Influence of the Local Site Condition on Seismic Response of a PWR-Reactor Building

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ABSTRACT

The influence of local site conditions on soil-structure interaction (SSI) response of a PWR containment building founded on 11 different sites was investigated using substructure SSI analysis procedures. The structures were analyzed for both surface and embedded foundation conditions for each site except one half- space site with shear wave velocity 5000 fps. A total of 23 analysis scenarios are presented. Responses (peak accelerations and response spectra) at selected locations in the structure were compared. The results indicate that the local site conditions have a significant influence on SSI responses.

1. INTRODUCTION

The local site conditions have a potentially significant influence on structrual response and are a source of modeling uncertainty for seismic probabilistic risk assessments (PRA) of a nuclear power plant. To investigate and identify this potential influence, a typical PWR-containment building, such as the Zion Nuclear Power Plant, was placed at a series of generic sites and the SSI response was analyzed by the CLASSI program [1] . Control motions consist of 10 synthetic time histories whose spectra matches the U.S. NRC R.G. 1.60 design spectrum.

In this study generic sites were generally classified into two categories: uniform half-space sites; and layered half-space sites. The characteristics of site stiffness were defined by different shear wave velocities of 500, 1000, 2000, 3500 and 5000 fps. For layered half-space sites, the thickness of the soil deposits varied from 36 ft to 250 ft. Bedrock shear wave velocity varies from 3500 fps to 9000 fps. In addition, the Zion specific site was investigated.

For each site condition, a series of SSI analyses was conducted for both surface and embedded foundations. Two embedment depths were considered: 36 ft and 59 ft which correspond to a ratio of embedment depth to equivalent radius (E/R) of 0.46 and 0.75, respectively.

2. STRUCTURES AND MODELS

The Zion containment building is comprised of two essentially independent structures a containment shell and a concrete internal structure. The containment shell is a cylindrical pre-stressed concrete structure 147 ft in diameter. The cylinder is topped with an elliptical dome 211 ft above the foundation. The

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internal structure includes the reinforced concrete support structure and the NSSS itself. The internal structure extends about 50 ft above the foundation mat to the operating floor. The containment shell and the internal structure interact only through the foundation which is 157 ft in diameter and about 13 ft thick. The containment shell was modeled using a series of vertical beam elements, with shear and bending characteristics appropriate for a circular cylindrical shell. Masses and rotary inertias were lumped at node points. Inertias affecting both bending and torsional response of the shell were included. The reinforced concrete internal structure was represented by a three-dimensional finite elment model consisting of plate and beam elements and it included a simplified model of the NSSS. The structure model contained about 3800 stuctural degrees-of-freedom. The models for the containment shell and the internal structure are shown in Fig. 1.

3. SEISMIC INPUT MOTIONS

An ensemble of 10 sets of three components of acceleration time histories (two horizontal 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 single excitation and provide stable results.

In all of the analyses, the control point was defined on the surface of the soil. The wave propagation mechanism was assumed to be vertically propagating shear and dilatational waves which, in conjunction with the soil properties, defines the spatial variation of motion. Specification of the control point and the spatial variation of motion in conjunction with assumptions made in the SSI analyses themselves define the relationship between the free-field ground motion and the foundation input motion.

4. ANALYSIS PROCEDURE

The substrucure approach as implemented in CLASSI was used in this study. CLASSI (Continuum Linear Analysis for Soil-Structure Interaction) is a set of computer programs for analyzing the effects of SSI on the dynamic response of structures using a substructure approach. This approach solves the SSI problem in three steps: determination of the foundation input motion; determination of the foundation impedances; and analysis of the coupled soil-structure system.

The foundation input motion is the response of a massless foundation to the specified free-field motion. This motion differs from the free-field motion except for the case of a surface foundation subjected to vertically propagating waves. The effects of the rigid foundation on the incident wave are taken into account by introducing a wave scattering matrix. Each column vector of the matrix represents the response of the massless foundation subjected to a given motion. Foundation impedances characterize the force-displacement behavior of the foundation soils. Their amplitudes depend on the soil properties, the geometry of the foundation and the frequency of excitation. For a viscoelastic material, impedances are both complex valued and frequency dependent. For a rigid foundation, the impedances are defined by a 6 x 6 matrix. The final step of the CLASSI procedure is performing the SSI analysis. The results of the first two steps are combined with a structural model to solve the equations of the coupled soil-structure system. Structural response is calculated from the resulting motion of the foundation including SSI effects, using modal coordinates. All calculations are performed in the frequency domain. Time domain solutions are obtained by inverse Fourier transformation.

5. PHYSICAL AND ANALYSIS SCENARIOS

Table 1 itemizes 23 scenarios which form the basis for the results presented here. Basically, sites were classifed into two categories: half-space and layered half-space sites. Soil profiles denoted half-space are uniform half-spaces with soil properties of: density of 130 pcf, Poisson's ratio of 0.4, and soil material damping of 5% of critical. Differences in stiffness characteristics are defined by differing shear wave velocities, Vs, of 500 fps, 1000 fps, 2000 fps, 3500 fps, and 5000 fps. Soil profiles denoted by a layer thickness are shallow soil layers overlying a stiff bedrock. A single soil layer over bedrock was considered in all cases except case 23 which corresponds to the Zion Nuclear Power Plant site and is composed of three layers over bedrock. Soil layer stiffness was defined by shear wave velocities of 1000 fps or 2000 fps. The underlying bedrock was typically assumed to have a shear wave velocity of 5000 fps, a density of 150 pcf, Poisson's ratio of 0.33, and material damping of 2% to 3% of critical. A few selected cases (19,20 and 23) assumed a bedrock shear wave velocity of 9000 fps.

Both surface and embedded foundation conditions were considered for each site condition. Two embedment depths were considered for a number of cases -- 36 ft and 59 ft which correspond to embedment ratios (E/R) of 0.46 and 0.75, respectively.

6. RESULTS AND DISCUSSION

Peak accelerations and response spectra at 26 selected nodes and forces for 36 elements were calculated for each earthquake. The mean values (over the ten earthquakes) of each component were compared case-by-case: The overall mean ratios of response and coefficients of variation (COVs) for peak accelerations, peak forces, and in-structure response spectra values were presented in Ref. 2. Here, we present selected data. The effect of site conditions on peak accelerations on the foundation mat, the mid-height of the containment shell (Node 16), the operating floor of the internal structure (Node 936) are presented here.

Effect of Site Stiffness on Dynamic Response

The effect of site stiffness on the peak acceleration at three selected locations for half-space sites is shown in Table 1 (case 1 to 9). In general, for structures either with surface or embedded foundations, the maximum responses of the structures situated on soft sites are smaller than those of the structures situated on stiff sites. This is due to the larger radiation damping effects and frequency shifts of the structures out of the resonant frequency range. The layered sites also show a similar tendency (cases 13,14,21 and 22). Embedment of the foundation (E/R=0.46) reduces peak acceleration of the basemat response about 18% for the case of shear wave velocity of 3500 fps. This reduction increases to about 32% for the case of shear wave velocity of 500 fps.

Fig. 2 shows the effect of site stiffness on in-structure response spectra (2% damping) at three selected locations for a surface founded structure. At the foundation level, the frequency content between 2 Hz and 12 Hz is reduced substantially as the site becomes softer. At the mid-height of the containment shell (Node 16), the dominant frequency shifts significantly from the stiff site(VS= 3500 fps) to the soft site (VS = 500 fps). The spectral acceleration changes from 200 ft/sec/sec for the stiff site to 30 ft/sec/sec for the soft site. At the operating floor of the internal structure two major peaks show strong reductions in amplitude and a shift in frequency as the velocity of the site changes from 3500 fps to 500 fps. Figure 3 shows the comparison of response spectra for the embedded foundation (E/R = 0.46). In general, spectral accelerations at the corresponding frequencies are smaller than those of the surface foundation case. The effects of site stiffness on response are similar to the surface foundation case.

Effect of Soil Layer Thickness on Dynamic Response.

Studies of earthquake motions recorded at several shallow soil sites have shown that stiff shallow soil layers may significantly amplify seismic waves [3] . Data also showed that predominant site frequencies do exist in a soil layered system primarily due to the propagation of nearly vertical shear waves. When a structure is founded on a shallow soil site, the natural frequencies of the structure may coincide with site frequencies and the structure may experience large response. Table 1 (case 11 to 23) shows the maximum acceleration of selected points in the structure founded on layered sites. Note that in case 12, the thickness of the thin soil layer (36 ft) is equal to the embedment of the structure so that the foundation of the structure is directly founded on the top of bedrock with shear wave velocity 5000 fps. A general trend can be seen: for the surface founded structures (cases 11,13,16 and 4), maximum accelerations increase as the thickness of the soil layer decreases. Apparently, the frequency content of the foundation input motion in high frequency ranges are amplified by the higher site frequencies of the thinner sites. For the cases of embedded structure (i.e. cases 12,14,16, and 8), the maximum responses of the structure at the foundation level is not sensitive to the thickness of the soil layer due to the filter effect of the embedment. However, as expected, the rotation in case 12 is much smaller. It is also noticed that the responses between the case of 250 ft soil layer and the half-space are not much different.

Figure 4 shows comparison of response spectra at selected locations for the surface founded structure situated on four different site conditions: soil layers of 36 ft, 110 ft, 250 ft and half-space. Based on the shear wave velocity of 1000 fps, the dominant frequencies of the three layered sites are 6.9 Hz, 2.3 Hz and 1 Hz. Significent effects are observed for the cases of thin soil layers (36 ft and 110 ft.). The sharp spectral peaks disappear for the cases of thick soil layer 250 ft. The shape and magnitude of response spectra between the cases of 250 ft soil layer and half-space are quite similar. Figure 5 shows the similar comparison for the embedded structure (E/R = 0.46). At all three selected locations, the responses are significantly affected by amplifications of thin soil layers (36 ft and 110 ft). Rocking response spectra on the foundation for case 12 (not shown in this paper) are much smaller than other cases. Again, the shape and magnitude of response spectra between the cases of 250 ft soil and half space are about the same.

7. CONCLUSIONS

Local site conditions have a significant influence on SSI responses. For of uniform half-space sites, the response is sensitive to the stiffness of the site for both embedded and non-embedded foundations. The peak spectral accelerations, dominant frequencies, and zero period accelerations, vary significantly with the changes in shear wave velocity of the site. For layered half-space sites the effects depend on the thickness and stiffness of the soil deposit, embedment of the foundation, and the impedance contrast between the soil layer and the bedrock. The influence is important for the structure founded on the surface of shallow soil deposit overlying competent rock. The influence becomes less important if the structure is deeply embedded (E/R = 0.75). For thick soil sites having shear wave velocity larger than 1000 fps and having soil thickness greater than 3.5 times the radius of the structure, the effect of soil thickness is not important.

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Table 1-Identification of Physical Scenarios for the Containment Building and the Maximum Responses at Three Selected Locations

Case No.	Soil Profile	V (fps)	Foundation Condition	Max. Acceleration (X,Z in Ft/sec^2) and Max. Rotation (YY in Rad/sec^2) Foundation X	Foundation Z	Foundation YY	Shell(Mid-Ht) X	Operating floor X	Operating floor Z
1	Half-Space	5000	Surface	7.05	5.21	.020	20.10	10.83	6.00
2	Half-Space	3500	Surface	7.22	5.40	.030	17.70	9.77	6.11
3	Half-Space	2000	Surface	7.47	5.43	.054	15.20	9.09	6.35
4	Half-Space	1000	Surface	7.37	4.73	.061	9.04	7.07	6.08
5	Half-Space	500	Surface	6.29	3.91	.053	5.74	5.60	4.61
6	Half-Space	3500	E/R = 0.46	5.95	4.85	.015	16.83	8.13	5.24
7	Half-Space	2000	E/R = 0.46	5.77	4.77	.027	12.42	7.21	5.36
8	Half-Space	1000	E/R = 0.46	5.17	4.43	.038	8.20	5.85	5.12
9	Half-Space	500	E/R = 0.46	4.26	3.68	.033	4.79	4.32	4.11
10	Half-Space	1000	E/R = 0.75	4.60	4.18	.032	8.11	5.27	4.80
11	36 ft. soil/rock	1000/5000	Surface	10.06	9.72	.098	19.77	11.71	10.81
12	36 ft. soil/rock	1000/5000	E/R = 0.46	5.26	4.49	.013	13.14	7.94	5.14
13	110 ft. soil/rock	1000/5000	Surface	7.69	6.39	.077	13.64	8.63	8.27
14	110 ft. soil/rock	1000/5000	E/R = 0.46	5.65	4.85	.048	11.73	6.95	5.78
15	110 ft. soil/rock	1000/5000	E/R = 0.75	5.13	4.13	.037	9.84	5.53	5.04
16	250 ft. soil/rock	1000/5000	Surface	7.37	4.68	.062	9.56	7.33	6.21
17	250 ft. soil/rock	1000/5000	E/R = 0.46	5.29	4.47	.039	8.11	5.96	5.13
18	250 ft. soil/rock	1000/5000	E/R = 0.75	4.62	4.22	.032	8.04	5.30	4.77
19	110 ft. soil/rock	1000/9000	Surface	7.70	6.72	.081	14.13	8.81	8.70
20	110 ft. soil/rock	1000/9000	E/R = 0.46	5.69	5.09	.048	11.88	7.06	5.85
21	110 ft. soil/rock	2000/5000	Surface	7.82	6.51	.062	19.41	10.52	7.60
22	110 ft. soil/rock	2000/5000	E/R = 0.46	6.00	5.01	.030	15.23	7.64	5.64
23	Zion soil/rock (3 layers)	600-910-1390/9000	E/R = 0.46	5.78	5.11	.058	15.66	8.30	6.41

*Note E/R denotes for the embedment radius ratio

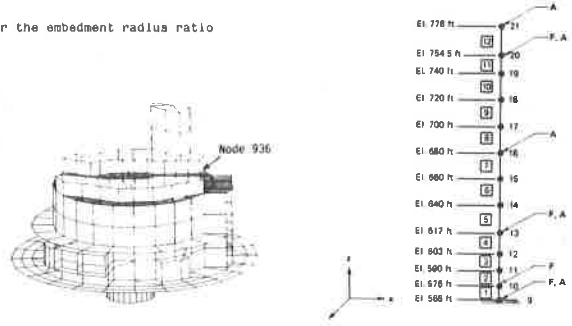

Fig. 1 SSI models for the Zion internal structure and containment shell

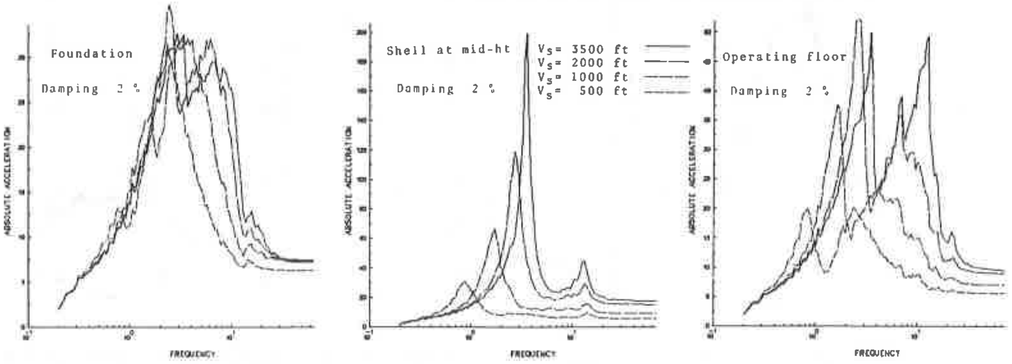

Fig. 2 Effect of stiffness of half-space sites on response spectra - Surface foundation

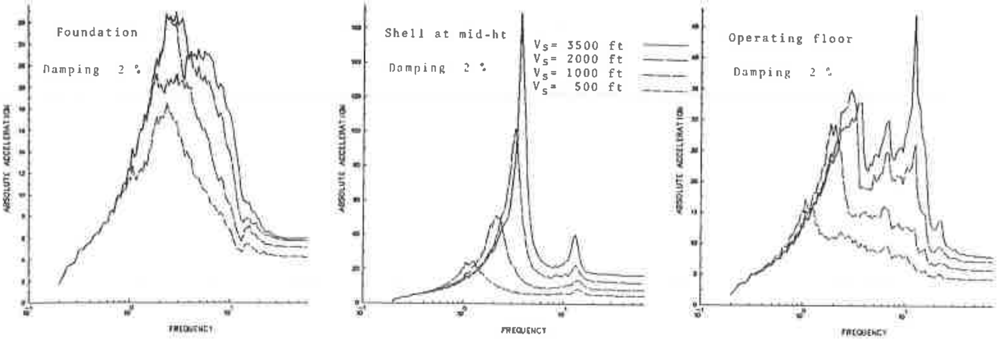

Fig. 3 Effect of stiffness of half-space sites on response spectra ,Embedded foundation E/R=.46

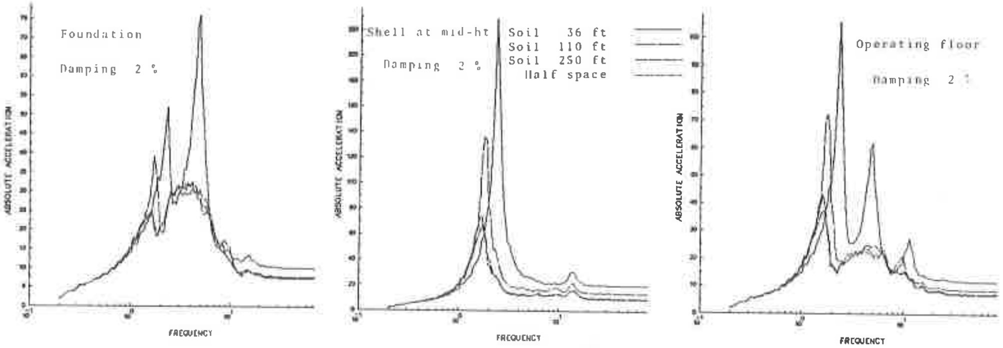

Fig. 4 Effect of soil thickness of layered sites on response spectra - Surface foundation

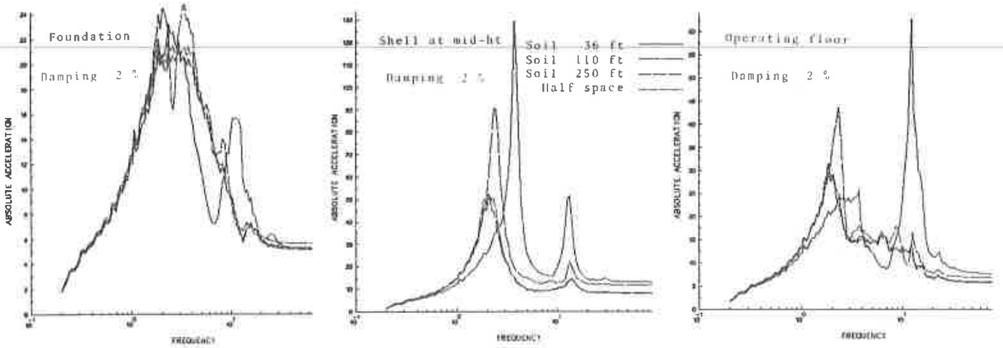

Fig. 5 Effect of soil thickness of layered sites on response spectra, Embedded foundation E/R=.46