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# Methodology for Nonlinear Seismic Analysis in Assessment of Nuclear Power Plant Structures

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## 1. Introduction

Performance goals of Nuclear Power Plant (NPP) for 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 DBE ground motion and deterministic approach uses to consistent with the hard-core components' functionality, and in Japan the amplified ground motion for BDBE is used to check deterministically the seismic margin of SSC design based on the DBE Ss. The Ss ground motion allows the nonlinear behaviors of the soil and the superstructures.

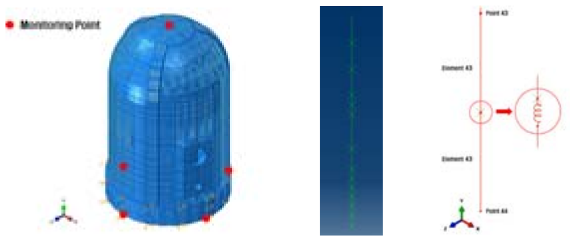
Nonlinear analysis is currently becoming a popular tool for performance and safety evaluations of structure and pipe systems, and the skill has been adapted to assess the safety of NPPs' structures under severe accident condition and a large commercial aircraft impact of the beyond design basis events. In ASCE 4-16 and KEPIC STB (2020 Ed.), the nonlinear seismic analysis methods and its specifications are provided, but the details for the nonlinear analysis and seismic margin assessment are not defined in those design codes.

This paper presents a recent development of the nonlinear soil-structure interaction (SSI) analysis including the nonlinear behavior of superstructure of NPP in Korea, reviews possible arguments for the deterministic approach for the seismic margin assessment of NPPs' structures based on the nonlinear analysis.

## 2. Nonlinear Structural Analysis

The seismic response analysis is to calculate the seismic responses in structure, and the results are applied to design and assessment for the individual SSCs of NPP. For the BDBE, the structure expects the nonlinear behavior due to the factors of concrete crack and steel's yielding, and a simplified model of the structure is necessary for full nonlinear SSI analysis. The simplified model should be demonstrated by an appropriate method that the model does not include the error of the analysis results. Luckily, JEAG 4601-2015 provides the details for the simplified model such as skeleton curve and hysteresis model for the nonlinear analysis. And the safety criteria for concrete structure is also defined as the shear strain of $2X10^{-3}$, and these specifications are already demonstrated through a long time researches. This study makes both models of three-dimensional finite element and simplified beam stick model, and the demonstration are performed using a large-scale shear wall test results.

Fig. 1 shows both models of three-dimensional FE model and beam stick model for the containment structure, and the comparison results of both modelling methods represent in Fig. 2. As shown in figures, the displacement and acceleration responses are good agreed in both model analyses as an error less than 5%.




(a) FE model (b) Beam stick model

Fig. 1. Analysis models for the containment structure

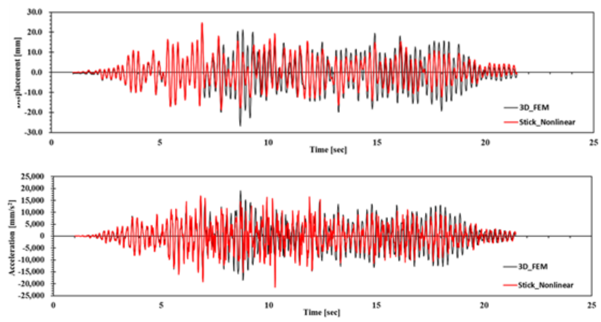



Fig. 2. Comparison of displacement and acceleration time histories

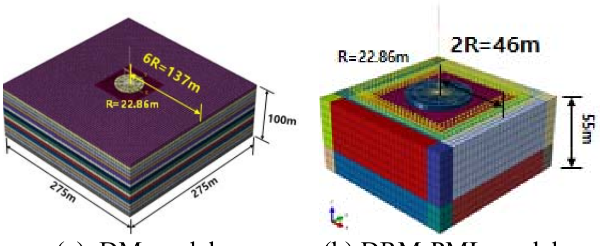
## 3. Nonlinear Soil-Structure Interaction Analysis

For the DBDE, the soil and rock will behave elastic-plastically and its shear strains are generally 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 taken account for the seismic margin assessment of NPPs structures against the BEDE.

For consideration of the elastoplastic behavior of soil/rock during shearing deformation under the BDBE, a proper constitutive model and parameters should be applied for the soil/rock model including its volume changes like dilations. And a proper relationship of nonlinear shear and volumetric stress-strain should be also defined for detection of yielding or failure of the soil/rock. In that sense, the kinematic hardening model of ABAQUS program is judged to be very appropriate, and the IAEA-TECDOC-1990 also suggests the program as a representative to represent 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 and the verification is carried out by comparing in-structural responses to low-level ground input motion, and the responses are preliminary compared with the results according to JEAG 4601-2015's seismic analysis procedure. Another important factor of nonlinear behavior under the BDBE, friction and slipping behavior between concrete foundation-soil/rock, is implemented using ABAQUS Fric model and verified with a proper example analysis.

Fig. 3 shows the analysis models for applying the direct method (DM) and domain reduction method (DRM) as the nonlinear SSI analysis methods allowed in ASCE 4-16 and KEPIC STB. And Fig. 4 shows the comparison results of nonlinear SSI analyses of the containment structure as the conditions of with and without contact behavior at the concrete foundation. An analysis model with the sway-rocking (SR) spring idealized the soil behavior based on JEAG 4601-2015 is also used for the nonlinear SSI analysis as the same condition, and the responses are compared with the results of this study; DRM with perfect matched layer (PML). The responses under the condition that considers structural nonlinearity, soil/rock nonlinearity, and concrete foundation-soil/rock contact are definitely much smaller than the analysis results considering individual nonlinearity.




(a) DM model (b) DRM-PML model

Fig. 3. Analysis models for the containment structure

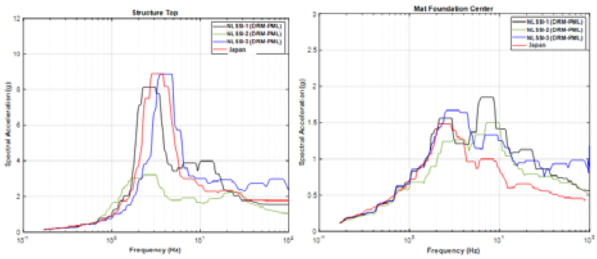



Fig. 4. Comparison of horizontal and vertical direction responses

## 4. Summary and Discussions

This study includes the development and verification of the nonlinear SSI analysis methodology to be applied to the seismic margin assessment for the NPPs' structures based on the requirements of design codes and their specifications, and the developed results are summarized in this paper.

Although the models and the analysis methods in this study are based on ASCE 4-16 and KEPIC STB, verification and validation for the nonlinear SSI modelling and simulation using commercial software ABAQUS may be additionally required in the time domain for the seismic margin assessment and its licensing of NPPs' structures. Especially, the volume changes in soil/rock modeling according to level of shear stress and strain may be important for the accuracy in modeling and analysis results.

This study applied the kinematic hardening model for simulating soil/rock nonlinear behavior, and at low-level ground input motion, the analysis accuracy is verified. The shear strain-stress cyclic behavior can be largely different according to the level of ground input motion, therefore if this condition is not considered in the simulation, the error rate of the nonlinear SSI analysis can be increased. In case of the rock, it is judged that this effect in cyclic response is expected to be small, but verification is necessary.

## Acknowledgement

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