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MECHANISTIC AND PROBABILISTIC SEISMIC ASSESSMENT OF STRUCTURES AND COMPONENTS IN NUCLEAR POWER PLANTS

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ABSTRACT

The purpose of this current research project at the Ohio State University is to perform realistic assessment of risk from seismic and other external and internal events by performing structural analyses and uncertainty analyses for commercial nuclear power plants (NPP). This paper summarizes the overall research project and then describes dynamic response of two- and three-dimensional models of a containment structure. The effects of number and type of elements used in the detailed finite element (FE) models are discussed. Dynamic and modal responses of the FE models, continuous mass stick model, and lumped mass stick model are compared. The goal is to develop sufficiently accurate and simple structural models so that they can be quickly analyzed under multiple input ground motions for seismic probabilistic risk assessment (SPRA). The project aims to integrate SPRA with internal events PRA for NPP structures and to estimate the failure probabilities of nonstructural components under specified ground motions.

INTRODUCTION

Although there has been assessment of external event risks at nuclear power plants (NPPs), the potential magnitude of external event risks and their combined effects, e.g., seismic and flood, was made evident by the events at the Fukushima Nuclear Power Plant. The methodology for performing seismic probabilistic risk assessment (SPRA) has evolved over the past forty years. Some aspects of that methodology are believed to be extremely conservative. With support from the U.S. Department of Energy (DOE), a research project at The Ohio State University (OSU) is developing a toolset and framework for the examination of seismic and other external event risks at NPPs, which could be used to incorporate methodological improvements developed within the DOE's Risk Informed Safety Margins Characterization (RISMC, 2015) program, as well as integrating these events with the internal event probabilistic risk assessment (PRA). The goal is to develop a new dynamic failure analysis module within the Multiphysics Object-Oriented Simulation Environment (MOOSE), which is a computer simulation environment developed at Idaho National Laboratory (INL) (Gaston et al., 2009).

The current DOE funded research at OSU has four major analysis steps comprising traditional SPRA: 1) seismic hazard analysis and development of input ground motions considering earthquake and site characteristics, 2) structural model development for systems, structures, and components (SSCs) at a NPP site, 3) calculation of probability of failure of SSCs including common cause relationships, and 4) system analysis to calculate the frequency of core damage. As part of this research project, to date, simplified lumped mass stick models and detailed finite element (FE) models of representative NPP structures have been developed using commercial software to reduce the computational demand in uncertainty quantification. Structural failure probabilities of critical components are being calculated. Modal analyses are performed using stick and FE models for the containment structure to determine dynamic properties including mode shapes and fundamental frequencies. Dynamic time history and response spectrum analyses of the 2-D and 3-D stick models have been performed. Dynamic accelerations, displacements and response spectra are calculated at critical heights of the containment building. The data will be used to develop fragility functions of nonstructural components such as pipe or cabinet systems that may be attached to the containment structure.

Figure 1 presents the proposed framework for performing of SPRA within the MOOSE environment and integrating it with the internal event PRA. Through the seismic hazard analysis, the external loads for SSCs are characterized. In addition, soil-structure interaction are considered in modeling of the building structure. Essential structural and non-structural components (NSCs) in NPPs are selected for critical accident scenarios induced by seismic shaking. Their seismic performance is analyzed using various structural dynamic analyses of FE models, and their failure probabilities are estimated comparing to their fragility functions. These items are based on a dynamic analysis of plant system behavior, failure modes, and secondary effects on other components (such as the failure of a tank leading to the release of water which leads to failure of a pump), while accounting for uncertainties in a mechanized fashion through RAVEN (Rabiti et al. 2012). This main structural analysis module is planned to be programmed to operate under the MOOSE platform (Gaston et al. 2009). Also, different software tools including OpenSees (2015) and SAP2000 (2015) are being used to develop and validate simplified structural models or "lumped mass stick models" of SSCs so that various linear or nonlinear dynamic analyses can be efficiently performed to develop fragility curves of different components. More detailed finite element modeling and analyses are performed using the commercial software ANSYS (2015) to initialize the detailed uncertainty analysis.

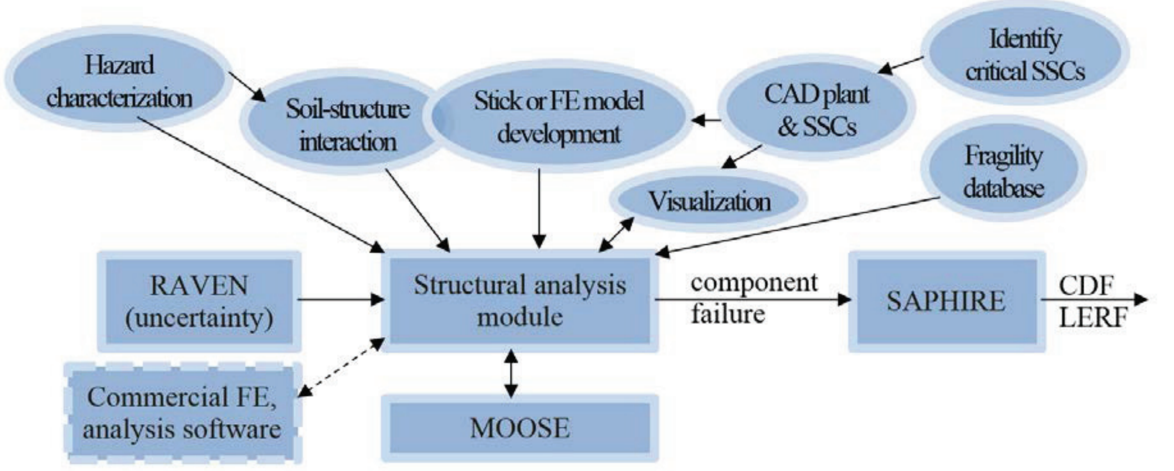


Figure 1. Flowchart of the approach to seismic probabilistic risk assessment.

One of the challenges of this research is the development of prototypic demonstration cases. Detailed design information and risk assessment studies for actual nuclear power plants are not publicly available information. The most detailed publicly available NPP and system risk information are provided in the support documents to NUREG-1150 (1990) and other reports such as Smith et al. (1981). Although some important details are missing, much information can be inferred from the data provided in these reports. Thus, the case studies involve a pseudo-plant design that has realistic features of actual nuclear power plants but does not represent a specific nuclear power plant.

The research team has been collaborating with utility and industry partners. Based on their system knowledge, the industry and utility partners have provided information to assure that the features of the pseudo-plant used in the case studies are realistic. This requires characterization of a number of features that include both plant geometry and system descriptions, locations of equipment within the plant.

SEISMIC PRA APPROACH

The details of the research approach and activities that are being performed are the following (Figure 1):

1) *Determine input ground motion(s) at the NPP site representing the dynamic seismic loads to be applied on the structural models.* This activity (indicated as “Site characterization” in Figure 1) provides the input for the structural models that are developed and analyzed. Soil-structure interaction effects need to be considered separately to determine the actual input load on the plant buildings. Currently, we assume that the power plant is located on a rock site in central and eastern United States (CEUS). Ground motions selected in this research will match the specified GMRS for typical CEUS rock site (EPRI 1015108, 2007).

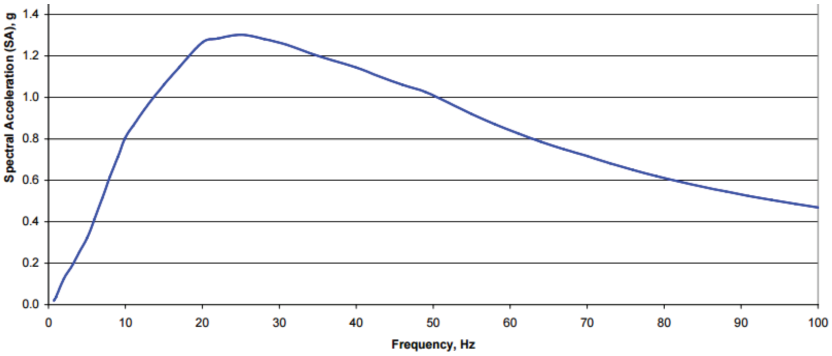


Figure 2. Target Ground Motion Response Spectrum (GMRS) for typical CEUS rock site (EPRI 1015108, 2007).

2) *Develop a list of SSCs included in the PRA model, for which seismic fragilities and spatial interactions are to be obtained.* Since there are various building structures and diverse NSCs in NPPs, the first step of an SPRA is the development of a Seismic Equipment List (identified as “Critical SSC’s” in Figure 1). The critical SSCs are selected in order to quantify those combinations of system failures leading to core damage, referred to as cut sets.

3) *Develop finite element models of plant SSCs and FE model of the global structure.* For the implementation of the proposed method and to illustrate the modeling and analysis procedures, characteristic structures and systems are analyzed for the pseudo-design. For the purpose of our first case studies, the following structures have been identified for analysis: a reactor containment building, an auxiliary building, and condensate storage tanks.

4) *Perform seismic analysis of plant structures for the input time histories developed in Step 1 above to calculate seismic displacements, stresses, forces and moments on structural components, equipment and structural system.* The structural analysis module will be validated using simplified stick models in structural analysis programs (e.g., SAP2000, OpenSees, 2015) or with detailed models using commercial FE software (e.g., ANSYS, 2015). The simplified stick models are necessary to reduce the enormous computational demands for uncertainty quantifications. Therefore, both detailed 3D models and simplified stick models are developed, and their dynamic analysis results are compared for the validation of the simplified stick models. Modal analyses are performed to determine dynamic properties including mode shapes and fundamental frequencies. Dynamic time history and response spectrum analyses of FE models are conducted, and the results are compared.

5) *Obtain fragility parameters for the selected SSCs and assess the probabilities of failure of safety-related SSCs.* Various industry and U.S. Nuclear Regulatory Commission (NRC) databases exist for the fragility of characteristic equipment that will be a resource to the tool set (Bandyopadhyay et al.1991, and EPRI 1994). The capability will also be provided in the structural analysis module for the determination of the fragility of simple systems by analysis.

6) *Use conditional failure probabilities of SSCs obtained in Step 5 with frequency of seismic input load levels to determine SSC failure probability as a function of earthquake magnitude.*

7) *Combine seismic failure of SSCs with internal event PRA to obtain seismic PRA (SPRA).* Calculate risk measures such as consequence exceedance curves, core damage frequency (CDF), and large early release frequency (LERF). The goal is to include an interface between the seismically-induced failure assessment and the Level 1 PRA modeling performed in SAPHIRE (Smith et al. 2009). In order to account for uncertainties, the process is repeated many times using a sampling scheme to obtain confidence levels of the output risk measures. The process will be automated in this project.

This project aims to assemble a tool set to establish the interfaces among each of the SPRA steps listed above. The overall process is demonstrated for an example problem. The challenge for this project has been development of an SPRA capability that can be exercised by an analyst reliably with a reasonable amount of training and provide analysis tools that better enable the analyst to verify models or interpret results. The SPRA capability is also needed to provide the flexibility to address the range of containment designs and systems encountered in the existing population of plant designs, to explore potential improvements in SPRA methodology, or to apply the analysis to the assessment of specific issues.

MODELING AND ANALYSIS OF PSEUDO-PLANT

Building configurations for the Zion and Surry power plants (Figure 3) are used as guidance to develop models for the pseudo-plant buildings and their configuration. Specifically, containment structures, auxiliary building, and condensate storage tanks are modelled in this research.

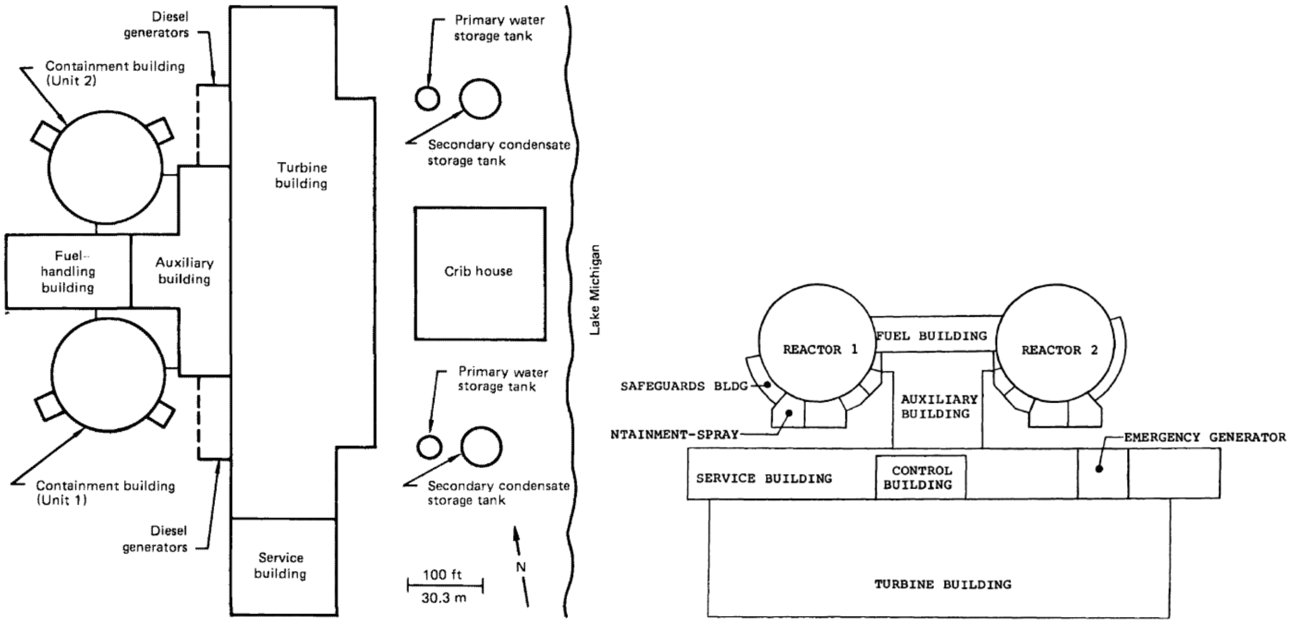


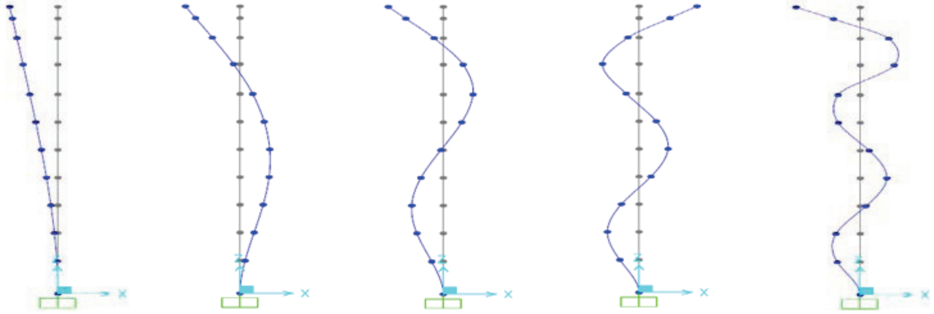
Figure 3. Site plan of Zion (left) and Surry (right) nuclear power stations (Smith et al. 1981, and Bohn et al. 1987).

Modeling and Analysis of Reactor Containment Building

FE and lumped mass stick models of the concrete containment structure were generated (Figure 4). The base of the structure is assumed to be fixed. Modulus of elasticity and shear modulus of concrete are assumed to be 6.8×10^6 N and 2.6×10^6 N, respectively. Unit weight and Poisson's ratio of reinforced concrete are assumed to be 150 kN/m^3 and 0.278, respectively. In order to obtain reliable numerical models with an appropriate number of finite elements, sensitivity analyses were conducted. Various types of finite elements including 10-node tetrahedral elements, 8-node solid hexahedral elements and 20-node solid hexahedral elements were used and the calculated dynamic responses were compared. Different numbers of elements, such as 492 (minimum number), 2736, 4864, 7600, and 12640 (maximum number), were used in order to optimize the size of FE models with sufficient accuracy.

(a) (b) (c) (d) (e)

Figure 4. Numerical models of the containment structure: (a) Containment building (SASSI Manual, 2009), (b) FE model with 12,640 elements, (c) FE model with 492 elements, (d) simplified model with continuous mass distribution, and (e) simplified stick model with lumped mass

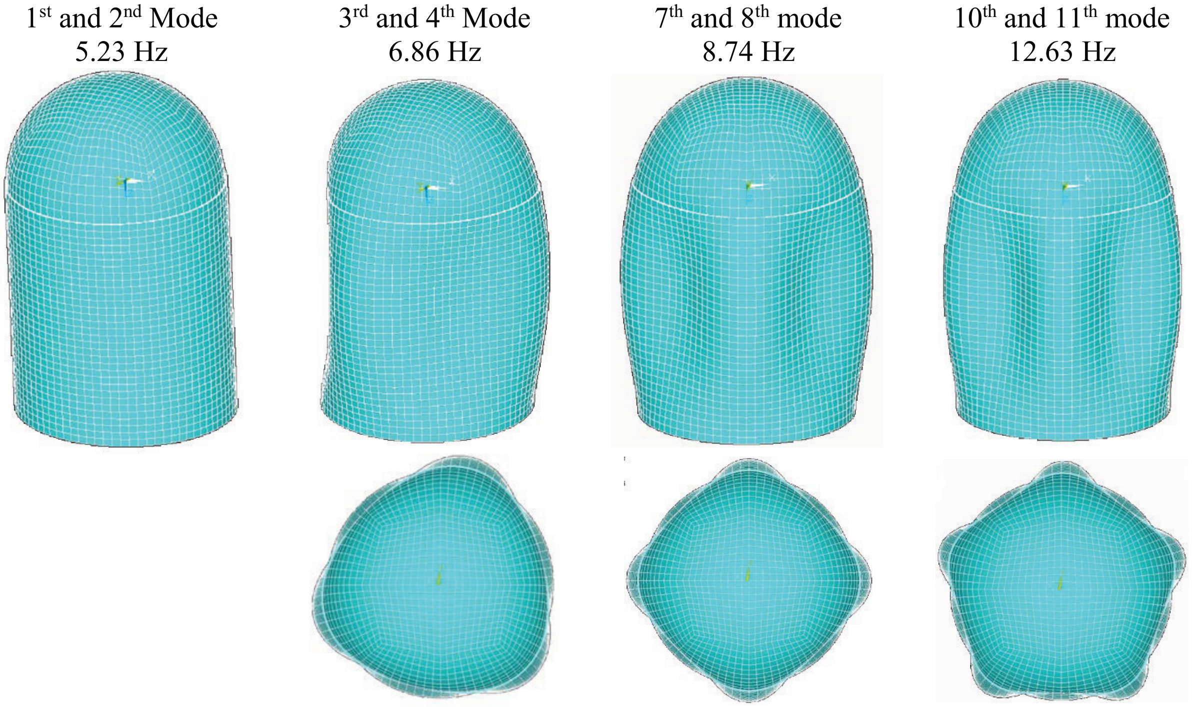


	1st mode	2nd mode	3rd mode	4th mode	5th mode
Lumped mass	5.34 Hz	16.08 Hz	29.38 Hz	42.26 Hz	53.24 Hz
Distributed mass	5.24 Hz	14.89 Hz	28.63 Hz	30.02 Hz	44.18 Hz
Mode participation	76.0%	16.9%	4.3%	1.6%	0.6%

Figure 5. Dynamic frequencies and mode shapes of stick models of containment building.

Figures 5 and 6 show mode shapes and fundamental frequencies of 2D stick models and a detailed 3D model with 20-node solid elements, respectively. Stick models are generated in two ways. One includes continuously distributed mass (Figure 4d), and the other is modeled with lumped mass (Figure 4e)). As shown in Figure 5, the mode shapes are identical but the frequencies are slightly different. Compared to the detailed 3D model, the stick models are limited in ability to capture additional mode shapes such as various 3D effects of containment structures, but the first fundamental frequency and mode shape are matched reasonably well. Figure 5 shows that the overall dynamic response of the lumped mass stick model is dominated (76%) by the first or fundamental mode of the structure. Effective mass contribution of the second mode to total mass, or the contribution of second mode to total dynamic response is 16.9%. Therefore, approximately 93% of the stick model response is contributed by the first two modes.

As presented in Table 2 and Figure 6, FE models with 20-node hexahedral finite elements provide the most stable dynamic analysis results. For instance, the FE model with reduced number of elements (492 elements) provides very similar fundamental frequencies and dynamic response to those of the FE model with large number of elements (12,640 elements). Acceleration and displacement time histories are calculated at critical heights of the containment building. Figure 6 presents sample of displacement and acceleration time history analysis results at the top of the containment building to compare detailed 3D FE models and simplified 2D stick models.


1st and 2nd Mode
5.23 Hz

3rd and 4th Mode
6.86 Hz

7th and 8th mode
8.74 Hz

10th and 11th mode
12.63 Hz

Figure 6. Selected dynamic mode frequencies and mode shapes of the 3-D FE containment model.

Table 2. Time-History Analysis Durations

FE models	Number of elements	Fundamental frequency (Hz)	Analysis duration (minute)
2D Stick model with lumped mass	11	5.34	2
2D Stick model with distributed mass	11	5.24	4
8-node solid hexahedral finite elements	492	5.35	18
20-node solid hexahedral finite elements	492	5.23	35
8-node solid hexahedral finite elements	12,640	5.24	108
20-node solid hexahedral finite elements	12,640	5.23	225

A damping ratio of 5% and first 5 seconds of the El Centro ground motion was used as input to calculate the dynamic response of four different containment models shown in Figure 7. For the calculated accelerations, with respect to the model with 12,640 20-noded elements, the mean squared errors were calculated as 0.0057, 0.4205, and 11.58 for the 20-noded 492 element model, 107 line element model, and 11 line element stick model, respectively. Two of the detailed 3D models with different number of elements provide very similar results, while the two stick models have small differences. The errors in the peak displacement and acceleration responses in the lumped mass stick model are larger than the corresponding errors in the continuously distributed mass model when compared to the results from detailed 3D models.

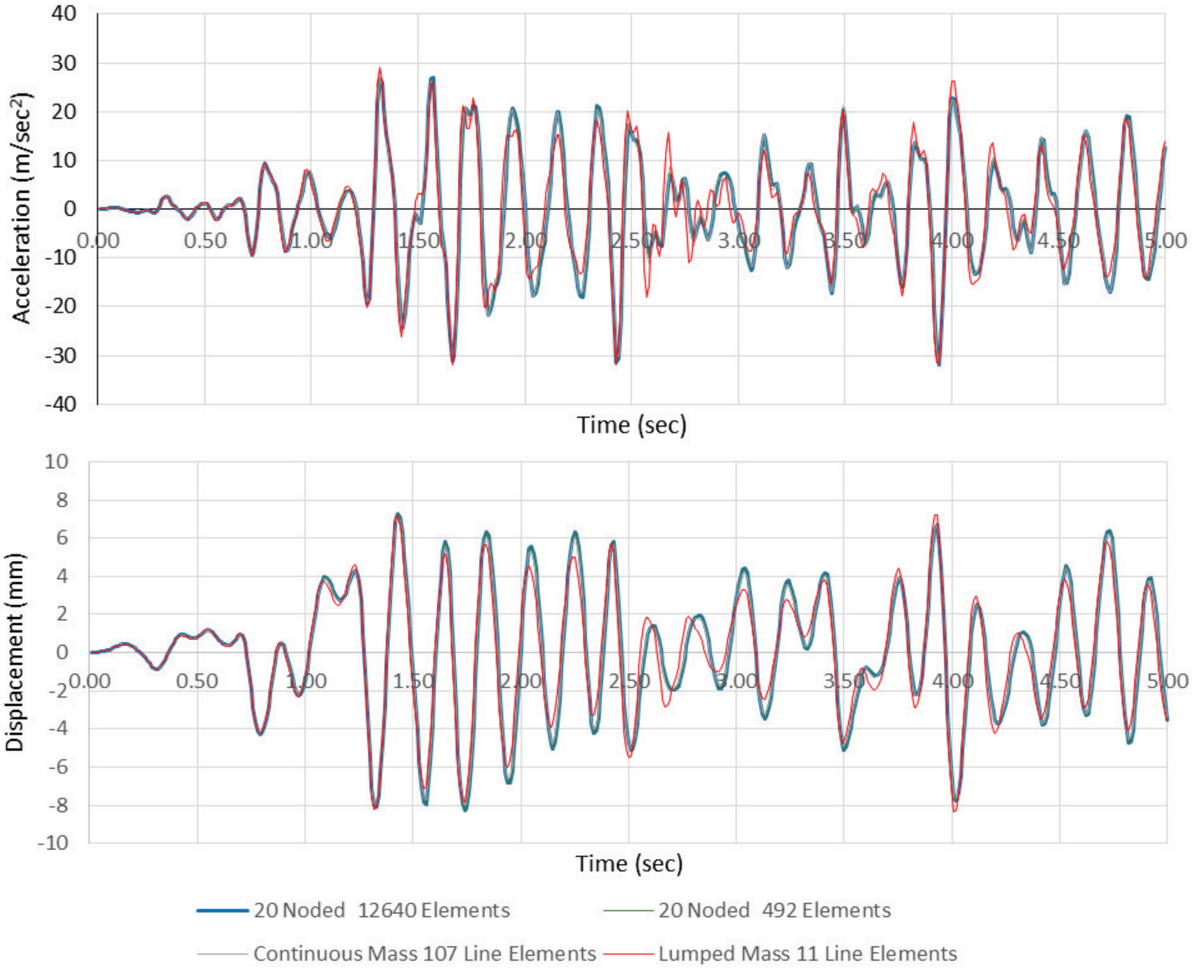


Figure 7. Acceleration and displacement time histories calculated at the top of containment models.

Modeling of other SSCs

In addition to the FE models of building structures, numerical models of NSCs which are contained in the buildings are also generated to evaluate their seismic performance. Among various NSC, this project focuses on a condensate storage tank, steam generator-piping system in containment building, and electrical cabinets in auxiliary building. Their numerical models are generated and validated with simulations or available experimental data. Based on these numerical models, the seismic performance of NCSs evaluated through time-history analysis for the selected ground motions. A number of performance measures such as displacements, stresses, member forces and moments in structural and NSCs are used for the development of their fragility functions and estimation of failure probabilities of the system. As shown in Figure 7, finite element model of a 15.2 m diameter and 11.4 m tall steel condensate storage tank with 12.7 mm shell thickness is created (Nie et al. 2012). The geometry and properties of steam generator and piping systems are taken from the example in SASSI User's Manual (2009). The fragility functions of electrical cabinets such as Battery Rack, Switchboard, and MCC are estimated from shaking table results.

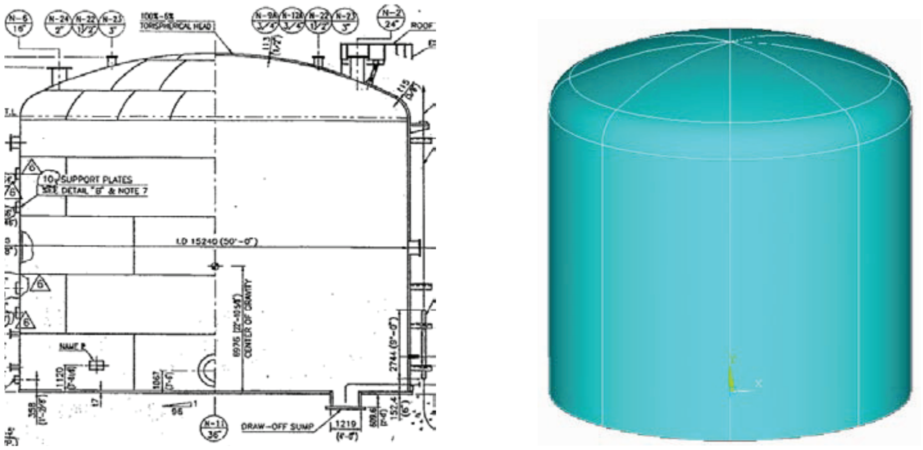


Figure 8. Condensate storage tank elevation (Nie et al. 2012) and 3D FE model of the tank

CONCLUSIONS

The efforts to date to integrate SPRA with internal events PRA have concentrated on investigating the effectiveness of reduced order models to model the seismic behaviour of NPP structures and to estimate the failure probabilities of NSCs under specified ground motions.

Lumped mass and distributed mass stick models cannot capture torsional and higher mode effects for the symmetrical containment building. However, it was found that fundamental mode frequency and the corresponding dynamic behavior are captured relatively well. Calculated dynamic accelerations are more accurate than the displacements when the stick model is used. For the detailed model of the containment model, 20-noded solid hexahedral finite elements result in more accurate results compared to 8-noded solid hexahedral finite elements. Very large number of finite elements may not be necessary when 20-noded finite elements are used. The error can be relatively low while the analysis time can be reduced significantly, for example when 492 finite elements are used instead of 12,460 elements.

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