

Uncertainty in Mathematical Models of a Typical Nuclear Power Plant Structure

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Summary

We seek to quantify variations in dynamic characteristics and seismic response of nuclear power plant structures caused by different modeling assumptions. For our subject structure we choose a modification of the Zion nuclear power station auxiliary/fuel-handling/turbine building complex. We apply four modeling idealizations to the structure--a detailed finite element model, a detailed finite element model with masses lumped at selected nodes, a detailed finite element model with the constraint of rigid floors, and an equivalent beam model. Dynamic characteristics (frequencies and mode shapes) and response quantities (peak nodal acceleration and in-structure response spectra) are determined for the models and compared. Variations in frequencies are explained as a function of the assumptions within the models. The significance of the variation in response is discussed in relation to the subsequent use of the response data for design purposes.

Our results indicate that all four modeling approaches preserved total mass and rotational moments of inertia. We see a greater variation in the frequencies of comparable modes, the coefficients of variation ranging from 0.09 to 0.31. The effect of the different modeling assumptions is most evident in the large variations seen in the response of locally flexible areas of the structure. In particular, the choice of location of lumped mass points profoundly affect the models' dynamic behavior.

We conclude that large variations in dynamic characteristics and response can be introduced by modeling assumptions when a need exists to reduce the number of dynamic degrees of freedom.

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1. Introduction

The development of a mathematical model to represent the dynamic characteristics of a nuclear power plant structure is subject to a number of sources of variability. Arriving at values for structural behavior at points in the structure, within elements (beams, walls, slabs, etc.), and in the overall building is subject to uncertainty. In addition, the translation of engineering drawings into a mathematical model is subject to the judgment of the analyst. In a linear model, the mass, stiffness, and damping characteristics are affected by the analyst's decisions.

Because of these uncertainties a single analytical description of a structure does not exist, and therefore the criteria used in creating such a description may be significant in predicting a structure's response to seismic excitation. Models are idealized approximations of reality, and it behooves the seismic/structural analyst to understand to what degree model variations affect predicted dynamic behavior. As a part of the Seismic Safety Margins Research Program (SSMRP), we sought to quantify the uncertainty or variability caused by differing model idealizations.

2. Structural Model Development and Evaluation

2.1 Physical Structure

We obtained plant specific data from the Zion nuclear power station, Zion, Illinois, U.S.A. The structure considered in the present study is a modification of the Zion auxiliary/fuel-handling/turbine building complex. Only the auxiliary, fuel-handling, and diesel-generator buildings were modeled. This portion of the complex, a connected group of heavy, shear wall buildings constructed of reinforced concrete, is typical of nuclear power plant structures. In plan view, the buildings form a T-shaped unit with an assumed plane of symmetry along its east-west axis. This geometry leads to uncoupled horizontal response along the plane of symmetry and coupled horizontal and torsional response in the perpendicular plane.

Figure 1 shows a schematic section of the complex obtained by passing a cutting plane along the axis of symmetry. Exterior walls have been removed so that significant internal features of the building can be seen. The reinforced concrete floor slabs at several elevations are not continuous through the structure. Due to the lack of floor slabs, a large flexible wall exists in the fuel-handling building area. Although the actual building is embedded to a depth of 50 feet, in developing the mathematical models, the structure was truncated at grade and soil-structure interaction was not included in our fixed-base response analysis. Several response points and values referenced later in this report are also shown in the figure.

2.2 Mathematical Models

Four different structural models were developed for the study. The assumptions incorporated in these models, all commonly used by the nuclear industry, are the source

of variability we wished to investigate. It was necessary, then, to minimize or eliminate other potential sources of variability within the response analysis. To accomplish this, we specified the same nominal material property values and floor and roof loads for all models. Damping values used in the response analysis were also given.

Model 1. Model 1 is a detailed finite element model. It represents a "best estimate" idealization of the structure in that the fewest simplifying assumptions were applied during its development. Results obtained with Model 1 served as the basis of comparison for the other models.

Thin plate and shell elements were chosen to define the flexibility of both concrete shear walls and floor slabs. In discretizing the structure single elements modeled the height of shear walls between adjacent slabs. Whenever possible, the widths of the elements were chosen to give an aspect ratio close to unity. Material densities were used by the analysis code to calculate mass values at all active nodes. This gave a total of 1490 dynamic degrees of freedom. For Model 1, 122 modes with frequencies less than 33 Hz were extracted for use in subsequent response analyses.

Model 2. Model 2 is a detailed finite element model that used the same element discretization as Model 1. Unlike the uniform mass distribution of Model 1, however, mass is lumped in Model 2 at selected nodes. The dynamic degrees of freedom of all massless nodes are condensed out of the modal analysis. This procedure effectively eliminates "local" modes believed not significant to structural response. Model 2 contained 255 dynamic degrees of freedom, and 125 modes with frequencies less than 33 Hz were used to define Model 2's dynamic characteristics.

Model 3. Masses were lumped in Model 2 in order to reduce the number of dynamic degrees of freedom. In Model 3, reduction of degrees of freedom was achieved by assuming that all concrete slabs and roofs are rigid diaphragms. The rigid floor assumption is incorporated through a master/slave approach whereby the response of each floor slab can be defined by a single master node. The node is located at the overall center of gravity of the particular slab and its attached shear walls. The slab mass and inertia are lumped at this point. All other nodes within the boundary of the slab are rigidly slaved to the particular master node.

Concrete shear walls are represented by plate elements. The discretization of the walls was the same as that in Model 1 and 2. The mass and inertia of the shear walls were calculated using density values input to the analysis code and then combined with other concentrated weight values. Thirty-two modes were extracted from the model's 132 dynamic degrees of freedom.

Model 4. The last model of the study represents a lumped mass/shear beam idealization of the subject structure. Separate beam models were constructed for the fuel-handling building, the auxiliary building, and the two diesel-generating buildings. All floor slabs and roof diaphragms were considered rigid within the individual "sticks." The mass and inertia of each slab and attached shear walls were lumped in a node located at the slab system center of gravity. A single beam element represented the effective shear stiffness of all walls between adjacent slabs. This element was located at the shear centers of the particular shear wall system. All elements connecting the mass centers to the shear centers were essentially rigid in

accordance with the assumption of rigid floors. Diaphragm stiffnesses accounting for the flexibility of the slabs and tributary walls were included as elements connecting the sticks of the various structures to form a single overall model. The fuel-handling building was connected to the auxiliary building by one element representing the roof diaphragm. Each diesel-generator building was more tightly coupled to the auxiliary building with a total of 4 connecting elements representing the floor and roof diaphragm stiffnesses. Twenty-one modes with frequencies less than 33 Hz were extracted from 80 dynamic degrees of freedom.

3. Analytical Method and Results

Once the models were defined, we performed comparative analyses to determine variability in dynamic characteristics and response. In-structure response was determined through a series of time history analyses using modal superposition. We subjected the four models to simultaneous base acceleration in each of the three orthogonal directions. Synthetic time history records were used as input. The response spectra of the synthetic input records were reasonably flat in the frequency range corresponding to the models' structural frequencies. This eliminated the potential bias introduced by a time history record whose spectra shows a greater response amplification at selected frequencies.

3.1 Dynamic Characteristics

The mass characteristics of the four models showed excellent agreement. Table 1 lists the translational mass and the inertias about the north-south, east-west, and vertical axes. The mean (μ), standard deviation (σ), and coefficient of variation (Ω) for each quantity are also given.

Table 2 lists the frequencies of comparable modes. These modes were selected for comparison because they contributed most to structure response as indicated by mass participation. Not all of the modes could be identified with confidence in each of the four models. For those cases, no frequencies are listed.

Compared to the statistics of the inertia properties, greater variation is seen in the frequencies of identified modes. In Model 2, mass was lumped at selected nodes, while a uniform stiffness distribution was retained. The modal mass that in Model 1 would participate in several modes is now combined into a single mode for Model 2. The result is a decrease in corresponding frequency.

Model 3 gave the highest frequency for each mode shown in Table 2. The assumption that all floor and roof diaphragms are rigid increases the model stiffness without affecting the mass. The result is an increase in modal frequencies. We determined that the rigid diaphragm assumption was not appropriate for this structure in that it failed to capture the slab flexibility, gave an overstiff model of the subject structure, and resulted in the higher frequencies.

The shear beam approach used in Model 4 also assumed rigid floor diaphragms. However, the assumption was applied only within each of the four structures composing

the subject complex. The stiffness of the slabs and walls running between the auxiliary building and the fuel-handling and diesel-generating buildings was modeled directly with flexibility coefficients. This approach avoided the shortcomings seen in Model 3 and gave surprisingly accurate results.

3.2 Dynamic Response

Because of the difficulty in identifying comparable modes, dynamic response was chosen as another means of model comparison. The response points were chosen to evaluate both gross structural behavior and local response.

Figure 1 gives the peak acceleration response of the center of gravity of each separate floor slab (response points 1 through 6). We found the variation in peak acceleration to be comparable to the variation in computed frequencies. It appears that symmetry of the structures along the east-west axis tended to decrease the variability in calculating the corresponding peak accelerations.

Considering nodes other than the slab centers of gravity, much higher variation in peak acceleration is seen. Although no single model consistently contributed most to the variation in response, the effect of certain modeling assumptions can be identified. The peak acceleration of nodes along the west wall in the fuel-handling building is also shown in Fig. 1 (response points 7 through 9). The large variation in response is primarily attributed to the acceleration given by Model 3. Unlike the other models, the mass of the water in the spent fuel pit is lumped in Model 3 at nodes on both floor slabs and external shear walls. These masses produce several flexible modes with large mass participation that contribute to the large response. The uniform mass distribution of Model 1 and the lumped mass methods of Models 2 and 4 do not produce this effect.

The north-south acceleration of the large south wall in the fuel-handling building is given as point 10. Because it is unsupported over a large area, the response of the wall is governed by local flexibility rather than the gross stiffness of surrounding slabs or walls. Owing to their detailed element discretization and uniform mass distribution in the wall area, Models 1 and 3 were able to capture the large local response. Although a detailed element discretization was used in Model 2, the lumped mass distribution effectively eliminated all local wall modes. The response of the wall resulted only from gross structural behavior and a much lower acceleration level was seen. In developing Model 4, all mass was lumped at slab centers of gravity. This approach cannot capture local modes and is therefore ineffective in determining local response.

The differences in wall response are graphically illustrated by the response and coefficient of variation plots of Fig. 2. Using data from Models 2 or 4 as input, a subsequent component response analysis would yield grossly unconservative results.

4. Conclusions

In this study we attempted to isolate and quantify the variability in dynamic response resulting from different structural modeling assumptions. The subject structure

was a complicated shear wall building typically found at nuclear power plants. The models were developed by highly experienced analysts. Dynamic characteristics and response quantities were compared.

We found that all modeling approaches preserved total mass and rotational moments of inertia. The coefficients of variation for these quantities were small. A greater variation was seen in the frequencies of comparable modes. The range in the coefficient of variation was 0.09 to 0.31. In their report on structural modeling, Hadjian, et al.,¹ recommended using a coefficient of variation equal to 0.10 to define the dispersion of frequencies calculated for complex structures by experienced engineers. Our results suggest a greater variation.

The effect of the different modeling assumptions was most evident in the large variations seen in the response of locally flexible areas of the structure. The method used in each model to define the relative distribution of stiffness and mass in these areas dictated whether the local response was accurately determined. In particular, the location of lumped mass points profoundly affected the models' dynamic behavior. Lumping mass at nodes allows the analyst to selectively include or exclude vibratory modes and to subsequently bias response values. When such local accelerations are desired, care must be taken to insure that simplifying assumptions do not eliminate significant structural modes.

Large variations in dynamic characteristics and response can be introduced by modeling assumptions when a need exists to reduce the number of dynamic degrees of freedom. The analyst must be able to justify the model assumptions in terms of the interpretation and use of subsequent response data.

5. References

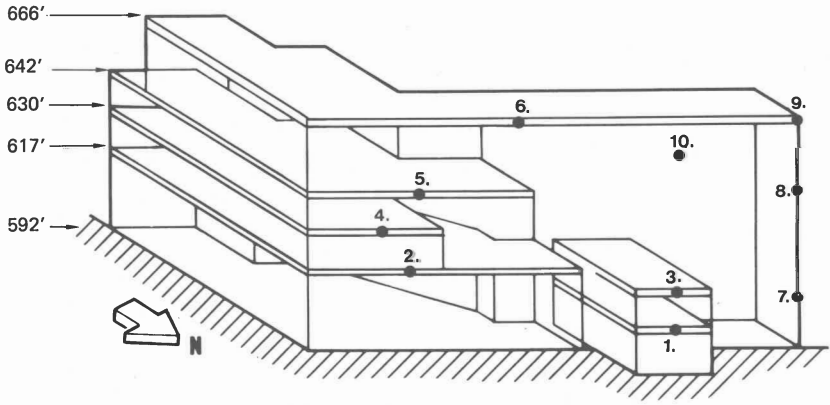
1. Hadjian, A. H., Smith, C. B., Halden, A., and Ibanez, P., "Variability in Engineering Aspects of Structural Modeling," Sixth World Conference on Earthquake Engineering, New Delhi, India, 1977.

TABLE 1. Mass and inertia values used in analyzing the four models.

Model	Mass (lb sec ² /ft)	Inertias (lb ft sec ²)		
		I _{E-W}	I _{N-S}	I _{vert}
1	3.08×10^6	3.64×10^{10}	4.63×10^{10}	6.97×10^{10}
2	3.06×10^6	3.38×10^{10}	4.68×10^{10}	6.66×10^{10}
3	3.08×10^6	3.39×10^{10}	4.16×10^{10}	7.07×10^{10}
4	3.15×10^6	3.39×10^{10}	4.54×10^{10}	8.30×10^{10}
Mean (μ)	3.09×10^6	3.45×10^{10}	4.50×10^{10}	7.25×10^{10}
Standard deviation (σ)	3.94×10^4	1.27×10^9	2.36×10^9	7.21×10^9
Coefficient of variation (Ω)	0.013	0.037	0.052	0.100

TABLE 2. Frequency comparisons of selected modes in the four models (Hz).

Model	Mode description					
	Torsion	Gross E-W	Fuel N-S	Diesel E-W	Fuel N-S	Vertical
1	10.02	10.04	10.99	11.36	13.52	27.52
2	8.66	8.74	9.07	9.90	12.14	18.85
3	15.25	15.13	---	---	16.51	---
4	---	8.74	11.30	11.76	12.65	26.08
Mean (μ)	11.31	10.66	10.45	11.08	13.70	24.15
Standard deviation (σ)	3.48	3.04	1.21	0.98	1.96	4.65
Coefficient of variation (Ω)	0.31	0.28	0.12	0.09	0.14	0.19



East-west response (ft/sec²).

Elevation	Model				Statistics		
	1	2	3	4	μ	σ	Ω
1. 602' (fuel)	32	32	34	33	32.75	0.957	0.029
2. 617' (aux)	44	46	44	43	44.25	1.258	0.028
3. 617' (fuel)	33	33	38	34	34.50	2.380	0.069
4. 630' (aux)	57	68	51	53	57.25	7.588	0.133
5. 642' (aux)	57	65	60	65	61.75	3.95	0.064
6. 666' (aux)	63	67	78	86	73.50	10.472	0.142
7. 617'	69	33	168	34	76.00	63.577	0.837
8. 642'	80	38	168	65	87.75	56.252	0.641
9. 666'	46	48	78	53	56.25	14.796	0.263

North-south response (ft/sec²).

Elevation	Model				Statistics		
	1	2	3	4	μ	σ	Ω
1. 602' (fuel)	32	32	32	32	32	0.000	0.000
2. 617' (aux)	38	36	43	49	41.50	5.800	0.140
3. 617' (fuel)	32	32	32	33	32.25	0.500	0.016
4. 630' (aux)	43	52	50	60	51.25	6.994	0.136
5. 642' (aux)	48	48	56	67	54.75	8.995	0.164
6. 666' (aux)	54	49	64	81	62.00	14.119	0.228
7. 617'	41	37	50	34	40.50	6.95	0.172
8. 642'	54	47	72	67	60.00	11.518	0.192
9. 666'	76	57	86	75	73.50	12.069	0.164
10. 642'	112	64	114	68	89.50	27.197	0.304

FIG. 1. Schematic view of structure with labeled response points.

MODEL 1 - DETAILED FEM N - S
 MODEL 2 - LUMPED MASS FEM N - S
 MODEL 3 - RIGID FLOOR FEM N - S
 MODEL 4 - SHEAR BEAM MODEL N - S

GENERATED 12/16/90
 D= .020
 GENERATED 12/16/90
 D= .020
 GENERATED 12/16/90
 D= .020
 GENERATED 12/16/90
 D= .020

4. SPECTRA (NORMAL)
 VARIATION IN RESPONSE - EL 645
 FUEL HANDLING EXTERNAL SOUTH WALL
 COEFFICIENT OF VARIATION

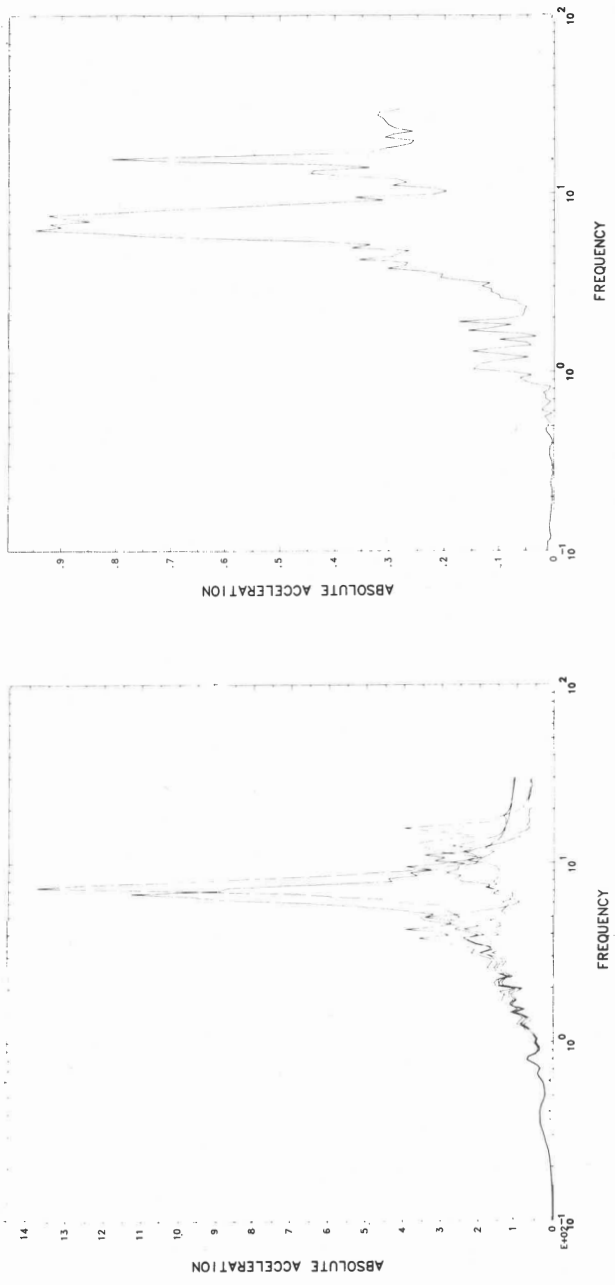


FIG. 2. Floor response spectra and coefficient of variation plots for response node on fuel-handling building south wall.

