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SYNOPSIS: This paper reviews the seismic soil structure interaction (SSI) analysis performed for the Modular High Temperature Gas-Cooled Reactor (MHTGR). The large depth to diameter ratio of the silo requires proper modeling of embedment and silo flexibility when evaluating the response of the structure to seismic loads. The computer program SASSI was used to perform the three dimensional SSI analysis in order to take full advantage of embedment in reducing seismic response.

Acceleration response spectra were computed for three soil sites at various points in the silo walls and internal vessels. The results demonstrated the effectiveness of embedment in reducing the seismic response. In general, the lowest silo and vessel accelerations occurred in the softest site where the SSI effects are the most pronounced. For a rock site, embedment eliminated the problem faced by structures founded at grade of amplification at the structure's fundamental modes.

INTRODUCTION

Various soil strata can have widely varied effects on the dynamic response of a deeply embedded structure. First, the presence of soil modifies the free field motion acting on the soil-structure system. Second, the soil often makes the system more flexible, thus decreasing the fundamental frequency to below that of the fixed base case. Finally, the radiation of energy from the structure into the soil increases the damping of the final system. It is therefore necessary to account for these potentially opposing effects in the soil-structure interaction methodology used to predict the seismic response. This paper reviews the effect of various soil sites on the seismic response of a deeply embedded reactor silo, the Modular High Temperature Gas-Cooled Reactor (MHTGR).

The MHTGR is an advanced reactor concept being developed under U.S. Department of Energy (DOE) funding. The objective of the MHTGR program is the development of a safe, economic nuclear power option. The reference concept is composed of four 350 MWt reactor modules coupled to two turbine generator sets producing a net electrical output of 538 MWe [Neylan, A., et al, 1988]. Each reactor module is housed in a separate underground concrete silo structure embedded to a depth of 48.9m. The top 9.1m of each silo structure is rectangular in plan, with dimensions of 22.9m x 40.8m. The remainder is circular, having a diameter of 18.3m. A reactor module (RM) consists of two vertical steel vessels - a reactor vessel and a steam generator vessel - in a side-by-side configuration connected by a coaxial crossduct. The significant features of the design are the passive rejection of decay heat from the reactor utilizing the natural circulation of outside air through heat removing panels on the cavity walls and the use of embedment to reduce the seismic response of both the reactor building and its components. Figure 1 shows an isometric view of the reactor building and the major components.

ANALYTICAL METHODOLOGY

Today's state-of-the-art earthquake engineering allows the influence of local site conditions on the seismic motion to be taken into account when determining the response of a soil-structure system. The MHTGR silo is a relatively stiff, deeply embedded structure with a large depth-to-diameter ratio, which may be embedded in a soft site, thus it is important to consider the SSI effects.

The computer program SASSI [Lysmer, J. et al, 1981] was used to perform the three-dimensional (3-D) SSI analysis. The program was selected to take full advantage of embedment in reducing seismic response. The program can model in two or three dimensions multiple embedded flexible foundations with arbitrary shapes. It uses the complex response method and the flexible volume substructuring technique. The soil material is modeled using complex stiffness moduli and a hysteretic damping mechanism. The site is represented by a horizontal layered soil system overlaying an elastic halfspace or a rigid base. The structure(s) are idealized by standard two- or three-dimensional finite elements. Primary nonlinear effects in the free field and secondary nonlinear effects in a limited region near the structure can be considered by the Equivalent Linear Method [Seed, H. B., et al, 1969].

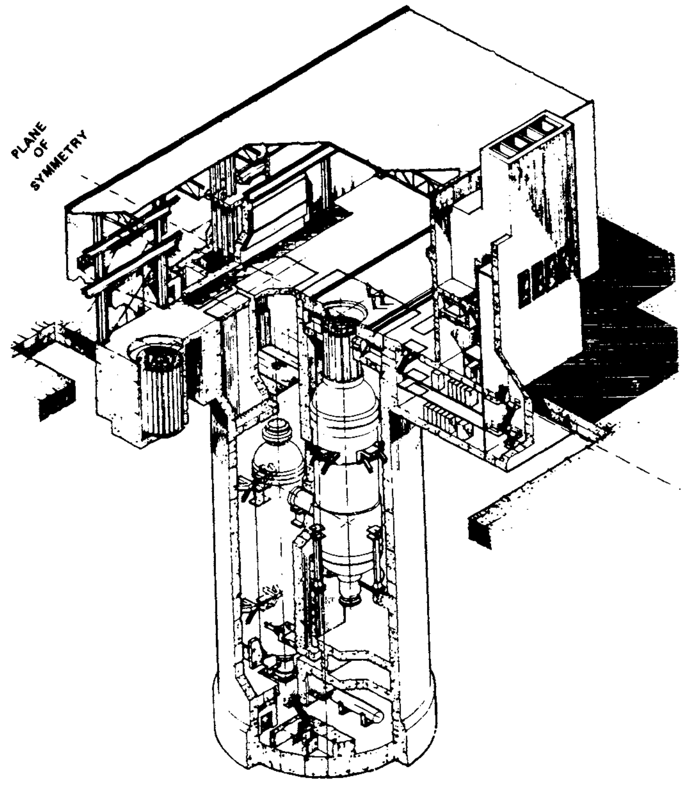


FIGURE 1. Isometric View of MHTGR Reactor Building

The dynamic loading can be either a seismic environment consisting of an arbitrary 3-D superposition of inclined body waves and surface waves or external dynamic loads. Transient input time histories are handled by the Fast Fourier Transform Technique.

To demonstrate the validity of the program SASSI during its development, it was used to compute the seismic response of the Humboldt Bay Nuclear Power Plant to the Ferndale Earthquake of June 7, 1975. The Humboldt Bay Power Plant and the MHTGR have similarities in the configuration of the reactor building. It is the only plant in the U.S. where the reactor is housed in a deeply embedded silo to a depth of 26.5m below grade. The structure consists of two major parts: a cylindrical portion 18m in diameter, and an upper rectangular portion 12m x 23m. The accelerations recorded in the silo were significantly smaller than the free-field accelerations at grade, clearly demonstrating the effectiveness of embedment in reducing earthquake induced loadings. The SASSI computed motions were shown to be in good agreement with those recorded inside the plant [Tajirian, F., et al, 1984].

SITE CHARACTERISTICS

The MHTGR is being designed for a wide range of potential sites with the objective of enveloping the response at 85 percent of the existing U.S. nuclear sites. To satisfy this requirement, the seismic analysis would have to cover a range of shear wave velocities (V_S) from 305 to 2,438 m/s. These represent the uniterated low strain soil properties.

Three sites were selected based on the findings of a previous study which examined ten typical sites which met the MHTRG requirements. It was concluded that, in general, the three site conditions enveloped the results. These three sites were used in the analysis discussed in this paper and are as follows:

- Stiff rock halfspace (ROCK)
- Linearly varying soil site (LVSS). V_S increasing with depth from 335m/s at grade to 762 m/s at the silo base.
- Soft soil over rock (SSOR). 22.9m of soil with a V_S of 335 m/s overlying rock with V_S of 2,438 m/s.

The soil model consists of horizontal layers resting on a uniform half-space. The properties vary with depth, but remain constant within the individual layers.

SEISMIC DESIGN CRITERIA

A complete three-dimensional SSI analysis requires that the response of the structural system be computed in the two horizontal directions and the vertical direction. The seismic design response spectra used in the analysis are based on the horizontal and vertical U.S. NRC Regulatory Guide 1.60 spectra [U.S. NRC, Reg. Guide 1.60, 1973], scaled to a maximum acceleration of 0.15g, which is the Operating Basis Earthquake (OBE). The Safe Shutdown Earthquake (SSE) is equal to twice the OBE.

The free-field input motion consists of two horizontal and a vertical synthetic acceleration time histories that are statistically independent. Their response spectra, in general, envelope the design spectra for all applicable damping values. Each time history has a duration of 24 seconds and is digitized at 0.005 second intervals.

The damping values for structural components are in accordance with the NRC Regulatory Guide 1.61 recommendations [U.S. NRC, Reg. Guide 1.61, 1973].

The control point (location of the seismic input motion) is specified at grade for the LVSS and SSOR cases. The free field is assumed to be composed of vertically propagating body waves. All three directions were computed for each site. Since the rock site analysis was idealized (conservatively) as a fixed base analysis, i.e., the silo is assumed rigid, the same input motion is specified at all silo nodes in contact with the rock, while modelling the flexibility of all internal floors and walls.

ANALYTICAL MODEL

The reactor building silo contains the Nuclear Steam Supply System (NSSS), which includes the reactor vessel, core, steam generator, and tube bundles and is fully embedded below grade.The reactor building silo was modeled using a 3-D finite element model and included the silo external walls, interior walls, basemat, rectangular portion of the reactor building substructure, vent stack, Reactor Cavity Cooling System (RCCS) stack, and steel superstructure. The NSSS and its associated supports were added to the model. Two sets of boundary conditions were added to the model, resulting in a rigid silo model to be used for the rock site and a flexible silo model to be used for the LVSS and SSOR sites. Specifically, all the nodes connected to soil in the rock site model are fixed, whereas they interact with the soil in the other two models.

Computer costs for both models were reduced substantially by taking advantage of symmetry in the model. A plane of symmetry about the vertical plane parallel to the cross duct made it possible to analyze only half the model. The appropriate boundary conditions required to force a state of symmetry for excitation in the Y and Z directions were applied to all nodes on this plane. Similarly, antisymmetry boundary conditions were applied for excitation in the X direction.

The first site analyzed was that in which the silo is embedded in uniformly rigid rock. In this case the rock and the reactor building external walls behave as a single rigid unit during a seismic event. Consequently, global silo flexibility and SSI have negligible effects on the silo and the systems, structures, and components (SSCs) located therein, and points in the silo are expected to move with the ground. Furthermore, in the frequency range of interest, less than 30 Hz, the shortest wave length for the vertically propagating body waves in rock exceeds the length of the silo.

The second and third sites analyzed (the LVSS and SSOR sites) were analyzed using the full model, considering the effects of SSI and silo flexibility. The computer code SASSI was used to solve the site response, impedance, and dynamic response problems.

The 3-D SASSI structural model is shown in Figure 2. The below-grade portion was represented with a total of 484 shell elements. Above grade structures were represented using 35 3-D beam elements. In addition to the structural elements, the SASSI code requires that the excavated soil volume be modeled with solid elements having the same properties as the surrounding site. The soil model used 388 solid elements and is shown in Figure 3.

A complete model of the reactor core, reactor vessel, steam generator vessel, steam generator tube bundle, cross vessel, and hot duct was developed by the designers of these componentsusing 94 3-D beam elements and is shown in Figure 4. This model was attached to the silo walls using spring elements whose properties represented the vessel anchorage and specified boundary conditions. In general, this RM model is more detailed than models commonly used in SSI

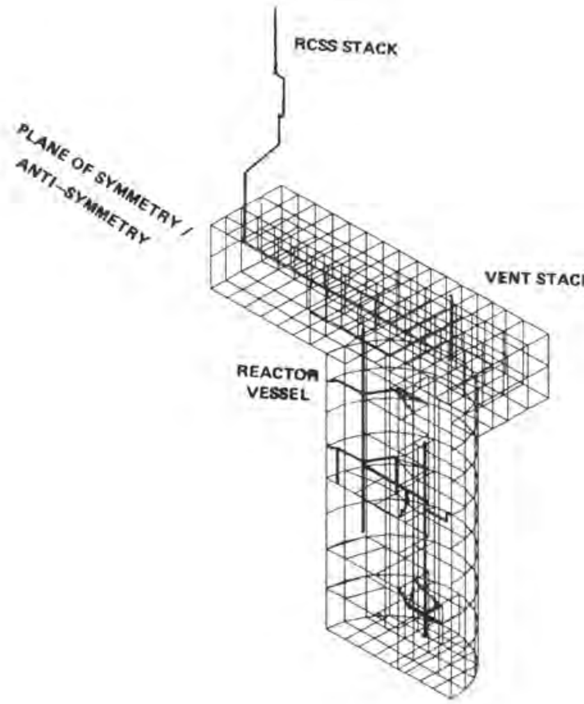


FIGURE 2. SASSI Structural Model

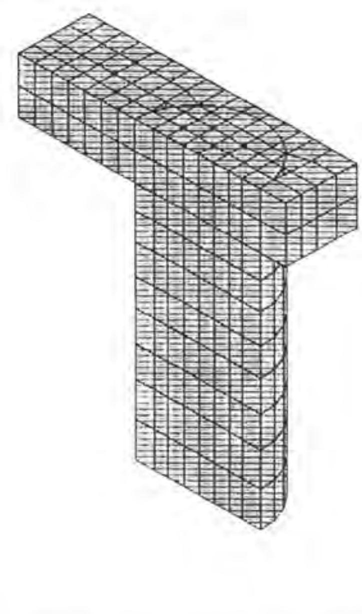


FIGURE 3. SASSI Excavated Soil Model

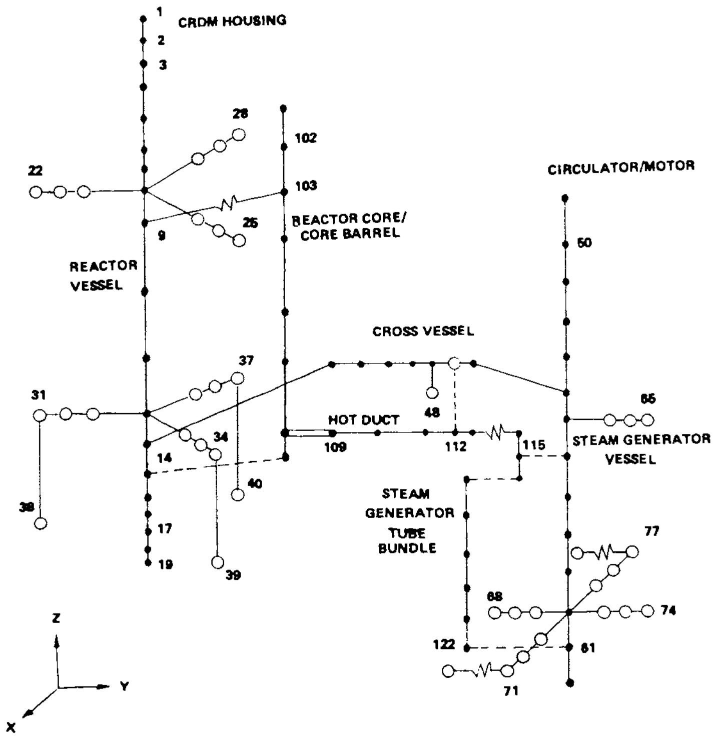


FIGURE 4. Reactor Module Model

analyses. This was done to eliminate the need for a multi-stepped analysis in which the results of the SSI analysis are used as input to a detailed RM model to eliminate potential for any amplifications which may result in the decoupling of the two systems. As a result, the design spectra or time histories developed in this SSI analysis can be used directly to evaluate the RM.

ANALYTICAL RESULTS

Acceleration time histories were computed for the three sites at various points in the silo walls and at points of interest in the internal structures. Acceleration response spectra were computed from the time histories for various damping levels. The response spectra used for design purposes were obtained by enveloping the raw spectra for the three sites, making the corrections described below for silo interaction effects and widened by plus or minus 15 percent. The spectra reported in this paper are the raw spectra for 2 percent damping.

MAXIMUM ACCELERATIONS

A plot of the maximum accelerations in the silo wall as a function of depth for the LVSS and SSOR sites is shown in Figures 5 and 6. For reference, the maximum acceleration for the rock site, which is 0.15g, and which is assumed to be constant with depth is also shown. The results demonstrate the effectiveness of embedment in reducing the seismic response. For the two soft soil sites it can be seen that the input motion levels are reduced. For elevations above -10m, there is some amplification in horizontal accelerations for the SSOR site and vertical accelerations for both sites. This amplification is not expected to affect the RM response since the RM supports are below this elevation. For the rock case, even though no reductions in input accelerations occur in the silo, embedment would prevent amplifications at the RM supports which would result if the MHTGR was not embedded due to usual amplification of the response between the base of surface founded structures and points at above grade elevations. Maximum accelerations at key points in the RM are given in Table 1. In general, the accelerations for the soil sites are lower than the rock sites; furthermore, the RM accelerations are lowest at the nodes with the deepest elevations.

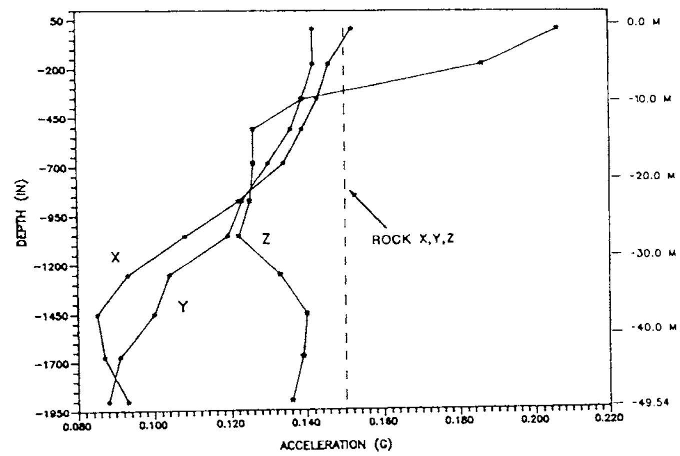


FIGURE 5. Maximum Acceleration in Silo (LVSS)

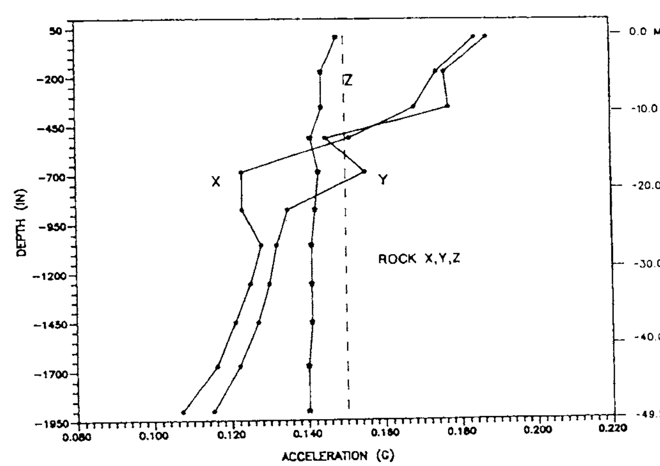


FIGURE 6. Maximum Acceleration in Silo (SSOR)

TABLE 1. Comparison of maximum Accelerations (G) in Reactor Module

LOCATION	NODE NUMBER	LVSS			SSOR			ROCK		
		X	Y	Z	X	Y	Z	X	Y	Z
CRDM HOUSING	1	0.59	0.39	0.19	0.53	0.34	0.22	0.64	0.72	0.46
TOP CORE SUPPORT	9	0.40	0.19	0.18	0.23	0.20	0.22	0.34	0.39	0.46
BOTTOM CORE SUPPORT	14	0.25	0.22	0.18	0.36	0.42	0.22	0.49	0.33	0.45
HOT DUCT	109	0.20	0.20	0.22	0.26	0.40	0.22	0.48	0.49	0.49
SG TUBE BUNDLE SUPPORT	122	0.14	0.17	0.21	0.20	0.32	0.18	0.35	0.40	0.50

ACCELERATION RESPONSE SPECTRA

The acceleration response spectra at increasing depths in the silo structure for 2 percent damping for the two soil sites are compared with the input spectra in Figures 7 and 8. These spectra were computed along the silo wall at elevations closest to the RM supports. For both soil sites, there is significant reduction in spectral accelerations at the lower supports, especially in the horizontal direction at frequencies between 1.5 and 8.0 Hz. The frequency at which the reduction in spectral accelerations occurs depends on the embedment depth of the node in question. In general, the RM response is highest for the rock case and the design of componenets with horizontal frequencies exceeding 5 Hz are controlled by the spectra for the rock case. However, in some instances, the soil spectra control the design when the critical frequencies for the componenets and systems are below 5 Hz. See Figure 9a. Figures 9 and 10 show a comparison of spectra computed at the lower reactor core support (node 14) and at the lower steam generator tube bundle support (node 122).

SEISMIC INTERACTION OF ADJACENT SILOS

Because of the proximity of the silos to each other, silo-to-soil interaction effects may result in responses that are different than what is computed for a single silo, especially for the soft soil cases. To quantify these effects, a 2-D SASSI analysis was performed for both a single silo (the base case) and all four silos. Maximum accelerations and response spectra were computed for both models and compared to determine the magnitude of the interaction effects. Based on the results of this study, the responses computed from the 3-D analysis would be adjusted to include these effects.

The result of the 2-D analysis for the LVSS site showed that, in general, the accelerations were highest in the inner two silos, and that in certain frequency ranges the spectral accelerations exceeded the spectral values for the base case. Based on these results, it was conservatively recommended to increase the 3-D horizontal and vertical spectra by 5 percent in the 1 to 2 Hz range, 20 percent in the 2 to 10 Hz range, and by 5 percent (horizontal) and 15 percent (vertical) for frequencies greater than 10 Hz.

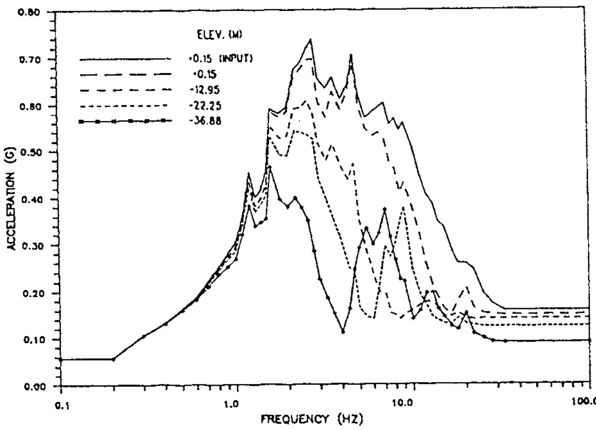
Interaction effects due to horizontal input perpendicular to the line of silos could not be represented in the 2-D models, and for the initial design phase the same adjustments computed for the other horizontal directions were applied.

Although the 2-D analyses described in this section are approximate, the results are expected to be more conservative than 3-D analysis. Because of the high cost of 3-D analysis, 2-D results will be used for assessing silo-to-silo interaction effects. However, a 3-D analysis which models more than one silo may have to be performed as a check of the final MHTGR design when a real site has been selected.

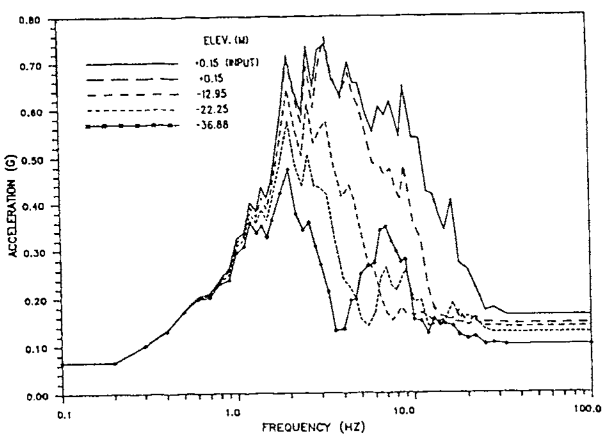
CONCLUSIONS

The results of 3-D seismic analysis of the MHTGR plant were presented in this paper. The response of the reactor building, which consists of a deeply embedded silo structure, and of the reactor module to seismic input was computed. The effectiveness of embedment in reducing seismic loads was demonstrated. The lowest silo and RM accelerations occurred in the LVSS site, which was the softest site analyzed, and where the SSI effects were more pronounced. For the rock site, embedment eliminated the problem (faced by structures which are founded at grade) of amplifications at the structure's fundamental modes.

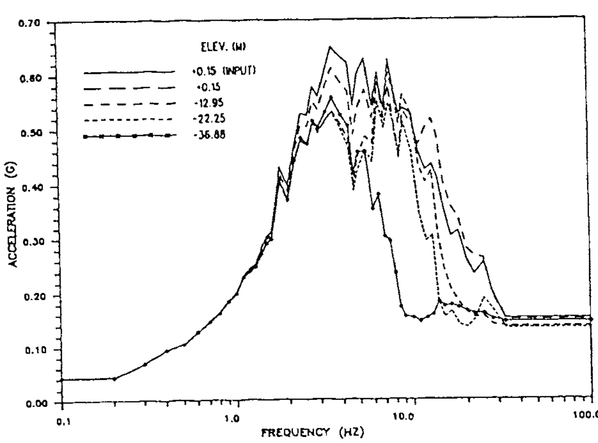
A comparison of the response spectra computed in the RM showed that in the vertical direction the shape of the spectra were similar and with the rock site giving the highest accelerations. In the horizontal direction, the peak spectral accelerations of the SSOR and LVSS cases usually occurred at the same natural frequencies, which were often lower than those for the rock site, and in general, the LVSS case giving the lowest spectral accelerations except at a few locations in the lower frequency ranges.



a) Horizontal - X

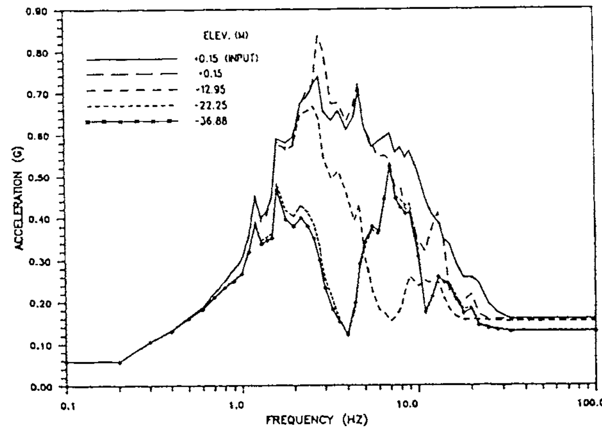


b) Horizontal - Y

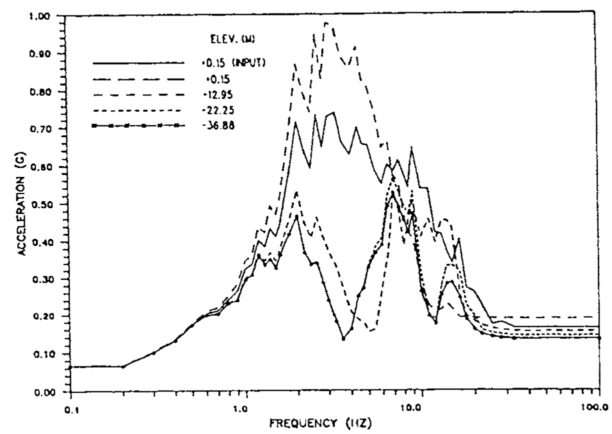


c) Vertical

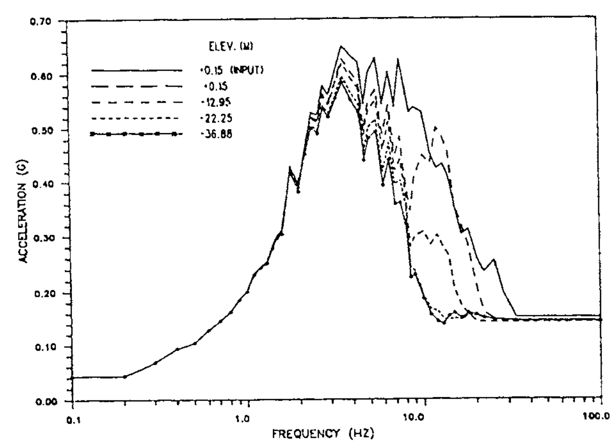
Fig. 7 Silo Spectra for LVSS Site, 2% Damping



a) Horizontal - X

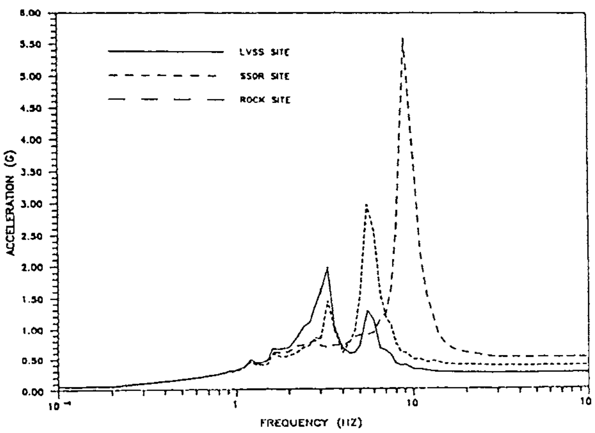


b) Horizontal - Y

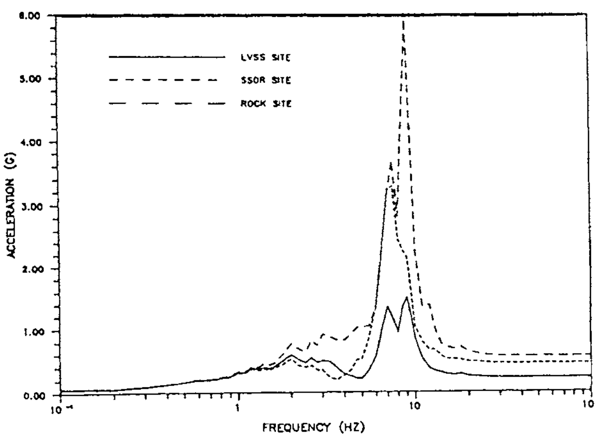


c) Vertical

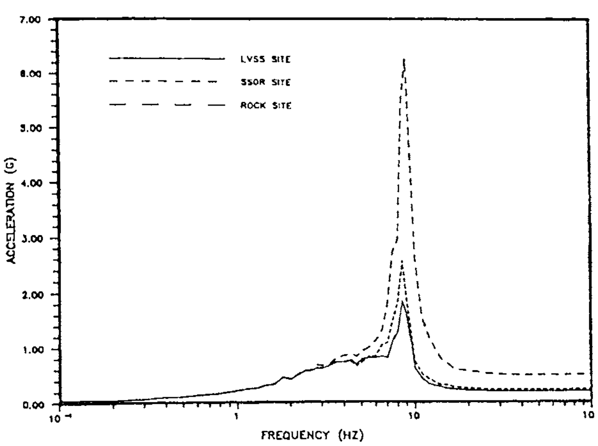
Fig. 8 Silo Spectra for SSOR Site, 2% Damping



a) Horizontal - X

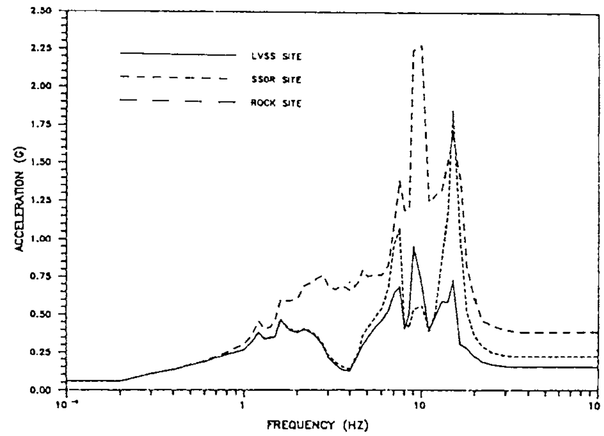


b) Horizontal - Y

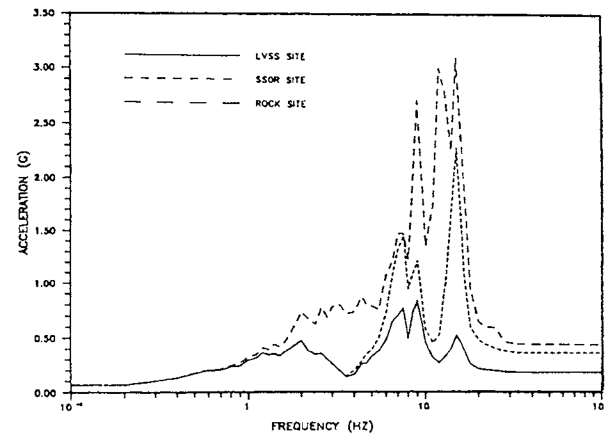


c) Vertical

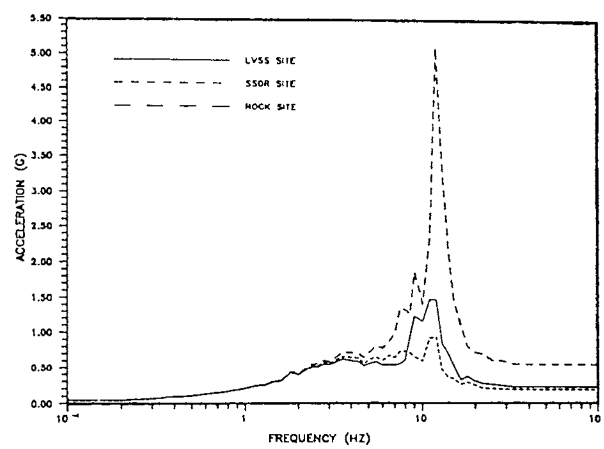
Fig. 9 Comparison of Spectra at Lower Core Support, 2% Damping



a) Horizontal - X



b) Horizontal - Y



c) Vertical

Fig. 10 Comparison of Spectra at Lower Steam Generator Tube Bundle Support, 2% Damping

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