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SSI Analysis for Base-Isolated Nuclear Power Plants Using Iterative Approach

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1. Introduction

The nuclear accident due to the recent earthquake in Japan has triggered importance of safety of nuclear power plants(NPP). Therefore, safety of NPPs much higher than other structures is required. An earthquake is one of the most important parameters which govern safety of NPPs among external events. Application of base isolation system for NPPs can reduce the risk for earthquakes. At present, a soil structure interaction(SSI) analysis is essential in seismic design of NPPs in consideration of ground structure interaction. In the seismic analysis of the base-isolated NPP, it is restrictive to consider nonlinear properties of seismic isolation bearings due to linear analysis of SSI analysis programs such as SASSI. Thus, in this study, SSI analyses are performed using an iterative approach considering material nonlinearity of isolators.

2. Methods and Results

In this section, how the SSI analysis model is set up is described. Analysis model description, seismic input motions, isolator design, and concept of an iterative analysis are included in detail. Also, the results of soil-structure interaction for the analysis model are shown in the following.

2.1 Analysis Model

A model applying an iterative approach consists of Reactor Containment Building(RCB), Reactor Containment Internal Structures, Reactor Coolant System and Auxiliary Building(AB), and isolation system. Except basemats of upper and lower structures, all upper structures including isolators are modeled with beam elements which have linear properties. Specifically the isolators are described with effective stiffness and effective damping ratios. The RCB and AB structure are represented by lumped mass beam-stick models in seismic analysis. AB is separated into four individual-area sticks, which are interconnected by horizontal beams whose stiffness are adjusted to simulate diaphragm behavior of slabs.

454 isolators are installed in the analysis model connecting an upper basemat of upper structures to a lower basemat of bottom. In the iterative analysis, a bilinear model is considered for isolators and described in the Section 2.3 in detail. In this study, Lead-plug Rubber Bearings(LRB) are representatively used. The finite element model is shown in Fig. 1.

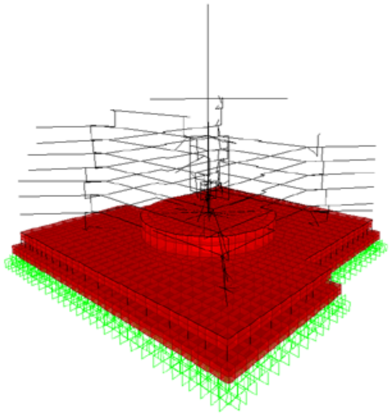

Fig. 1. Finite element model.

2.2 Seismic Input Motion

Seismic input motions are design spectrum compatible ground motions, matched to the US NRC Regulatory Guide(RG) 1.60. They are developed by enveloping RG 1.60 of US NRC as the base which is enriched to the higher frequency range. The spectral matching for these input motions is performed at multiple damping ratio targets. The spectrally matched input motions are scaled to 0.5g of peak acceleration for Safe Shutdown Earthquake. Fig. 2 shows the final input motions which envelop target spectrums and satisfy Standard Review Plan(SRP) 3.7.1 of US NRC.

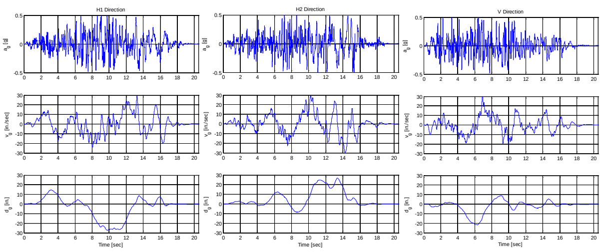

Fig. 2. Seismic input motions based on US NRC RG 1.60.

2.3 Isolator Design

The analysis model is supported by 454 isolators distributed between the upper basemat of superstructures and the lower basemat. The isolators are designed and installed to satisfy a target frequency of base-isolated NPPs. It is very important for isolators to meet displacement criteria as well as to support upper structures. The bilinear material properties of isolators are schematically shown in Fig. 3 and the properties of isolators are described in Table I.

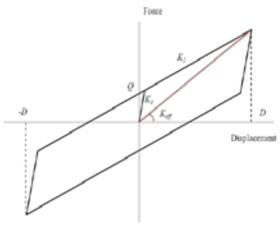

Fig. 3. Bilinear material properties of isolators.

Table I: Isolator properties

Parameters	Value
K_1	4814.19 kip/ft
K_2	481.419 kip/ft
F_y	104.575 kip
Q_d	94.118 kip
D	0.984ft
K_{eff}	577.042 kip/ft
ξ_{eff}	0.103

2.4 Iterative Approach

Iterative approach is originally used for site response analysis on soil properties. By using effective shear strain of soil, the analysis is iteratively performed to find free field site response[1]. The same approach was employed in the previous research[2]. In this study, the same approach is applied for the iterative SSI analysis but the upperstructure and seismic input motions are different. The concept of iterative approach for soil and bearings are shown in Fig. 4 and it shows how we can apply the iterative approach to SSI analysis for base isolated structures. Fig. 5 illustrates how the approach can be done iteratively.

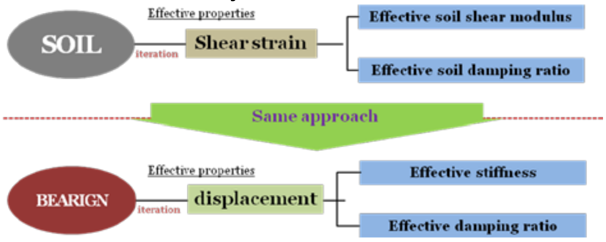

Fig. 4. Concept of iterative approach considering material nonlinearity of bearings.

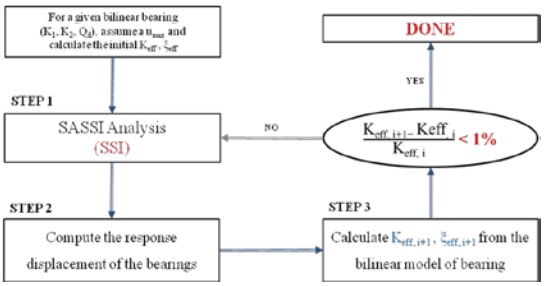

Fig. 5. Flowchart of iterative approach for base-isolated structures.

2.5 SSI Analysis Results

During iterative analysis, convergency should be checked at each of iterations based on effective stiffness of isolators. The effective stiffness can be converted to effective displacement and convergency of iteration can be easily identified using a load vs. displacement curve. Fig. 2 shows how well effective displacements for each of iterations are converged to an original load-displacement curve of the isolator.

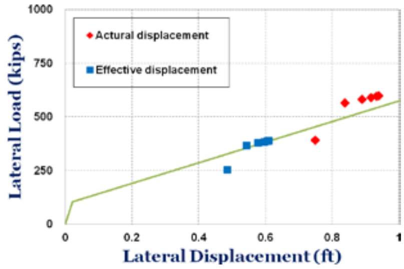

Fig. 6. Load-displacement curve of the isolator showing iteration steps

Fig. 7 shows spectral accelerations of SSI analysis results at each elevation of RCB. The red line is horizontal input motion, the gray lines are spectral accelerations for linear(non-iterative) SSI analyses, and the colorful lines are spectral accelerations for iterative SSI analyses.

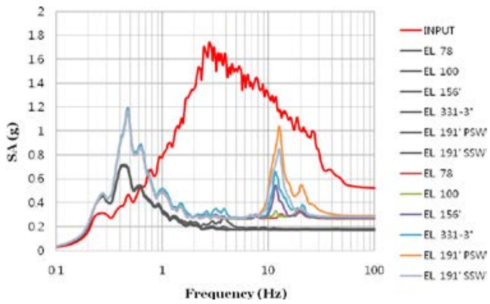

Fig. 7. Comparison between horizontal spectral accelerations for linear(non-iterative) analysis and iterative analysis.

3. Conclusions

By performing the SSI analysis using an iterative approach, nonlinear properties of isolators can be considered. The results of the SSI analysis show that the response of the base-isolated NPP with base isolation systems is significantly reduced horizontally. Also, the results of the SSI analysis using a linear(non-iterative) approach underestimate the spectral acceleration because the effective linear model can not consider nonlinear properties of isolators.

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