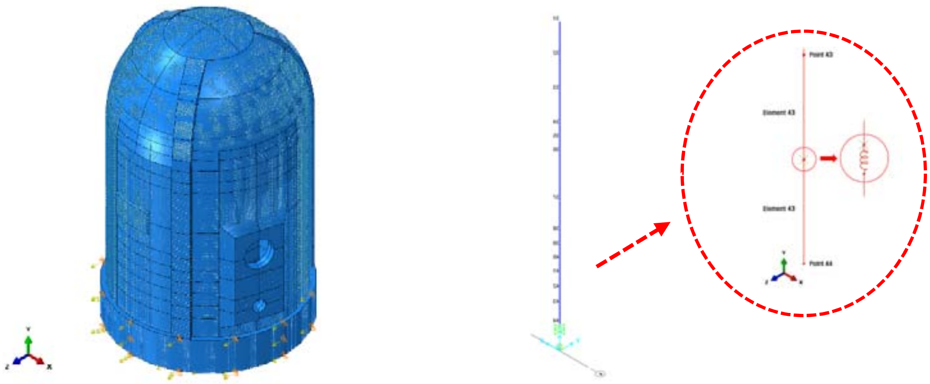

Figure 11. FE model and beam stick model for the RCB

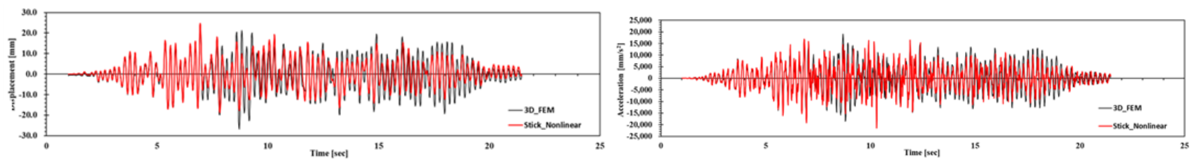


Figure 12. Comparisons of displacement and acceleration time histories

### *Nonlinear SSI Analysis*

For the DBDE, the soil and rock will behave elastic-plastically and their shear strains are generally in between $10^{-4}$ and $10^{-2}$ cyclic shear strain ranges because the soils are highly nonlinear materials during earthquakes, and the contact zone of concrete foundation-soil/rock may represent frictional and slipping behavior. Therefore, both phenomena need to be considered in the seismic margin assessment of NPPs structures against the BDBE.

For the implementation of elastoplastic behavior of soil/rock during shearing deformation under the BDBE, a proper constitutive model and parameters should be applied to the soil/rock model including its volume changes like dilations. A proper relationship of nonlinear shear and volumetric stress-strain should also be defined for detection of yielding or failure of the soil/rock. In that sense, the kinematic hardening model in ABAQUS program is considered to be very appropriate, and the IAEA-TECDOC-1990 (2022) also suggests the program as a representative to simulated the elastoplastic behavior of the soil/rock.

In this study, the nonlinear SSI analysis techniques are developed using ABAQUS program with the kinematic hardening model to simulate the nonlinear soil/rock behaviour in the near field adjacent to the basemat. The developed techniques are verified by comparing the structural responses at the low-level ground input motion, whereas the responses are preliminary compared with the analysis results using the SR model according to JEAC 4601 (2015). Another important factor of nonlinear behavior under the BDBE, friction and slipping behavior between concrete foundation-soil/rock, is implemented using “Fric” model of ABAQUS and is verified with a proper example analysis.

Fig. 13 shows the direct method (DM) and domain reduction method (DRM) with perfect matched layer (PML) which are introduced as the time-domain nonlinear SSI analysis methods in ASCE 4 (2017) and KEPIC STB (2022). Fig. 14 shows the comparison results of nonlinear SSI analyses of the RCB with and without the consideration of a contact behaviour at the concrete basemat. The nonlinear SSI analyses using the SR model are also performed with the same condition, and these responses are compared with the results from the nonlinear SSI analyses with the DRM with PML. As shown in Fig. 14, the floor responses, NL SSI-2, considering structural nonlinearity, soil/rock nonlinearity, and concrete basemat-soil/rock contact at the same time are definitely much smaller than the analysis results considering individual nonlinearity.

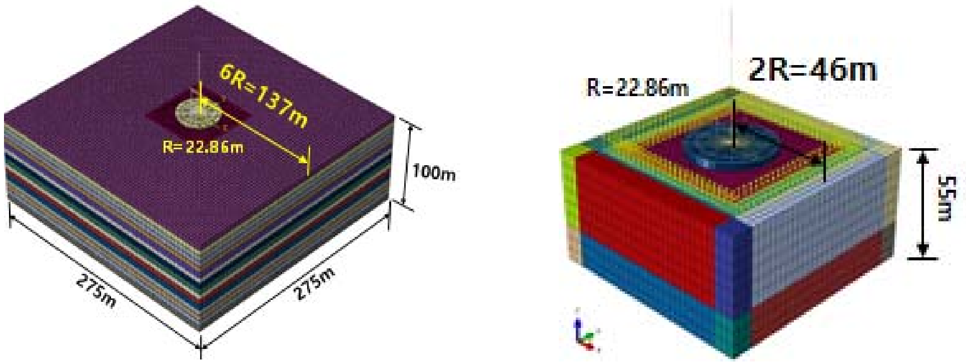


Figure 13. DM model and DRM-PML model for the nonlinear analysis of the RCB

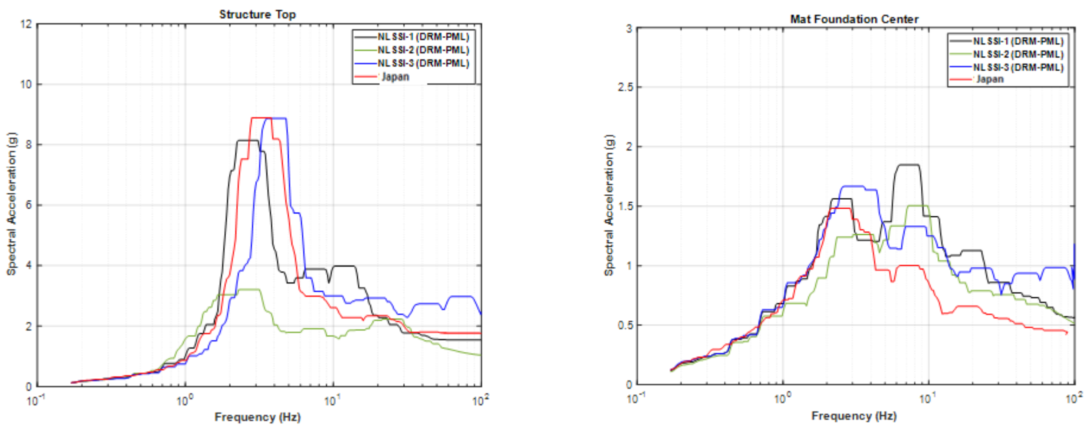


Figure 14. Comparisons of horizontal and vertical direction responses

## CONCLUSION

In this study, the linear and nonlinear seismic analyses of KSNP are carried out under beyond design-basis earthquakes, 0.4g, according to the seismic design standards and analysis procedures in Korea and Japan, respectively. Comparison of the seismic responses and evaluation of the stress level of the structure are also performed. In case of the RCB, significant difference is not shown in the response and the stress and strain levels slightly exceed the concrete cracking range. In case of the AB, the in-plane shear responses in the horizontal direction show the effect of nonlinear behaviour. In addition, this study develops and verifies the nonlinear SSI analysis methodology for their future application to the seismic margin assessment for the NPPs' structures based on the requirements of design codes and their specifications. The developed results are summarized and the responses are also presented in this paper.

The effect of nonlinear behaviour and the validity of the developed nonlinear SSI analysis technology are confirmed through comparisons of the responses of the KSNPs' structures to the BDBE. An additional verification may be required to apply the nonlinear SSI analysis method to the seismic margin assessments of nuclear power plants. In this study, the developed nonlinear SSI analysis technology will be future verified using the earthquake records of existing nuclear power plants.

## ACKNOWLEDGEMENT

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