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EVALUATION OF SEISMIC REDUCED-ORDER MODELS FOR AUXILIARY BUILDINGS

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ABSTRACT

Seismic probabilistic risk assessment (SPRA) integrates the failure probabilities of safety-related structures, systems and components (SSCs) in a nuclear power plant (NPP) to determine the associated risk to the public during a seismic event. In the performance of SPRA, the level of model fidelity – e.g., simplified 2D stick models versus detailed 3D finite element (FE) models – used to determine the failure probability of SSCs depends on the characteristics of the NPP structure being analyzed. Several cases of example NPP auxiliary buildings are investigated to determine the practicality and accuracy of using structural models with different levels of complexity. A detailed 3D FE model is developed from a realistic structure. Starting from this initial 3D FE model, increasing degrees of irregularity in terms of mass, stiffness, and geometry are modeled and investigated. Using modal and transient analyses, the dynamic characteristics of 2D and 3D models are determined, and the limitations of the simplification process from the varying 3D FE models to a 2D stick model are discussed. The results indicate that, depending on the design of the building, 2D stick models of auxiliary buildings may not adequately reflect the dynamic response of the structure.

INTRODUCTION

Seismic probabilistic risk assessment (SPRA) aims to evaluate the risk of a nuclear power plants (NPP) through various failure scenarios initiated by seismic events. One structure that is of particular importance for SPRA at NPPs is the auxiliary building due to its location and function. Auxiliary buildings are typically located near the containment building, which houses the reactor, and contain critical nonstructural components (NCs) such as systems for radioactive waste, chemical and volume control, and emergency cooling (NRC 2016). Due to the high rigidity of typical auxiliary buildings, operational failure of these NCs is significantly more likely than failure of the structure due to seismic events. However, to evaluate the failure probabilities of NCs under epistemic and aleatory uncertainties associated with the behavior of both the structure and NCs, simple yet sufficiently accurate reduced-order models (ROMs) are needed due to the computational challenges of accomplishing the task with finite element (FE) models. Reduction in model complexity, however, may lead to the loss of certain dynamic characteristics of the 3D structure (Sezen et al. 2015, and Althoff 2017).

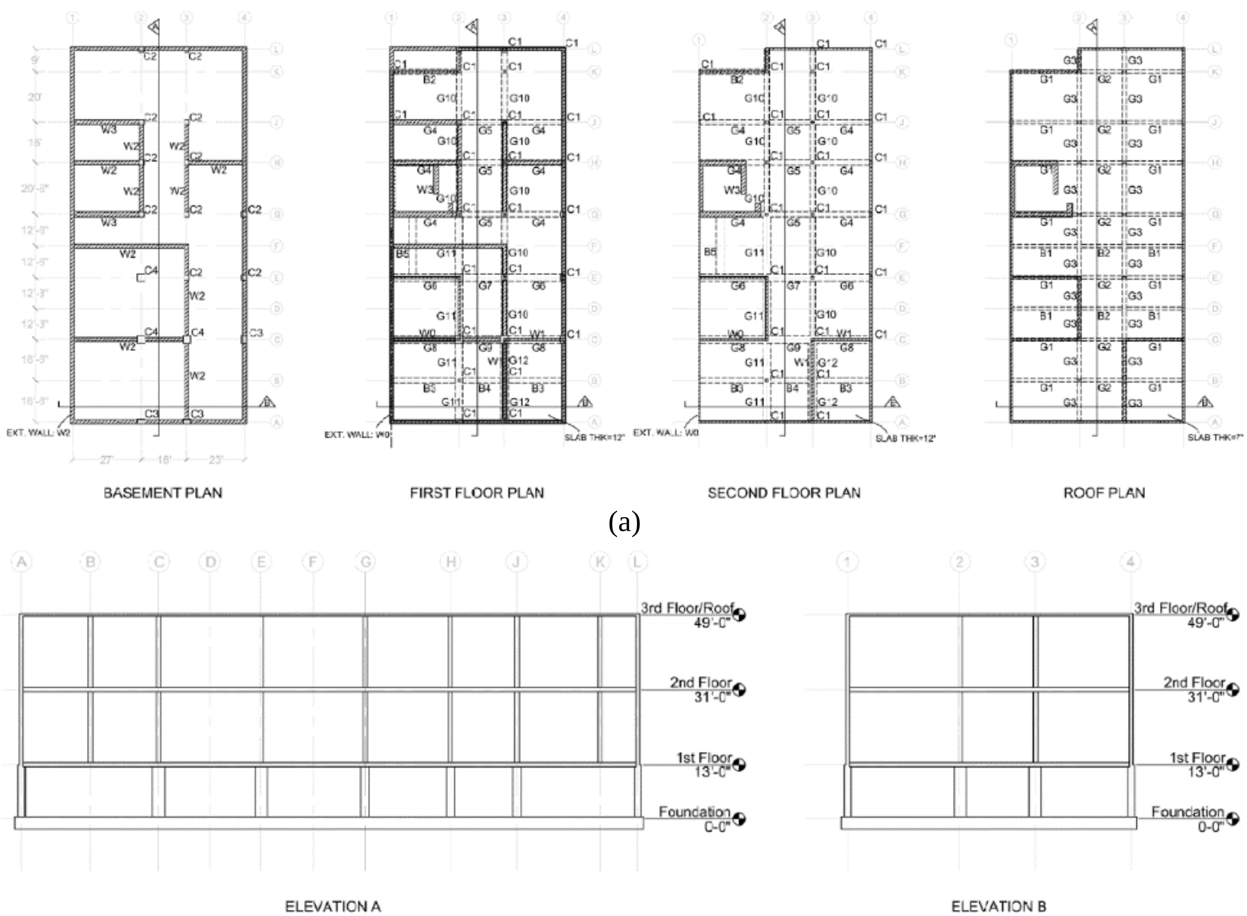
The goal of this research is to evaluate the capabilities and limitations of ROMs in predicting the dynamic response of auxiliary buildings. A further specific focus of the study is to investigate the effects of structural irregularity and slab flexibility on the dynamic response of ROMs. Detailed 3D and simplified 2D models are developed for auxiliary buildings with various degrees of structural irregularity. Modal and time history analyses are performed to determine and evaluate the dynamic characteristics and response of both the ROMs and detailed models. Results indicate that structural irregularity and slab flexibility have a significant impact on the dynamic behavior of 3D models and that the 2D models investigated cannot relatively accurately predict the response of structures with significant irregularity or non-rigid floor slabs.

MODEL DESCRIPTION

Realistic Auxiliary Building

Structural plans for NPP auxiliary buildings are typically not made available to the public for obvious security reasons. However, a realistic auxiliary building model was created using a partial plan set for a decommissioned NPP (HAER 1968) and basic structural engineering principles. The structural plans created to develop the realistic auxiliary building model are shown in Figure 1.

The original Connecticut Yankee auxiliary building was a reinforced concrete building with two upper stories and a partial basement. As with most NPP auxiliary buildings, the footprint of the Connecticut Yankee building was irregular in terms of both stiffness and geometry. Due to several heavy equipment loads, the mass distribution of the building was also significantly irregular. The realistic building model was developed with three full stories for simplicity, and included the same mass, stiffness, and geometry irregularities of the original Connecticut Yankee structure.



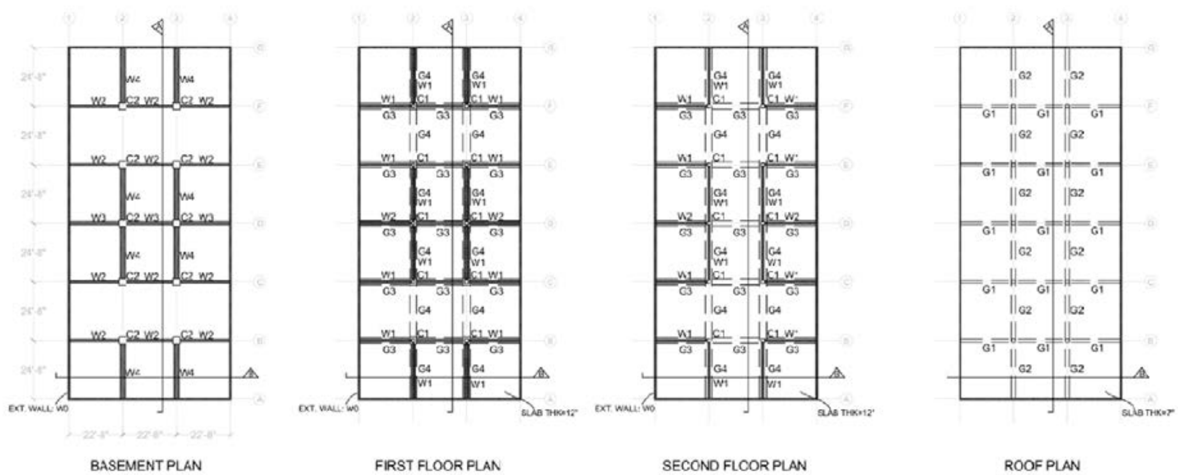
(b)

Figure 1. Structural plans for the realistic auxiliary building model: a) plan view, and b) elevation

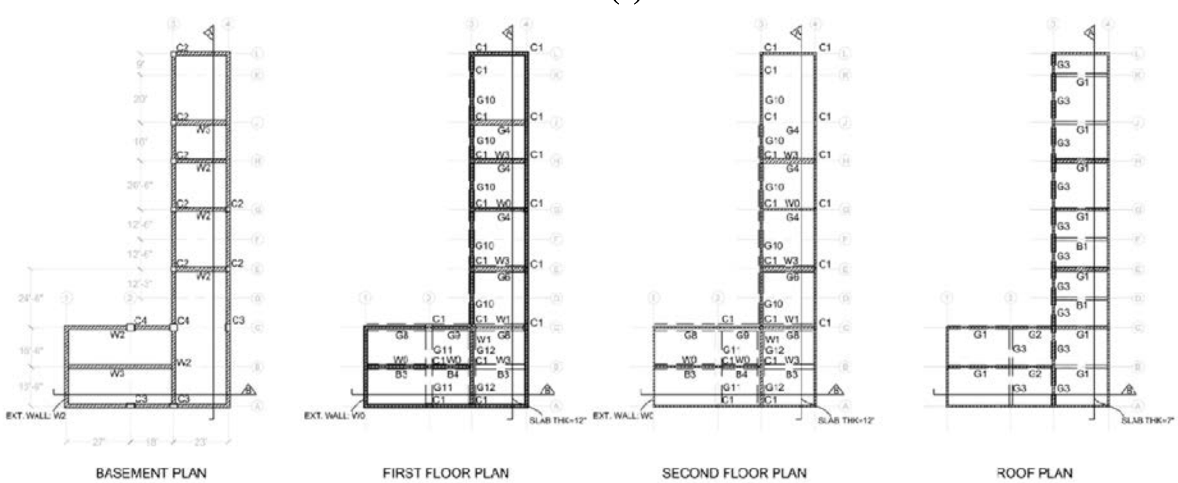
Case Study Building Models

Detailed 3D building models are able to capture torsional effects caused by mass, stiffness, and geometric irregularity that simplified 2D models typically cannot. To evaluate the adequacy for simplified models to capture 3D building characteristics during seismic events, five additional building cases were developed based off the realistic building model in Figure 1. Importantly, each case was developed so that the mass and stiffness of each case was approximately the same. Details of the models, assumptions and all analysis results can be found in Althoff (2017).

The first additional case (Case 0) was developed so that it was perfectly symmetrical in terms of mass and stiffness. This was accomplished by removing the geometry irregularities in the realistic case (Figure 1) and evenly distributing the mass and lateral load-resisting components at each floor level (Figure 2a).



(a)



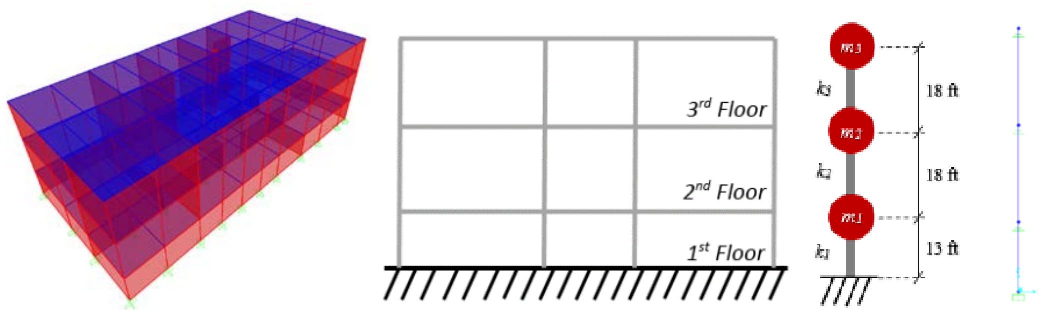
(b)

Figure 2. Structural plan view for additional building cases: a) Case 0, and b) Case 5

The remaining four cases (Cases 2 through 5) were developed so that the mass, stiffness, and geometry irregularity of each case increased compared to the preceding case. To accomplish this, lateral load-resisting components were strategically shifted around each building model's footprint, and a portion of the plan geometry was removed from each subsequent case's building model. Additional uniformly distributed mass was added to the remaining plan area at each floor level to maintain the same mass and stiffness relationship in all cases. Figure 2b shows the plan view of the case with the largest mass, stiffness, and geometry irregularity (Case 5). For dynamic analyses, focus was given to the realistic building (Case 1), the perfectly symmetrical building (Case 0), and the building with largest irregularity (Case 5).

Simplified 2D and Detailed 3D Models

Each case in this study was modeled with both detailed 3D and simplified 2D building models in SAP200 (2016). In 3D models, beam elements were used for beam and column frames, and shell elements were used for shear walls. For 2D models, lumped-mass stick models were developed from a flexibility analysis of the detailed 3D models. Due to the simplified nature of the 2D models, only one axis of the 3D building can be modeled. For dynamic analyses in this study, the transverse-axis (Figure 3) was modeled with simplified 2D models. In each simplified model, vertical beams were connected with lumped-masses m_i (i=1,2,3) to model each story of the 3D structure. For modeling purposes in SAP2000, equivalent moment of inertia values, I_i, (Table 1) for each vertical beam were calculated from the story stiffnesses, k_i, obtained from flexibility analysis of the 3D models.



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

Figure 3. Illustration of simplification process from 3D to 2D models: a) detailed 3D model, b) transverse-axis of 3D building, c) simplified 2D model illustration, and d) 2D model in SAP2000

Typically, simplified 2D models cannot capture torsional effects caused by geometry, mass, and stiffness irregularity, but another 3D building characteristic not captured by simplified 2D models is floor slab flexibility. In typical 2D model development, floor slabs are assumed to be completely rigid, i.e., slabs move in the horizontal direction as a rigid block. However, recent research (Nie et al. 2013) has emphasized the need to model floor slab flexibility for NPP structures. Similarly, several analysis and design codes, i.e., ASCE 7 (2010), mandate modeling floor slab flexibility with semi-rigid slabs to evaluate its impact on the interaction of lateral load-resisting components.

Table 1: Lumped mass and moment of inertia values for each 2D model

	Mass (kip-s^2/ft)			Moment of inertia (in.^{4} x10^7)					
				Rigid slab models			Semi-rigid slab models		
	m_1	m_2	m_3	I_1	I_2	I_3	I_1	I_2	I_3
Case 0	162.55	155.98	70.28	6.50	7.41	7.41	6.09	6.86	6.55
Case 1	165.1	151.15	69.85	7.33	6.68	6.78	5.75	5.19	4.74
Case 5	164.51	150.53	69.92	5.72	6.53	6.63	5.33	4.57	4.42

Detailed 3D and simplified 2D models were developed with both rigid and semi-rigid slabs to evaluate the effects of floor slab flexibility. In 3D models, rigid and semi-rigid slabs were modeled by assigning an elastic modulus value as infinitely high and as 3605 ksi (equivalent to 4 ksi concrete), respectively, for the floor slabs. For 2D models, rigid and semi-rigid slab models were developed from a flexibility analysis of the corresponding 3D model.

DYNAMIC ANALYSIS

Modal Analysis

General dynamic characteristics of both detailed 3D and simplified 2D models were evaluated and compared using modal analysis. Since 2D models were developed only for the transverse-axis of 3D models, only transverse-axis modes were evaluated and compared. For 2D models, the three degree-of-freedom (DOF) systems result in only three modes. However, 3D models have significantly many more modes due to the large number of DOFs in the models. Since modes with significant mass participation ratios indicate the modes that dominate the dynamic response of models, only modes with significant mass participation ratios were obtained from modal analysis of the 3D model. Tables 2 and 3 summarize the modal analysis results from all models in terms of natural frequency and mass participation ratio. To compare 2D and 3D models, modes with similar mass participation are grouped together to illustrate how it can take multiple modes in some 3D models to capture a particular dynamic response, whereas 2D models capture significant dynamic modes with one mode.

Table 2: Modal information for significant dynamic modes of 2D and 3D rigid slab models

Mode Number	2D Model		3D Model	
	Natural Frequency (Hz)	Mass Participation Ratio	Natural Frequency (Hz)	Mass Participation Ratio
Case 0				
1	16.14	81.4%	16.14 (Mode 1)	81.4%
2	41.96	13.8%	41.96 (Mode 5)	13.8%
3	50.71	4.8%	50.71 (Mode 8)	4.8%
Case 1				
1	16.07	77.5%	16.04 (Mode 1)	77.4%
2	41.79	13.8%	41.77 (Mode 5)	13.9%
3	49.87	8.7%	49.69 (Mode 7)	7.3%
Case 5				
1	15.31	81.1%	15.11 (Mode 1)	34.2%
			16.09 (Mode 2)	33.5%
			17.47 (Mode 3)	14.3%
2	39.46	14.9%	39.03 (Mode 5)	6.3%
			41.63 (Mode 6)	5.7%
3	48.00	4.0%	44.95 (Mode 7)	3.5%
			50.47 (Mode 9)	1.4%

Results in Table 2 illustrate that for models with rigid slabs and limited irregularity, 2D models are able to predict the general dynamic characteristics of 3D models. For the perfectly symmetric model (case 0 shown in Figure 2a), all natural frequencies and mass participation ratios for the three dynamic modes matched with 0% difference. As mass, stiffness, and geometry irregularity increased in 3D models, however, the ability for 2D models to capture the dynamic characteristics of 3D models decreased. For the realistic 3D model (case 1), three dynamic modes were captured by both 2D and 3D models; however, the natural frequencies of these modes were slightly different with differences of less than 1%. For the most irregular 3D model (case 5, Figure 2a), the 3D building model captured several additional transverse-axis modes with less significant mass participation. These modes for the 3D model of case 5 were less significant in the transverse-direction because they also had significant mass participation in the longitudinal direction. Dynamic characteristics of the 2D and 3D models were different for cases 0 and 1 due to their limited structural irregularity. Furthermore, since each transverse-axis mode of the case 5 3D model had less significant mass participation, several of these torsional modes were needed to capture the one transverse-axis mode of the corresponding 2D model (Table 2). Because of these several torsional modes, differences in natural frequencies between corresponding to 2D and 3D models were as high as 14% (Table 2).

Table 3: Modal information for significant dynamic modes of 2D and 3D semi-rigid slab models

Mode Number	3D Model		2D Model	
	Natural Frequency (Hz)	Mass Participation Ratio	Natural Frequency (Hz)	Mass Participation Ratio
Case 0				
1	15.54	81.0%	15.22 (Mode 1)	79.9%
2	39.97	13.1%	39.30 (Mode 9)	10.5%
3	48.43	5.8%	47.07 (Mode 15)	6.1%
Case 1				
1	14.11	76.9%	14.25 (Mode 1)	74.6%
2	35.62	11.9%	30.90 (Mode 6)	3.5%
			35.72 (Mode 8)	6.5%
3	43.45	11.2%	39.05 (Mode 11)	6.4%
Case 5				
1	13.40	76.4%	13.44 (Mode 1)	27.8%
			14.01 (Mode 2)	7.1%
			15.48 (Mode 3)	44.0%
			17.76 (Mode 4)	2.2%
2	34.40	12.1%	N/A	N/A
3	41.53	11.5%	36.69 (Mode 14)	11.7%

The floor slab flexibility introduced into the semi-rigid slab models had some noticeable, and important, effects on the general dynamic characteristic of 2D and 3D models. Perhaps most importantly, a decrease in stiffness of the structures for semi-rigid slab models is shown by comparing results in Tables 2 and 3. For example, the natural frequencies of the mode that dominates the dynamic response of the structure (mode 1) of the 3D models for case 1 were 16.07 Hz and 14.11 Hz for the rigid slab and semi-rigid slab models, respectively. Modes 2 and 3 follow this phenomenon also. Unlike the rigid slab 3D model for case 1, the semi-rigid slab 3D model captured four significant transverse-axis modes. Similar to rigid slab models with significant structural irregularity, the semi-rigid slab 3D model for case 1 captured multiple modes for one 2D model mode (Mode 2 in Table 3). Interestingly, the semi-rigid slab 3D models for Case 5 captured a total of 5 significant transverse-axis modes; however, none of the captured modes directly corresponded to the Mode 2 of the corresponding 2D model. Table 3 shows how the natural frequency of the last significant dynamic mode (36.69 Hz) of the Case 5 3D model is between the natural frequencies of the

Modes 2 and 3 (34.4 Hz and 41.53 Hz) of the corresponding 2D model. Interestingly, while the natural frequency of this 3D model mode is closer to Mode 2 of the 2D model, the mode shape (not shown, but available in Althoff 2017) has a closer resemblance to Mode 3 of the 2D model.

Transient Analysis

While modal analysis was used to evaluate and compare the general dynamic characteristics of 2D and 3D models, SPRA typically requires the maximum dynamic response of a structure at specific locations to evaluate the risk associated with the structure during seismic events. As such, an El Centro ground motion (Figure 4) from the 1940 Imperial Valley earthquake was selected for transient analysis. The selected ground motion was a 40-second, one-directional acceleration history recorded at USGS Station 117.

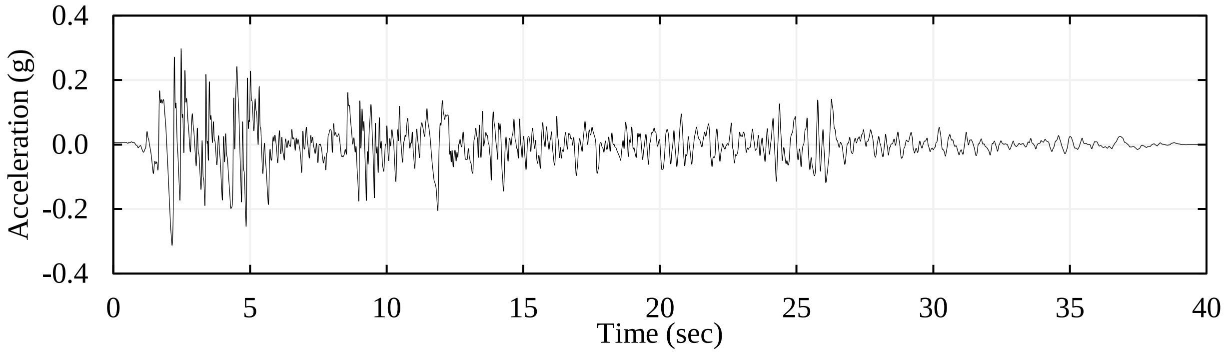


Figure 4. El Centro ground motion used for transient analysis

The one directional El Centro ground motion was applied to the 3D models in the transverse-direction for comparison to the 2D models. To illustrate the effects of structural irregularity and slab flexibility on the spatial response of 3D models, a few critical locations were evaluated during transient analysis. Critical locations for all models are at the third floor level due to the maximum dynamic responses occurring at this floor (Figure 5). For rigid slab models, Locations 1 and 3 in Figure 5 are, respectively, the locations of maximum and minimum dynamic response due to their outer plan location. For semi-rigid slab models, Locations 1 and 3 are selected for the same reasons as rigid slab models; however, Location 2 is also considered due to its location away from lateral load-resisting components.

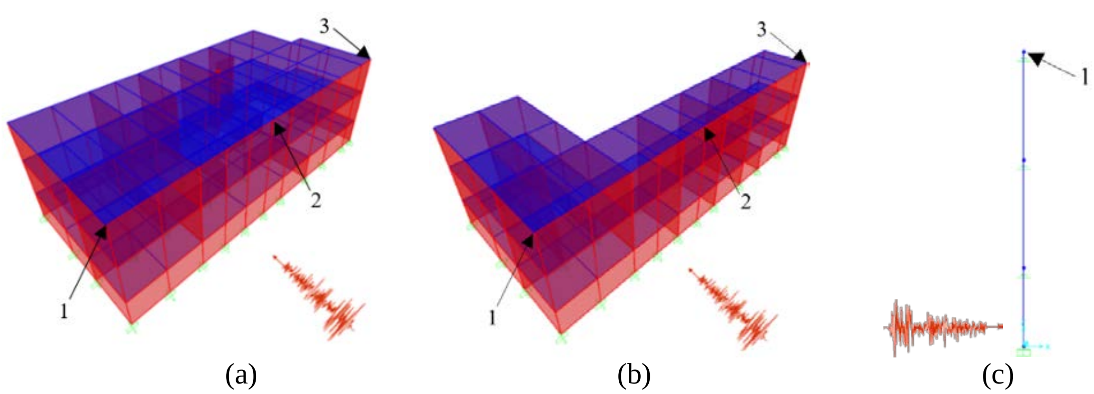


Figure 5. Critical locations for transient analysis: a) 3D Case 1, b) 3D Case 5, and c) 2D model

The El Centro ground motion used for transient analysis had a 40-second duration; however, the peak accelerations occurred in the first 10 seconds. For this reason, only the first 10 seconds of the response histories of all models are shown for the critical locations in Figures 6 through 9. Table 4 summarizes the peak acceleration responses and illustrates the importance of 3D models due to the effects of structural irregularity and slab flexibility.

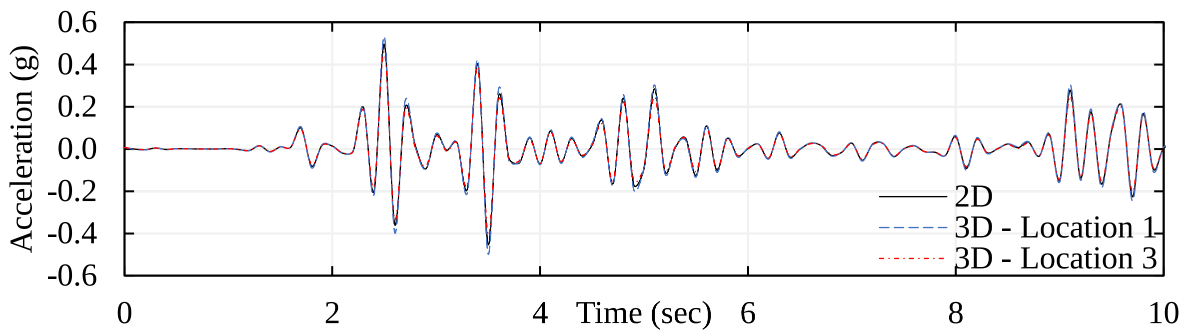


Figure 6. Acceleration response history for Case 1 rigid slab models

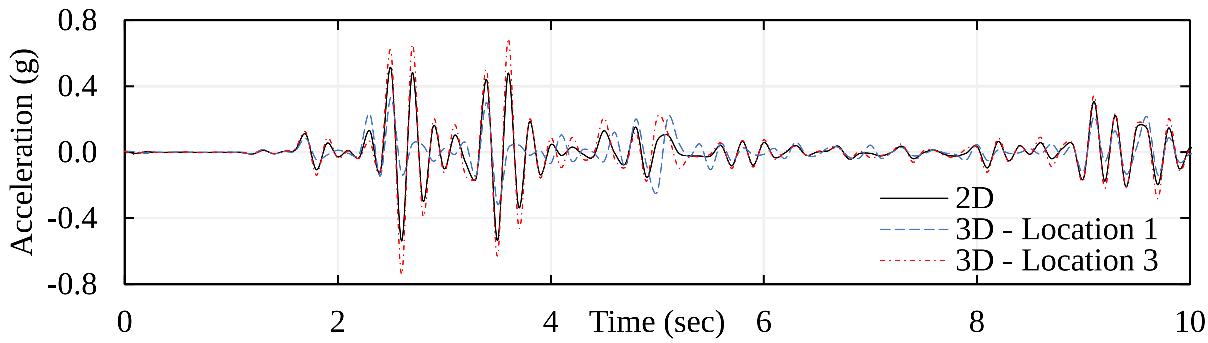


Figure 7. Acceleration response history for Case 5 rigid slab models

Acceleration response histories in Figures 6 and 7 reinforce how 2D stick models can relatively accurately capture the dynamic response of only 3D models with rigid slabs and limited irregularity. The acceleration response history in Figure 6 for Case 1 shows a close match throughout the history between the 2D model and locations of minimum and maximum response in the 3D model. However, Figure 7 shows how the 2D model can only capture the average response of the 3D model with a much more significant difference in the acceleration response history for Locations 1 and 2.

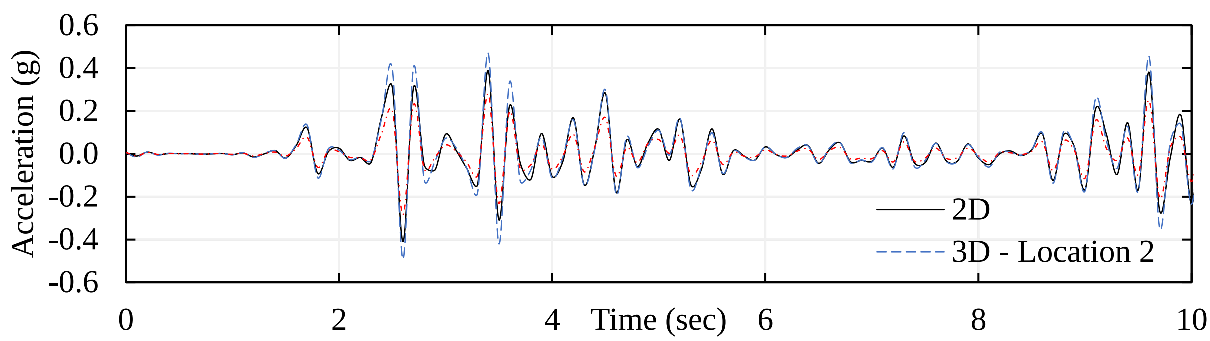


Figure 8. Acceleration response history for Case 1 semi-rigid slab models

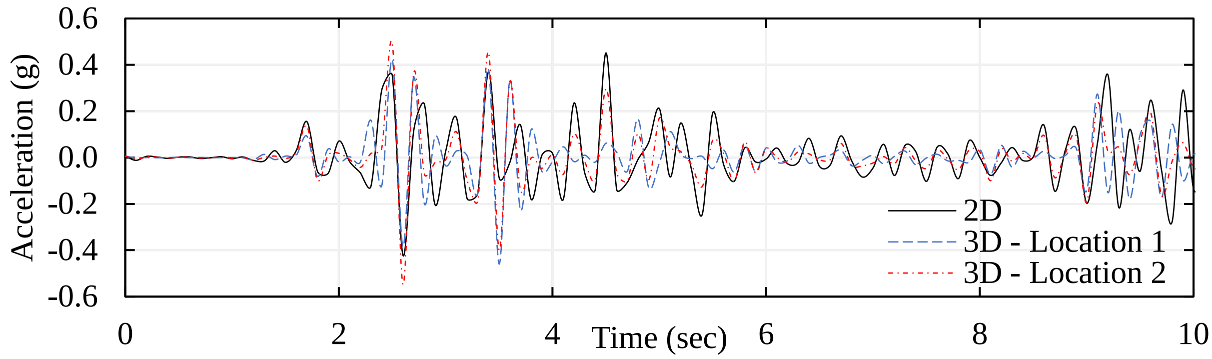


Figure 9. Acceleration response history for Case 5 semi-rigid slab models

Figures 8 and 9 further illustrate the effect slab flexibility has on the total dynamic response of 3D models. Figure 8 shows how even for case 1 with limited structural irregularity, the acceleration response histories of the 3D model's locations of maximum and minimum dynamic response are quite different. Figure 9 shows for Case 5, however, that the differences in acceleration response between the two locations of maximum and minimum response are not as drastic compared to the rigid slab 3D model.

Table 4: Summary of peak acceleration responses for Cases 0, 1, and 5

Case	2D	3D	
		Maximum location	Minimum location
	Acceleration response (g)		
Rigid slab models			
0	0.483	0.483 (all locations)	0.483 (all locations)
1	0.495	0.532 (location 1)	0.459 (location 3)
5	0.537	0.739 (location 3)	0.331 (location 1)
Semi-rigid slab models			
0	0.544	0.568 (location 2)	0.455 (locations 1 and 3)
1	0.410	0.492 (location 2)	0.284 (location 3)
5	0.451	0.548 (location 2)	0.460 (location 1)

The acceleration response histories help evaluate and compare models, but SPRA typically is more interested in the maximum dynamic response of a structure to compute its failure probabilities. Table 4 highlights how different the maximum spatial dynamic responses of 3D models can be for highly irregular structures. For Case 5 with rigid slabs, the percent difference between the locations of maximum and minimum response was 76%. For this case, the maximum difference between the 2D model and any location in the 3D model was 48%. For Case 5 with semi-rigid slabs, however, the maximum difference between the 2D model and any location in the 3D model was just 20%. Table 4 also illustrates how even for a perfectly symmetric case, semi-rigid slab 3D models capture different spatial responses due to slab flexibility capturing deformation of the slab between lateral load-resisting components. This dynamic behavior is not captured by rigid slab models.

CONCLUSIONS

This research evaluated the capabilities and limitations of reduced-order models for NPP auxiliary buildings. Both detailed 3D and simplified 2D models were developed in SAP2000 (2016) for potential auxiliary building designs with varying degrees of structural irregularity and slab flexibility. Modal and transient analyses were used to evaluate and compare the dynamic characteristics and response of detailed and simplified models. Specifically, the ability for 2D models to predict the spatial response of 3D models was evaluated.

Results from dynamic analyses indicate that both structural irregularity and slab flexibility have a significant impact on the dynamic characteristics and response of NPP auxiliary buildings. 2D stick models were able to capture the significant dynamic modes of 3D models with limited irregularity and rigid slabs with limited error (< 1%). However, 2D models were not able to capture additional torsional modes captured by 3D models when structural irregularity and slab flexibility were modeled (Case 5 in Table 1 and Case 1 in Table 2). Similarly, 2D models did not capture the spatial dynamic response of 3D models with structural irregularity or slab flexibility. Differences between maximum spatial acceleration response of 3D models and 2D models was as high as 48% (Case 5 with rigid slabs) and only as low as 18% (Case 0 with semi-rigid slabs).

Other simplified models for NPP auxiliary buildings should be investigated to more accurately predict its dynamic response when structural irregularity or slab flexibility is modeled. Developing 2D stick models for specific NC locations of interest could provide an appropriate solution for uncertainty quantification in SPRA. This and other simplified approaches are being developed and evaluated to more accurately predict the failure probabilities of NCs for different locations within an NPP auxiliary building to meet the computational challenges towards such an objective.

ACKNOWLEDGEMENTS

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