

SSI Response of a Typical Shear Wall Structure

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Abstract

The seismic response of a typical shear wall structure in a commercial nuclear power plant was investigated for a series of site and foundation conditions using best estimate and design procedures. The structure selected is a part of the Zion AFT complex which is a connected group of reinforced concrete shear wall buildings, typical of nuclear power plant structures. Comparisons between best estimate responses quantified the effects of placing the structure on different sites and founding it in different manners. Calibration factors were developed by comparing simplified SSI design procedure responses to responses calculated by best estimate procedures. Nineteen basic cases were analyzed - each case was analyzed for ten earthquakes targeted to the NRC R.G. 1.60 design response spectra.

1. Background

Three aspects of seismic response, for each earthquake level, are necessary for seismic risk analysis: best estimate or median level response, variability of response, and correlation of responses.

Median level response. The best estimate or median level seismic response given an earthquake occurrence is required. In general, best estimate response differs from the design values, even for the design level earthquake, because, in the latter case, design analysis procedures, parameter selection, and qualification procedures are conservatively biased. Hence, working with design values requires calibration.

Variability of response. Variability in seismic response resulting from variations in the earthquake excitation, the physical properties of the soil/structure/piping system and our ability to model them must be estimated.

Correlation of responses. Correlation of responses, i.e., the tendency for pairs of responses to have simultaneously high or low values, results from two sources--the level of the earthquake and the dynamic characteristics of the system. Both require consideration.

2. Objectives and Scope

Developing median level responses based on existing design information is desirable for performing a seismic PRA. At least two approaches exist to use A-E and vendor generated seismic response in the seismic PRA. Both approaches are based on calibrating the data -- estimating median level response (wall forces and moments, in-structure response spectra,

in-structure accelerations, etc.), as a function of earthquake level removing conservatism or non-conservatism from the A-E procedure. The two approaches are:

- o Develop a set of calibration factors for response quantities of interest based on comparing best estimate results with results of a design procedure.
- o Perform limited re-analysis of the nuclear power plant for which the seismic PRA is being performed. Generate seismic responses to be used in the systems analysis and to calibrate the A-E generated data.

The objectives of this study were two-fold:

- o The first objective was to develop building response calibration factors, i.e. factors which relate best estimate or median level response to responses calculated by selected design procedures. This objective may be viewed as addressing the questions: How much conservatism is introduced by ignoring SSI or by approximating SSI effects by a simplified procedure?
- o The second objective can similarly be viewed in the context of a question: What effect does placing an identical structure on different sites and with different foundation conditions have on structure response?

This effort concentrated on structure response -- wall forces and moments and in-structure accelerations -- with only a limited effort on subsystem response as represented by in-structure response spectra. The structure of interest was a shear wall structure intended to be representative of a typical nuclear power plant building. More complete documentation of the results is contained in Ref. 1.

Typical Shear Wall Structure. The structure is a part of the Zion auxiliary-fuel handling-turbine building (AFT) complex of the Zion nuclear power plant. Only the auxiliary, fuel-handling, and diesel generator buildings were modeled for this investigation. These structures are a connected group of heavy, shear-wall buildings constructed of reinforced concrete, typical of nuclear power plant structures. In plan view, the buildings form a T-shaped unit with a plane of symmetry along the east-west axis, leading to uncoupled horizontal response along the plane of symmetry and coupled horizontal and torsional response in the perpendicular plane. The structure complex was represented by a finite element model.

Response Quantities. In-structure accelerations, in-structure response spectra, and wall forces and moments were the dynamic response quantities of interest for this study. Node point and element locations were selected to represent overall structural behavior and local response. Peak accelerations and in-structure response spectra were calculated at selected nodes. Wall forces and overturning moments were calculated at the roof and floor slab elevations in the major load carrying walls. Responses in the minor walls were omitted from this study. To study shear wall behavior, sections were taken in the selected walls and axial load, in-plane shear force, and overturning moment were calculated. The wall forces and moments are a summation of the elemental forces over the wall length at the section elevation. Our data base for this study consisted of:

- o Three components of peak acceleration (two horizontal and the vertical) at seven node points and six components of peak acceleration (three translational and three rotational) on the foundation - a total of twenty-seven.
- o Axial load, in-plane shear, and overturning moment in eight walls - a total of

thirty-five sections, and six foundation responses (three forces and three moments)
- a total of 111 responses.

3. Elements of the SSI Analysis

The basic elements of any SSI analysis (cast in the format of the substructure approach) are specifying the free-field ground motion, calculating the foundation input motion, calculating the foundation impedances, determining the dynamic characteristics of the structure, and performing the SSI analysis, i.e. combining the previous steps to calculate the response of the coupled soil-structure system. Each aspect is described below. Our best estimate analysis included consideration of all aspects of SSI.

Free-field ground motion. Specification of the free-field ground motion entails specifying the control point, the frequency characteristics of the control motion (typically, time histories or response spectra), and the spatial variation of the motion. An ensemble of ten sets of three components of acceleration time histories (two horizontal aligned in the north-south and east-west directions and the vertical) defined the frequency characteristics of the free-field ground motion. Each set was generated to match the design response spectra of the US NRC Regulatory Guide 1.60. The three components were distinct and verified to be statistically independent. Ten earthquakes were used to average out the effects of a single excitation and provide stable results. In all the analyses, the control point was defined on the surface of the soil and the wave propagation mechanism was assumed to be vertically propagating shear and dilatational waves -- hence, defining the spatial variation of motion when included in the SSI analysis.

Foundation input motion. In general, the foundation input motion differs from the free-field ground motion in all cases, except for surface foundations subjected to vertically incident waves. First, the free-field motion varies with soil depth. Second, the soil-foundation interface scatters waves because points on the foundation are constrained to move according to its geometry and stiffness. The foundation input motion is related to the free-field ground motion by means of a transformation defined by a scattering matrix $[S(\omega)]$, which is complex valued and frequency dependent:

$$\{U^*(\omega)\} = [S(\omega)] \{f(\omega)\}$$

The vector $\{f(\omega)\}$ is the complex Fourier transform of the free-field ground motion, which contains its complete description. For surface-founded structures subjected to vertically incident waves or for SSI analysis where embedment effects are ignored, the foundation input motion is assumed to be identical to the free-field ground motion. This latter instance is a source of conservatism which was quantified here.

Foundation impedances. Foundation impedances $[K_g(\omega)]$ describe the force-displacement characteristics of the soil. They depend on the soil configuration and material behavior, the frequency of the excitation, and the geometry of the foundation. In general, for a linear elastic or viscoelastic material and a uniform or horizontally stratified soil deposit, each element of the impedance matrix is complex-valued and frequency dependent. For a rigid foundation, the impedance matrix is a 6 x 6 matrix which relates a resultant set of forces and moments to the six rigid-body degrees-of-freedom.

Structure model. The dynamic characteristics of the structure to be analyzed are frequently described by its fixed-base modes. In the present study, our best estimate analyses and

simplifications thereof use this form.

SSI analysis. The final step in the substructure approach is the actual SSI analysis. The results of the previous steps -- foundation input motion, foundation impedances, and structure model -- are combined to solve the equations of motion for the coupled soil-structure system.

In all of the analyses, the control point was defined on the surface of the soil and the wave propagation mechanism was assumed to be vertically propagating shear and dilatational waves -- hence, defining the spatial variation of motion when included in the SSI analysis.

Soil Profiles. Two basic soil profiles were considered. The first was a uniform half-space with varying stiffness characteristics defined by shear wave velocities (V_s) of 500 fps, 1000 fps, 2000 fps, and 3500 fps. The second basic soil profile was a single layer of soil overlying a stiff bedrock. Two layer thicknesses of 71 ft. and 110 ft. were considered. Two soil layer stiffnesses characterized by shear wave velocities of 1000 fps and 2000 fps were considered. One additional case was analyzed -- a fixed-base condition.

4. Foundation Impedances

The present investigation centers on a series of analyses for various site conditions, embedment conditions, and assumptions in the SSI analysis. Modeling the soil is a key element in the studies. For best estimate analyses, i.e. those cases which model the frequency-dependence of impedances and include scattering matrices for embedded foundations, impedances and scattering matrices were calculated explicitly for one set of material properties for each distinct soil profile (uniform half-space, 71 ft. layer over bedrock, and 110 ft. layer over bedrock). The softest soil properties of interest were used in the explicit calculation to ensure adequate treatment of the frequency range of interest for stiffer soils. The key elements of modeling each of the three foundation conditions are discussed next.

Surface Foundation Impedances. The foundation is idealized as a flat, T-shaped surface foundation. This idealization retains the basic characteristics of the foundation's dynamic behavior, such as different horizontal and rocking impedances for the two horizontal directions and appropriate coupling terms. The resulting impedances are a best estimate of the foundation's behavior. The reference point location was selected to minimize the ~~coupling impedances between horizontal and torsional motion and vertical and rocking~~ motion. It is approximately at the center of gravity for the foundation which is somewhat coincidental.

Embedded Foundation Impedances. For those cases where the structure's foundation is assumed to be embedded, i.e. embedded in an identical manner to the Zion AFT complex, impedances and scattering matrices were developed. The surface-founded impedances form the basis for the embedded case, i.e. the surface-founded values were corrected for embedment. To do so, an equivalent cylinder was developed with dimensions obtained by matching the total excavated volume and the surface area of the foundations. This results in a cylinder of equivalent radius of 112 ft. and an embedment depth of 39 ft. -- an e/r of 0.35. Scattering matrices were generated for this equivalent cylinder and used in the analyses.

Frequency Independent Impedances. One simplification investigated in the present study was

to develop constant frequency independent soil springs which represent force displacement characteristics of the soil. The soil stiffness was represented by six spring constants, three translational and three rotational, representing the diagonal terms of the impedance matrix. The spring constants were calculated for an equivalent, rigid circular footing resting on an elastic half-space. For the translational springs, the circular plan was selected to yield a surface area equal to that of the actual T-shaped foundation. The circular footings for the rotational spring constants were chosen to preserve the rotational inertia of the T-shaped foundation for north-south and east-west rocking and torsion. The same four uniform half-spaces discussed earlier were treated here.

5. The Structure Model

The dynamic characteristics of the structure were represented by its fixed-base eigensystem. In all, eighty modes were extracted and used. The total mass participating in the eighty modes was 83.8% in the north-south direction, 83.8% in the east-west direction, and 71.9% in the vertical direction. To account for non-participating mass, a "missing-mass" correction was applied.

6. Numerical Results

A number of physical and analysis scenarios were considered. Table I itemizes the 19 cases. Cases 1-15 represent best estimate scenarios provided the analysis scenario matches the physical characteristics of the soil, structure, and foundation. Cases 16-19 represent scenarios with simplifications in the SSI analysis procedure. These latter cases are denoted half-spaces, however, the procedure is typically applied as an approximation to numerous soil profiles other than a uniform half-space, i.e. assuming equivalent soil properties. Hence, cases 16-19 represent a broader class of sites. In cases 16-19, only structure damping was applied -- no attempt to include radiation damping was made.

Selected results are presented in Tables II, III and IV. Table II quantifies the effect of embedment on response for the site conditions of interest -- a reduction in response for the embedded case is observed. Table III quantifies the effect of performing a fixed-base analysis rather than including SSI effects for the sites of interest -- in general, significant conservatism is demonstrated. Table IV quantifies the effect of performing a simplified SSI analysis on response -- significant conservatism is observed.

The sensitivity of in-structure peak accelerations and peak forces to changes in structure damping was also studied. Many design procedures select conservatively biased damping values; also, as excitation levels increase and structure failure is approached, higher damping values (10% of critical or greater) can be expected. Fixed-base and two uniform half-spaces of shear wave velocities of 2000 fps and 1000 fps were considered. Structure damping of 4%, 7%, and 10% of critical were studied; comparisons between the three were made. The results show structure damping to be important only for the fixed-base condition. Whenever SSI is properly modeled and the site can be characterized as soil rather than extremely stiff rock, changes in structure damping have a minimal effect on response. This is due to the fact that one must consider the soil and structure as a system and the energy dissipation characteristics of the supporting media dominate the system's behavior.

7. References

1. JOHNSON, J. J., SCHEWE, E. C., MASLENIKOV, O. R., SSI Response of a Typical Shear Wall Structure, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20122, Vols. 1 and 2 (1984).

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Table I. Identification of Physical and Analysis Scenarios

Case No.	Soil Profile	V_g (fps)	Foundation Condition	Analysis Technique	
1	Fixed-base	Fixed-base	Surface	Best estimate	
2	Half-space	3500	↓		
3	↓	2000			
4		1000			
5		500			
6		3500			
7		2000			
8		1000			
9		500			
10		110 ft. layer		2000	Surface
11		↓	1000		
12	2000				
13	1000				
14	71 ft. layer		2000	Surface	
15	1000				
16	Half-space		3500	↓	
17	2000				
18	1000				
19	500				

Table II. Mean Ratios of Forces and Peak Accelerations for Surface -- vs. Embedded Foundation Conditions (Half-Space and Layered Sites)

	Characteristic V_g (fps)	Case Comparison	Peak Accelerations		Peak Forces	
			Mean	COV	Mean	COV
Half-Space	3500	2/6	1.25	.164	1.17	.054
	2000	3/7	1.26	.146	1.22	.067
	1000	4/8	1.31	.159	1.29	.095
	500	5/9	1.28	.163	1.29	.122
110 ft. Layer	2000	10/12	1.37	.156	1.31	.110
	1000	11/13	1.38	.148	1.37	.103
71 ft. Layer Surface vs. 110 ft. Layer Embedded	2000	14/12	1.63	.138	1.57	.139
	1000	15/13	1.74	.151	1.75	.127

Table III. Mean Ratios of Forces and Peak Accelerations for Fixed-Base vs. (Surface and Embedded Foundations; Half-Space and Layered Sites)

Characteristic	Case Comparison	Peak Accelerations		Peak Forces		
		Mean	COV	Mean	COV	
Half-Space Surface Foundation	3500	1/2	1.07	.261	1.23	.178
	2000	1/3	1.25	.389	1.42	.289
	1000	1/4	1.47	.500	1.64	.360
	500	1/5	2.02	.601	2.14	.403
Half-Space Embedded Foundation	3500	1/6	1.27	.231	1.44	.184
	2000	1/7	1.52	.373	1.73	.288
	1000	1/8	1.89	.486	2.11	.360
	500	1/9	2.52	.573	2.73	.401
110 ft. Layer Surface Foundation	2000	1/10	1.07	.421	1.23	.284
	1000	1/11	1.27	.504	1.39	.342
110 ft. Layer Embedded Foundation	2000	1/12	1.39	.393	1.60	.289
	1000	1/13	1.67	.464	1.90	.353
71 ft. Layer Surface Foundation	2000	1/14	.86	.380	1.03	.295
	1000	1/15	.99	.511	1.09	.347

Table IV. Mean Ratios of Peak Accelerations for Soil Springs vs. (Surface and Embedded Foundations; Half-Space Site)

Characteristic	Case Comparison	Peak Accelerations		
		Mean	COV	
Half-Space Surface Foundation	3500	16/2	1.53	.299
	2000	17/3	1.86	.354
	1000	18/4	2.44	.432
	500	19/5	2.11	.382
Half-Space Embedded Foundation	3500	16/6	1.84	.244
	2000	17/7	2.26	.348
	1000	18/8	3.12	.429
	500	19/9	2.65	.400