Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

NON-LINEAR SOIL-STRUCTURE INTERACTION ANALYSIS OF NUCLEAR POWER PLANT STRUCTURE USING MULTIPLE SEISMIC INPUTS

Youngsun Jang[1], Tae Min Kim[2]

[1] General Director, KONES Corp., Seoul, KOREA (ysjang@kones21.com)
[2] Section Chief, KONES Corp., Seoul, KOREA (kimtm@kones21.com)

INTRODUCTION

To improve the seismic capacity of Nuclear Power Plants, the concept of non-linear SSI (NLSSI) analysis was studied and is being applied to actual Nuclear Power Plant structural analysis. In this study, NLSSI analysis of Korean Nuclear Power Plant structures in the time domain was performed using the ABAQUS program. Parameters for NLSSI analysis include input motion, shear wave velocity profile of the supporting medium, and material properties of the superstructure. About 30 acceleration time histories were generated for the UHS ground response spectrum input and NLSSI analysis will be performed. These analysis results are provided for evaluating subsequent probabilistic seismic safety.

DOMAIN REDUCTION METHOD

DRM (Domain Reduction Method) is a method proposed by Bielak et al. by developing several theories for calculating effective seismic force, and is the most widely used technique when analyzing NLSSI by adopting the sub-structure method. This method is also provided in LS-DYNA (Lee et al., 2014).

The core concept of DRM is to express the problem to be analyzed as a superposition of a sub-structure that calculates the effective seismic force and a sub-structure that represents wave radiation due to this load. The effective seismic force is calculated using the mass matrix and stiffness matrix of the thin layer (one layer in finite element analysis) and the free field response in front and behind the thin layer.
ESSI, a representative time-domain NLSSI analysis software developed by applying DRM, has a DRM layer located outside the ground finite element as shown in Figure 1 and does not overlap with the energy absorption layer. ESSI is being developed by Professor Jeremic's research team at UC Davis, uses a Rayleigh damping layer as an energy absorption layer, and has the feature of providing a wide variety of non-linear constitutive models of the ground soil (Jeremic et al., 2011, Jeremic, 2016).

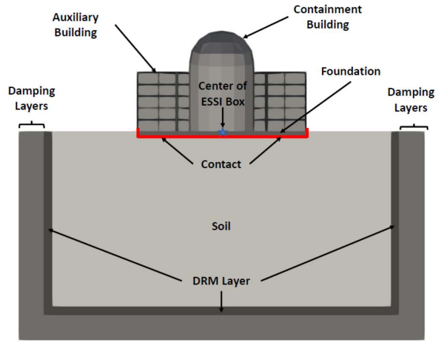

Figure 1. NLSSI Modeling Concept of ESSI Simulator Applying DRM and Rayleigh Damping Layer (Feng et al., 2016, Jeremic, 2016)

STRUCTURE MODELING

The structural analysis model of the Auxiliary Building of OPR1000 is divided into two parts, one is the finite element model of the shell element for the reinforced concrete shear wall structure above the foundation surface, and the other is the Domain Reduction Part below the ground surface.

For the structure model on the foundation, the shear wall and slab were modeled with thick shell elements, and some columns were modeled with beam elements. In total, 18,400 thick shell elements and 700 beam elements were used, as shown in Figure 2.

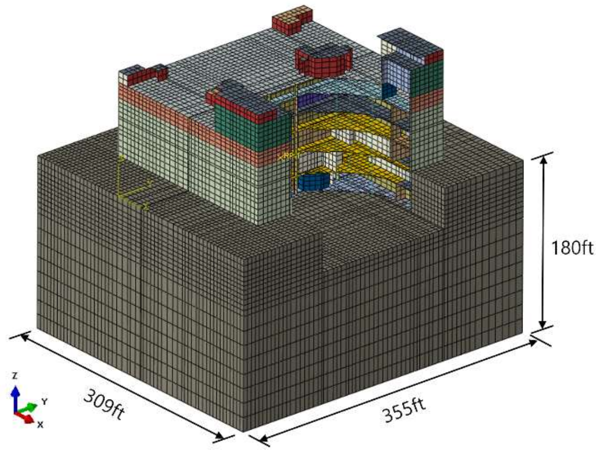

Figure 2. DRM Analysis Model

The Domain Reduction Part is the intermediate area between the ground soil and the structure, and was determined to be 309 ft (94m) x 355 ft (108m) considering the size of the structure model, which is 209 ft (64 m) x 235 ft (72 m) (Figure 3). In the depth direction, 180 ft (55 m) into the bedrock was modeled.

ANALYSIS PARAMETERS

There are several NLSSI analysis variables reflected in the analysis in this study, including seismic input motion, shear wave velocity profile, ground soil characteristics, and concrete material properties. The relationship between these variables and NLSSI can be shown as Figure 3.

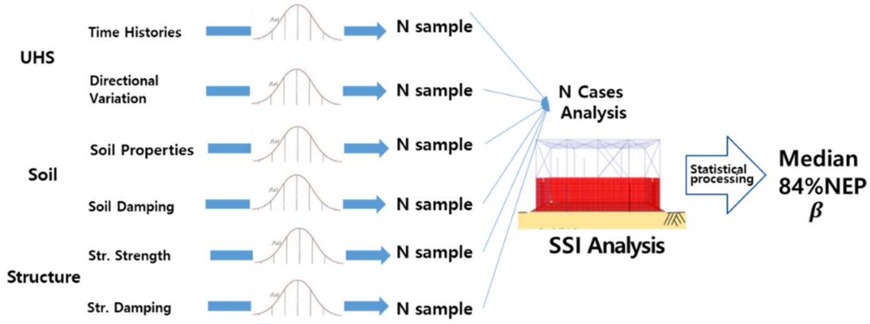

Figure 3. NLSSI Analysis Scheme with parameters

Seismic Input Motion

The seismic input of NRC Regulatory Guide 1.60 is mainly applied to the seismic design of Nuclear Power Plants. However, since this study is part of the seismic capacity evaluation of existing Nuclear Power Plants, the seismic input for evaluation of NUREG/CR-0098 and site-specific GMRS (Ground Motion Response Spectra) were applied.

First, an analysis was conducted on the UHS (Uniform Hazard Spectrum) of the Hanul Nuclear Power Plant site, which was preliminary calculated based on the site specific input motion of the Korean Nuclear Power Plant site. ZPA (Zero Period Acceleration) is the lowest initial level of 0.3g and is shown in Figure 4. An artificial acceleration time history compatible with UHS was created and used as an input motion, and the response spectrum can be seen to match well as shown in Figure 5.

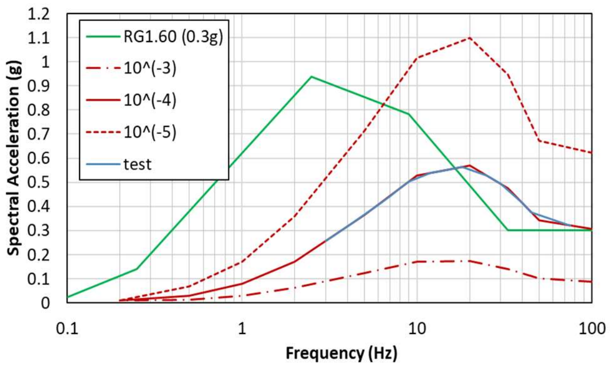

Figure 4. Input Motion Response Spectra (UHS)

To use the site specific GMRS as an input earthquake in the time domain, it was converted into a time history, and about 30 time histories were generated considering the directional variability for the 0.5g level. The acceleration time history curves for each direction generated by Response Spectrum Matching, as shown in Figure 5, are shown in Figure 6.

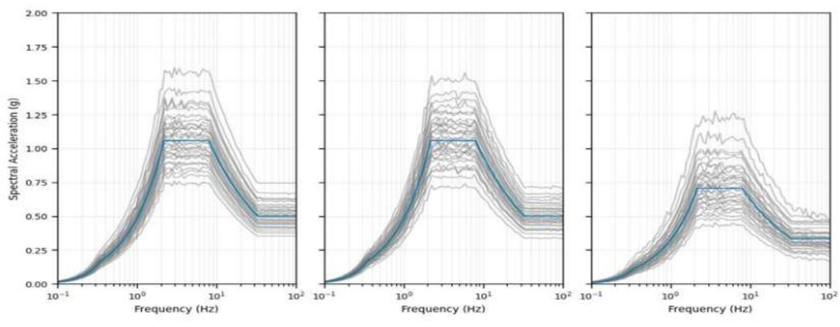

Figure 5. Response Spectrum Matching in Time History Generation

Shear Wave Velocity Profile

As for the site soil conditions, the shear wave velocity profile at NI (Nuclear Island) of Shin-Gori Units 1 and 2, where the OPR1000 reactor type was built, was applied, and the NI foundation was built on a Moderate Rock or harder. According to the FSAR of Shin-Kori Units 1 and 2, the shear wave velocity at the bottom of the foundation is approximately 6,600 ft/sec (2,010 m/sec) (Figure 8).

For the shear wave velocity distribution in Figure 8, a normal distribution curve with a standard deviation (σ=1005) corresponding to a coefficient of variation of 0.5 was drawn, and 30 shear wave velocity distributions were randomly sampled (Figure 9).

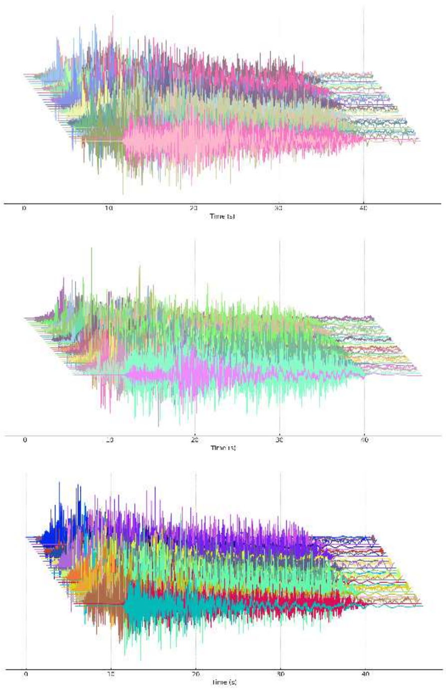

Figure 6. Acceleration Time Histories

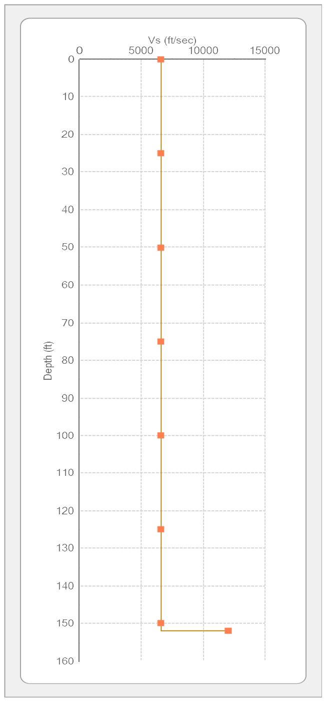

Figure 7. Shear Wave Profile of OPR1000

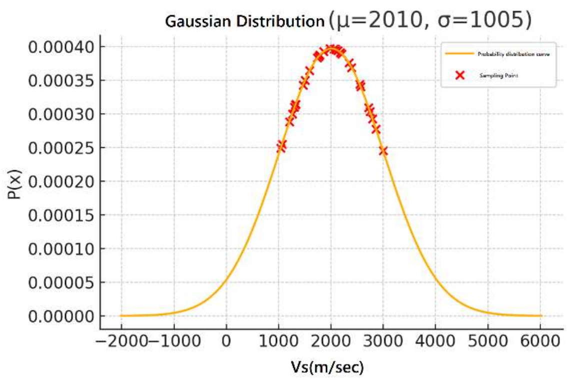

Figure 8. Gaussian Distribution of Shear Wave Profile

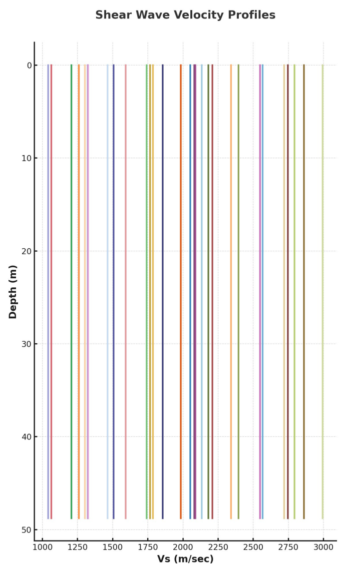

Figure 9. 30 Samples of Shear Wave Profile

Ground Soil Property

Because the ground soil properties of Shin-Kori Units 1 and 2 were above average rock, no tests were conducted on changes in shear modulus and damping ratio according to shear strain. Therefore, the generally applied Idriss rock characteristic curves were applied (Figure 10).

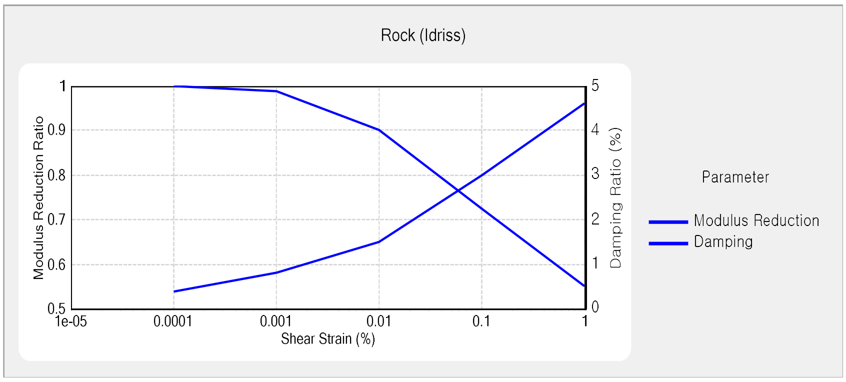

Figure 10. Material Properties of Rock by Idriss

Concrete Material

The non-linear material properties of reinforced concrete were applied to the non-linear model provided by the analysis program ABAQUS, and are shown in Figure 11. The elastic modulus in the linear state is Ec = 4.03x106 psi (27.8 GPa).

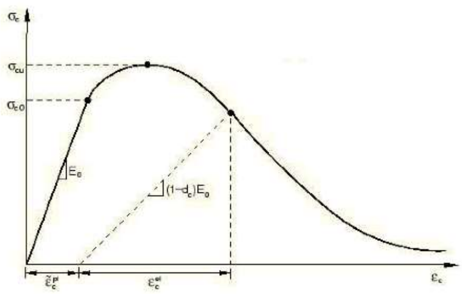

Figure 11. Material Property of Reinforced Concrete

ANALYSIS PROCEDURE

Non-linear SSI analysis was performed using ABAQUS. ABAQUS is a suite of powerful engineering simulation programs, based on the finite element method, which can solve problems ranging from relatively simple linear analyses to the most challenging non-linear simulations. ABAQUS contains an extensive library of elements that can model virtually any geometry. It has an equally extensive list of material models that can simulate the behaviour of most typical engineering materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock. Designed as a general-purpose simulation tool, ABAQUS can be used to study more than just structural (stress/displacement) problems. It can simulate problems in such diverse areas as heat transfer, mass diffusion, thermal management of electrical components (coupled thermal-electrical analyses), acoustics, soil mechanics (coupled pore fluid-stress analyses), and piezoelectric analysis.

NLSSI was performed through the following analysis procedures.

① Super-structure modeling: Figure 2
② DRM Part modeling

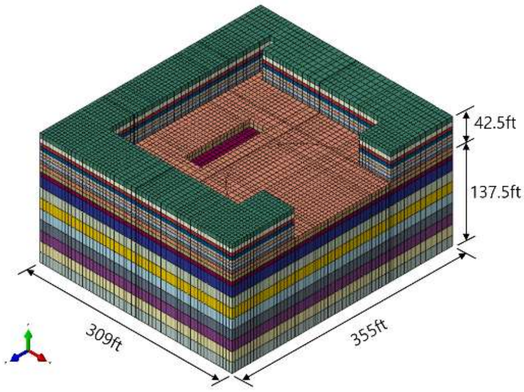

Figure 12. Analysis Model of DRM Part

③ Analysis Modeling for DRM Loads

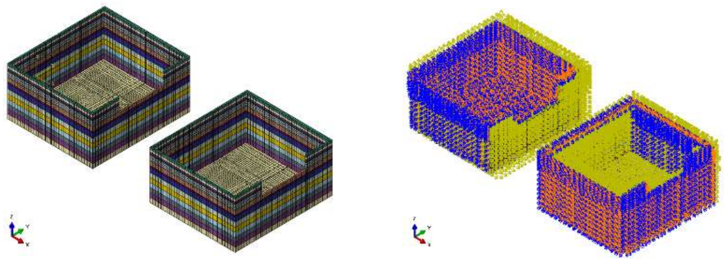

Figure 13. Analysis Model, Load Conditions and Boundary Conditions for Calculating DRM Effective Seismic Load

④ Site Response Analysis by Pro-Shake

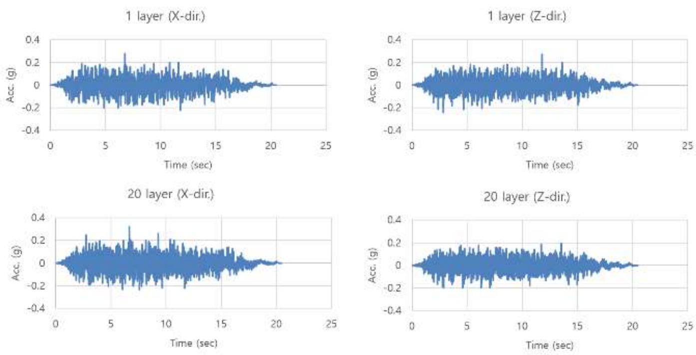

Figure 14. Site Response Analysis Results for Input

⑤ DRM(u_{FF}) load calculation according to shake input

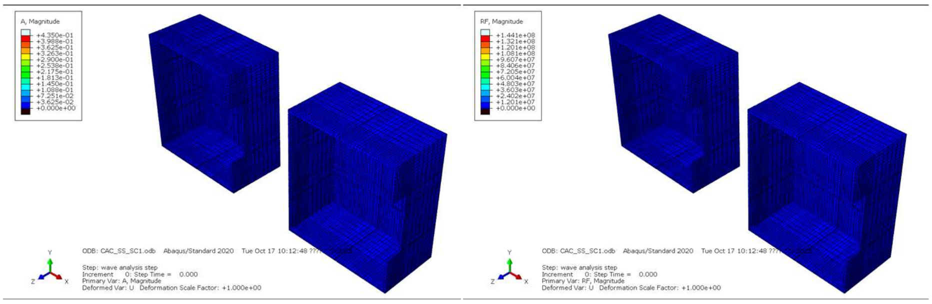

Figure 15. Acceleration Response by Input and Reaction Response
by Acceleration Response

⑥ Seismic response analysis for free-field ground model

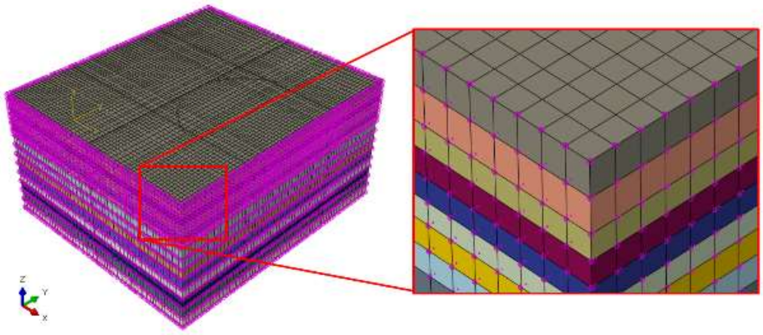

Figure 16. Energy Absorption Boundary Condition: Viscoelastic Boundary Applied

⑦ Seismic response analysis for ground model

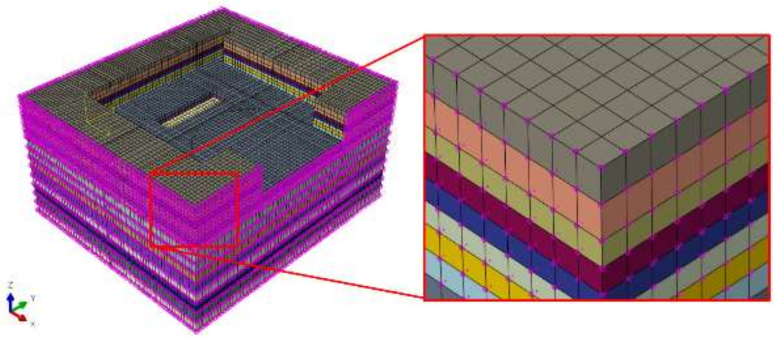

Figure 17. Energy Absorption Boundary Condition: Viscoelastic Boundary Applied

⑧ Seismic response analysis for the whole analysis model

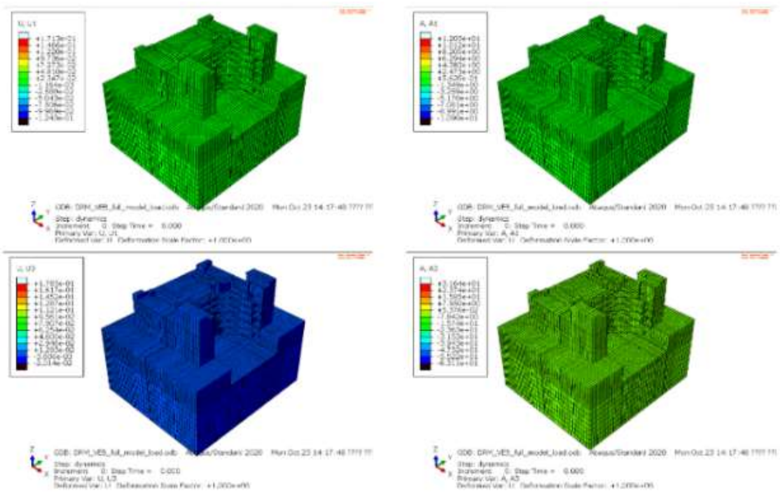

Figure 18. Analysis for the Whole Analysis Model

⑨ Floor response spectrum extraction for the whole analysis model

NLSSI Analysis

NLSSI analysis will be performed using a combination of the 30 time histories, shear wave velocity distributions, and superstructure stiffness variables described above.

CONCLUSION

The NLSSI (Nonlinear Soil-Structure Interaction) analysis process, along with the required variables and probabilistic sampling methods, has been reviewed. By conducting NLSSI analysis across a wide range of variable combinations, more realistic Floor Response Spectra (FRS) can be derived compared to linear analysis. As a result, the High Confidence of Low Probability of Failure (HCLPF) can be recalculated, thereby contributing to a reduction in the Core Damage Frequency (CDF).

ACKNOWLEDGEMENTS

This study was supported by the Technology Innovation Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. RS-2022-KP002849)

REFERENCES

N Bielak, J., Loukakis, K., Hisada, Y. and Yoshimura, C., *Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part I: Theory, Bulletin of the Seismological Society of America, 93(2), 817-824,* 2003

Lee, G.H., Hong, K.Y., Lee, E.H., Kim, J.M., *Verification of Linear FE Model for Non-linear SSI Analysis by Boundary Reaction Method, COSEIK J. Comput. Struct. Eng., 27(2), 95~102,* 2014

Feng, Sinha, Abell, Yang, Behbehani, Orbovic, McCallen, Jeremic, *Non-linear Effects in Earthquake Soil Structure Interaction of Nuclear Power Plants, SMiRT24,* Busan, Korea, 2017

Jeremic, B., *Development of Analytical Tools for Soil-Structure Analysis, Final Report to CNSC-CCSN, Contract No. 87055-10-0266*, 2016

Jeremic, B., Tafazzoli, N., Kamrani, B., Tasiopoulou, P., Jeong, C., *Report to NRC on: Investigation of Analysis Methods to Incorporate Multi-Dimensional Loading and Incoherent Ground Motions in Soil-Structure Interaction Analysis,* Department of Civil and Environmental Engineering, University of California, Davis, 2011

Seed, H. Bolton and Idriss, I. M., *Soil Moduli and Damping Factors for Dynamic Response Analysis, Report No. UCB/EERC-70/10, Earthquake Engineering Research Center, University of California, Berkeley, December, 48p,* 1970

ACS SASSI NQA Version 4.3.3 (IKTR3.3) *Including Options A-AA and NON An Advanced Computational Software for 3D Dynamic Analysis Including Soil-Structure Interaction User Manual Revision 7*, January 31, 2022

Jung Gon, Ha (2024). *Deterministic/Probabilistic Assessment of ISRS for Seismic PSA (Probabilistic Soil-Structure Interaction Analysis)*, Seismic PSA Issues and Current Issues Workshop, Korea Atomic Energy Research Institute (KAERI).

Youngsun Jang, Youngoh Lee (2024). *Seismic Response of NPP Considering the Non-Linear Soil-Structure Interaction Effects with DRM*, 31st International Conference on Nuclear Engineering (ICONE31), Prague, Czech.

NRC NUREG/CR-0098, *Development of criteria for seismic review of selected nuclear power plants,* 1978

Products: *ABAQUS/Standard/Explicit/CAE, 18.5.3 Concrete damaged plasticity*

https://*classes.engineering.wustl.edu/2009/spring/mase5513/abaqus/docs/v6.6/books/gsa/default.htm?startat=ch01.html*