A Quantitative Evaluation of Radiation Damping in Soil-Structure Interaction Effects

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Three-dimensional hybrid soil-structure interaction computer code, HASSI-1, was recently developed by the authors. HASSI-1 utilizes the three-dimensional hybrid modelling technique in representing soil-structure interaction, which has been developed at the University of California, Berkeley by the third author and S. Gupta. The modelling by HASSI-1 is achieved by partitioning the total soil-structure system into near-field and far-field with hemispherical interface. The near-field, which consists of the structure to be analyzed and a finite region of soil surrounding it, is modelled by ordinary finite elements. The semi-infinite far-field is connected to the near-field with required degrees of freedom to account for the loss of energy due to waves travelling away from the foundation.

To quantify the extent of radiation damping in the so-called dynamic soil-structure interaction effects, a typical nuclear reactor building resting on a soft rock foundation surface was analyzed by a classical method of stick model with soil spring, an ordinary two-dimensional finite element method (FLUSH) and a three-dimensional hybrid method (HASSI-1).

The result obtained by HASSI-1, differing from others, has indicated a remarkable reduction of seismic response of the reactor building due to radiation damping effect in the foundation as much as expected from the basic characteristics inherent to its analytical method. The computer time needed by HASSI-1 was almost equal to that by an ordinary two-dimensional dynamic finite element code.

The HASSI-1 is still limited in its applicability to general dynamic soil-structure interaction problems, however, it might offers a promising method to take account of due contribution of radiation damping effect in realistic soil-structure interaction effects.

1. INTRODUCTION

The purpose of this study is to quantify the extent of radiation damping in the so-called dynamic soil-structure interaction effects. Because of the tremendous computational effort involved in the three-dimensional (3-D) finite element analysis, soil-structure system is usually approximated by plane strain or axisymmetric modelling in the typical analysis. In the 2-D modelling of the soil system, the loss of energy due to waves travelling away from the foundation is apparently ignored because of the constraint in the direction normal to the plane. The axisymmetric modelling also prevent the wave propagation at the lateral model boundary.

Three-dimensional hybrid soil-structure interaction computer code HASSI-1, was recently developed by the authors. In the modelling by HASSI-1, the semi-infinite soil region is simulated by the far-field impedances at the boundary of the near-field soil-structure finite element model to account for the loss of energy due to radiation effects.

A typical nuclear reactor building of two stick models attached to a common rigid circular basemat which rests on a soft uniform elastic half-space was analyzed by HASSI-1, and the structural response was compared with those obtained from an ordinary finite element analysis and a classical analysis.

2. SOIL-STRUCTURE MODEL AND EARTHQUAKE MOTION

Geometry and properties of the soil-structure system

To illustrate the radiation damping effect in soil-structure interaction , example computer runs are carried out using the soil-sturcture model as shown in Fig. 1. The model consists of a 18-mass in 2-stick superstructures resting on a circular rigid basemat supported on a uniform elastic half-space. The superstructure model represents a typical nuclear power plant containment with its internal structures supported by a circular common basemat of radius 19.5m. The vibration mode of the model rigidly supported at the base are shown in Table I by the first seven modes.

The half-space foundation soil has unit weight of 2.08 ton/m^3, poisson's ratio of 0.33, and shear wave velocity of 567 m/sec, which corresponds to the shear modulus of 6.83 x 10^4 ton/m^2.

Damping for the superstructure model and the soil region are assumed as 2% and that 5%, respectively.

Free-Field Earthquake Motion

The horizontal free-field ground acceleration time-history with maximum acceleration of 1.0g, which has a 24-second duration, is shown in Fig. 2. The time-history normalized to 1.0g maximum acceleration has response spectra shown in Fig. 3. In doing the following analysis, the maximum acceleration of the ground motion was assigned as 0.1g.

3. METHOD OF ANALYSIS

3-D Analysis

The computer program, HASSI-1, uses the hybrid modelling technique [1] and the frequency domain solution method for the seismic time-history response analysis of a linear soil-structure interaction system. The soil-structure interaction model considered in this program is a hybrid model in which the dynamic characteristics of the structure and the foundation soil in the near field surrounding the structure are modelled by using finite elements; and the dynamic characteristics of the far-field foundation soil, considered to be a uniform elastic half-space, are modelled by using frequency dependent foundation impedances. The boundary of the near-field soil and the far-field soil is taken to be a smooth hemi-spherical surface for which the boundary impedances representing the far-field have been generated. In the soil-structure interaction model, these far-field impedances, properly lumped to be consistent with the near-field finite soil elements, are attached to the nodes of axisymmetric soil elements at the hemi-spherical boundary. Either a horizontal or a vertical seismeic acceleration input motion is considered to be a rigid boundary motion prescribed at the near-field and the far-field interface.

The stiffeness, damping (internal friction damping), and mass properties of the supersturcture was modelled by ordinally three-dimensional beam element. The uniform elastic foundation is modelled by 33 7-to-9 node axisymmetric solid elements in 60.9m radius hemi-spherical near-field soil region, and by 9 3-node spherical boundary impedance elements at the boundary of the near-field soil region, the geometry of the near-field soil model is shown in Fig. 4. The rigid basemat between the interface of the superstructure model and the near-field foundation model was simulated by "Master-slave transformation" procedure to impose the geometric constrains.

The soil-structure interaction model is subjected to a rigid horizontal ground acceleration input at the hemi-spherical boundary. This input motion is obtained through deconvolution of the prescribed horizontal free-field ground surface acceleration time history; the procedure of which is incorporated in the code. The first 18-second portion of this time history is used for the analysis.

2-D Plane Strain Analysis

In the 2-D simplification of 3-D structures, the superstructure with rigid circular basemat of radius 19.5m was converted into one with square basemat of 34.6m by 34.6m. Then, a one-meter wide slice of the structure and soil was considered in 2-D plane strain analysis by FLUSH code [2]. The rigid basemat was modelled by mass-less beam elements with enough rigidity to impose the geometric constraints.

The uniform elastic half-space foundation is modelled by 144 4-node rectangular elements; the geometry of the FLUSH soil model is shown in Fig.5

The input motion applied at the rigid lower boundary of the model was calculated through deconvolution of the prescribed horizontal free-field ground acceleration time-history by using one-dimensional wave propagation theory [3].

Axi-symmetric Analysis

The uniform elastic foundation is modelled by 144 4-node axisymmetric solid elements forming a 103.7m radius and 103.7m depth cylindrical soil region. The vertical degree-of-freedom at the lateral boundary was constrained.

The axisymmetric analysis was carried out using HASSI-1 code, which can be used for ordinally axisymmetric finite element analysis. The deconvolution of the free-field motion into the rigid boundary base input was performed by HASSI-1.

Classical Analysis

The rocking and swaying degree-of-freedom at the base of the structure were represented by soil springs of each component by continuum solution for rigid circular footing resting on elastic half-space [4].

Equivalent modal damping factors for the system and the modal frequencies are shown in Table II. The free-field acceleration time-history was applied directly to these supports of soil springs, and the dynamic response was evaluated by mode superposition technique taking into the first seven modes.

4. RESPONSE OF STRUCTURE

Response in 3-D analysis

Results of 3-D analysis by HASSI-1 code are plotted on Fig. 6, in the horizontal acceleration response spectra by 2% of critical damping of the top and basemat of the containment structure. Also shown in the figure is that of the free-field horizontal ground acceleration time-history. Interaction between the structure and soil system is negligibly small from the comparison of base motion with the free-field motion characteristics, except the reduction of the base response for frequencies higher than 9 Hz. On the other hand, the response spectrum of the top mass shows a prominent peak at 3 Hz; which can be attributed to the structural response amplified with the coupled rocking mode. The secondary peak at 9 Hz of considerably smaller in magnitude corresponds to a suppressed structural response coupled with the swaying mode.

Response in Axisymmetric Analysis

There is no significant difference between the results of the base motion response by the axisymmetric analysis (Fig. 7) and that by the 3-D analysis shown above. The resultant response at the top mass, however, shows considerably larger amplification in the 3.5 Hz rocking mode response.

Response in 2-D Plane Strain Analysis

The filtering effect on high frequency component of ground motion, observed in the 3-D results, is also present in the base response of the 2-D plane strain analysis, as shown in Fig. 8. In this case, however, the difference between the response of the basemat and the free-field ground motion becomes somewhat noticeable. A fairly large structural amplification has been obtained at the top mass.

The remarkable twin peaks in narrow frequency band were observed at 2.6 and 3.6 Hz. These two peaks show an apparent frequency shift from the results of rocking and swaying mode frequencies obtained by other methods in separable manner. This fact of frequency shift and narrow two peaks may mask the efficiency of 2-D analysis for essentially 3-D problems. By the way, the above same results have also been obtained from 2-D plane strain analysis using SAP-IV (time domain integration method) [5].

Response in Classical Analysis

The marked peaks of the top mass at frequencies of 3.4 and 8.4 Hz indicate a structural response of enhanced rocking and swaying modes, respectively, in the classical analysis shown in Fig. 9. In contrast to the results at the top, the base response at the rocking mode frequency is substantially small, while the swaying mode dominates on the response of the basemat.

5. EFFECT OF 3-D WAVE PROPAGATION

Horizontal acceleration spectra of the basemat obtained by each analysis method are replotted with the same ordinate in Fig. 10, for their comparison. The three different finite element approaches show a fairly simillar response of the basemat among the methods. The classical method, however, markedly differs from these results at the frequencies of rocking and swaying modes as well as in the higher frequency range. This deviation unique in the classical method may be attributed to the rather "static" treatment of soil springs represented only by the real part of rocking and swaying spring compliance functions; any external damping, e.g. major soil-structure interaction effect, is ignored. On the other hand, it is worth to note that the response spectra of the basemat in 3-D analysis and the free-field ground motion are in almost same in the range lower than 8 Hz (see Feg. 6).

The similar set of results at the top mass is shown in figure 11. The classical result again shows exceptionally large amplification in the structural response. Among the results of finite element approach, it becomes apparent that both the axisymmetric and 2-D plane strain shows equally larger response as compared with that of the 3-D results by HASSI-1 code by a factor of more than 2 at the 3 Hz rocking response. Their difference on the swaying mode response at about 9 Hz, on the contrary, becomes substantially smaller. These results may lead to an perspect that due to energy dissipating effect of soil under the basemat of the structure, the energy once transmitted to the superstructure could penetrate to the soil underneath, and contribute to the reduction of vibration of the supersturcture. In this point, it seems that axisymmetric analysis in somewhat 3-D model fashion but without theoretical radiation boundary could not have any surplus on the radiation damping effect to the response of the superstructure.

6. COMPUTATIONAL CONSIDERATIONS

The central processing unit (CPU) time shared to a super mini-computer system was 1.9, 1.8 and 1.0 hr for 2-D, 3-D and axisymmetric finite element analysis. In the 3-D and axisymmetric case, the time for deconvolution of the ground motion are included in their values.

7. CONCLUSION

The results obtained by HASSI-1, differing from others, has indicated a remarkable reduction of seismic response of the reactor building due to radiation damping effect in the foundation as much as expected from the basic characteristics inherent to its analytical mithod. The computer time needed by HASSI-1 this time was almost equal to that by an ordinaly two-dimensional dynamic finite element code, however, it could be further reduced by applying the economical interpolation procedure[6] incorporated in the code.

The HASSI-1 is still limited in its applicability to general dynamic soil-structure interaction problems, however, it might offer a promising method to take account of due contribution of radiation damping effect in realistic soil-structure interaction effects.

8. ACKNOWLEDGEMENT

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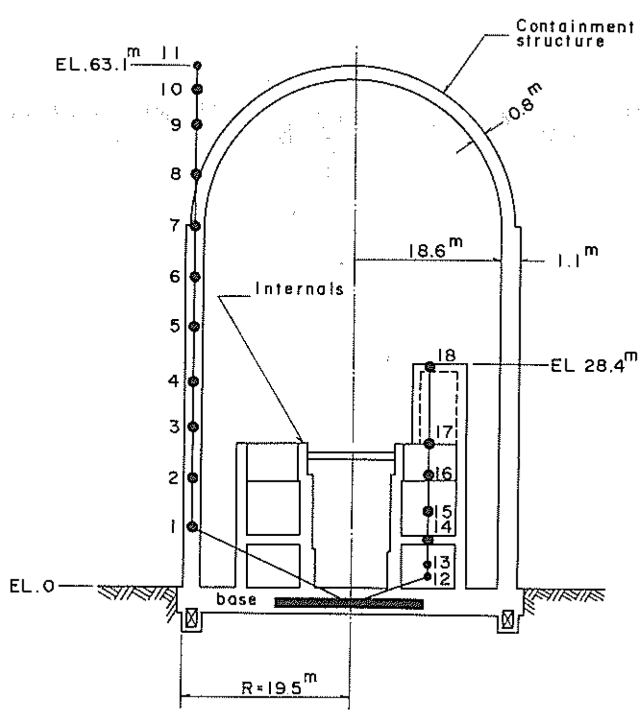

Figure 1. Superstructure Model

Table I
Vibration Characteristics of Superstructure

Mode no.	Freq.(Hz)
1	5.2
2	14.2
3	14.7
4	23.7
5	27.3
6	29.3
7	31.2

Table II
Vibration Characteristics of Stick Model with Soil Springs

Mode No.	Freq. (Hz)	Damping (%)	Participation Factor	Mode Type Containment	Internals
1	3.3	3.4	.0153	Rocking & 1st	Rocking
2	8.4	3.5	-.0057	Swaying & 1st	Swaying & 1st
3	14.4	2.4	-.0046	2nd	1st
4	18.7	2.3	-.0041	2nd	1st
5	24.7	2.1	-.0015		
6	29.6	2.1	-.0008		

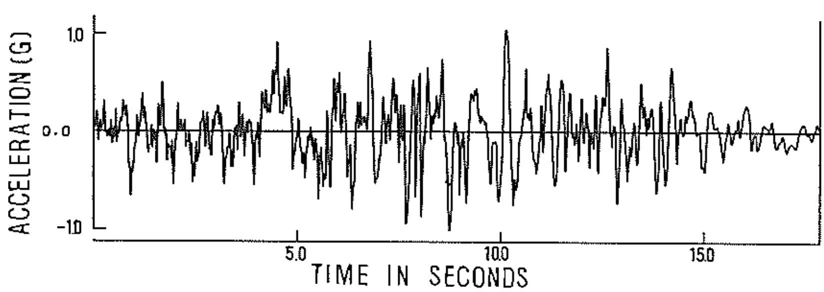

Figure 2. Horizontal Free-Field Ground Surface Acceleration Time-History (Normalized to 1.0 g)

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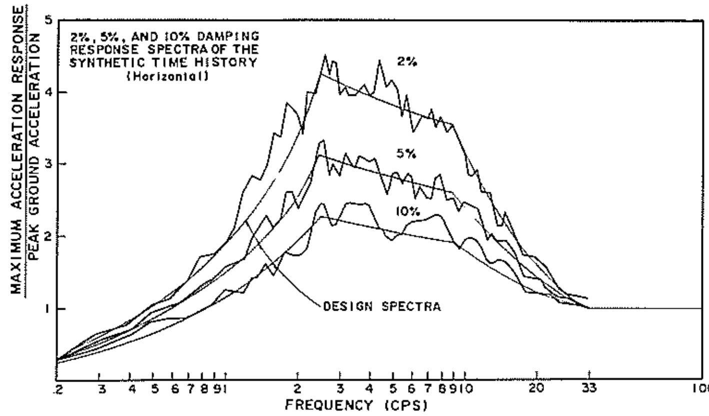

Figure 3. Response Spectra of Horizontal Free-Field Ground Surface Acceleration Time-History

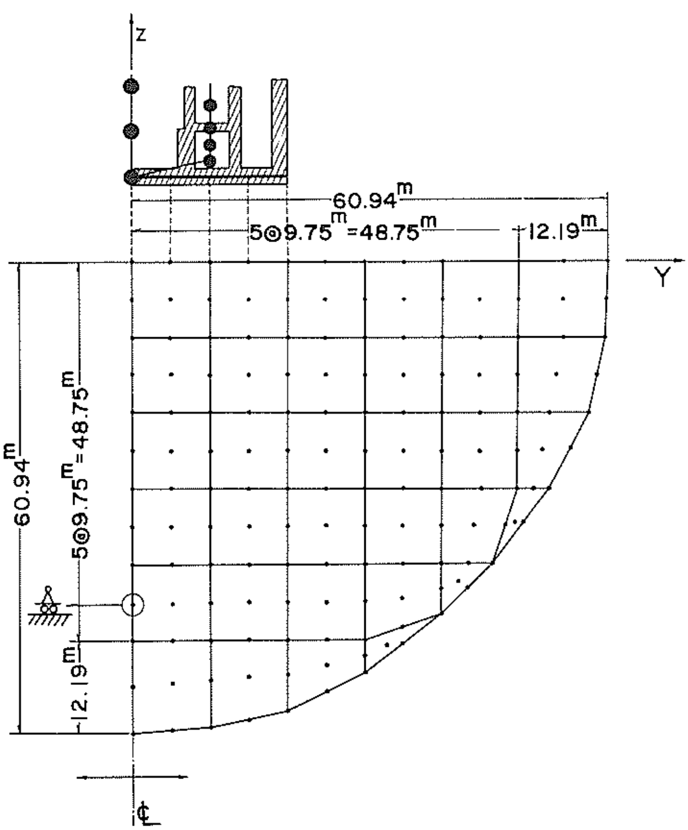

Figure 4. Hemi-Spherical Near-Field Foundation Soil Model

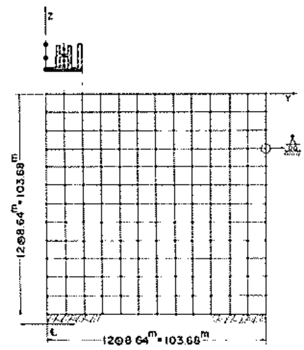

Figure 5. FLUSH Finite Element Model

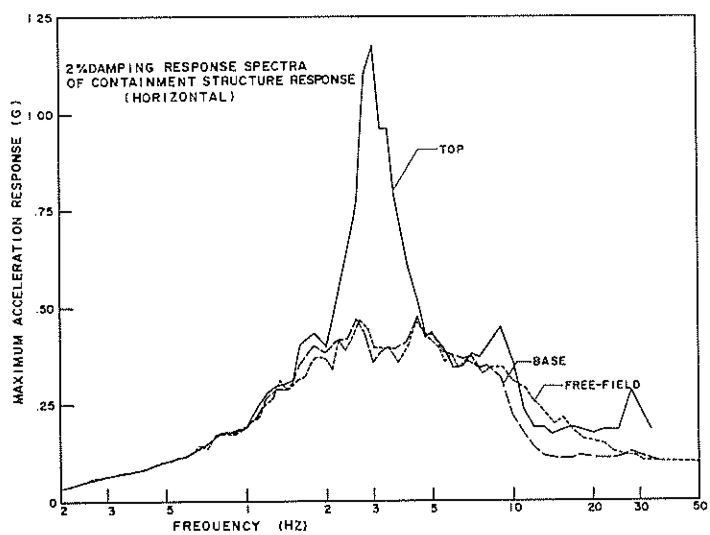

Figure 6. Response in 3-D Analysis

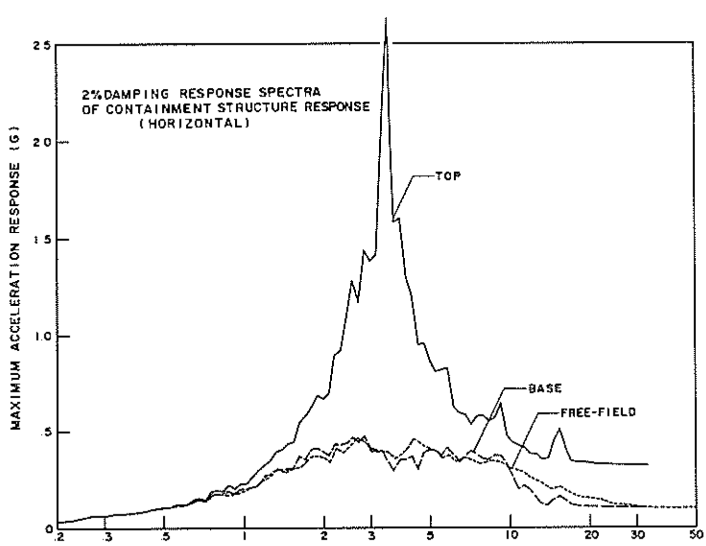

Figure 7. Response in Axisymmetric Analysis

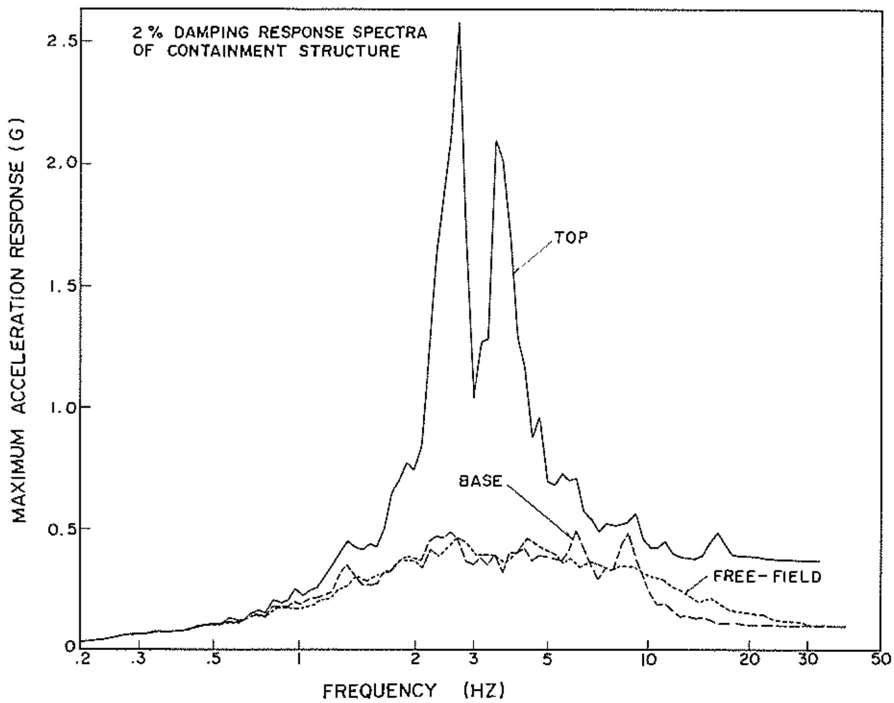

Figure 8. Response in 2-D Plane Strain Analysis

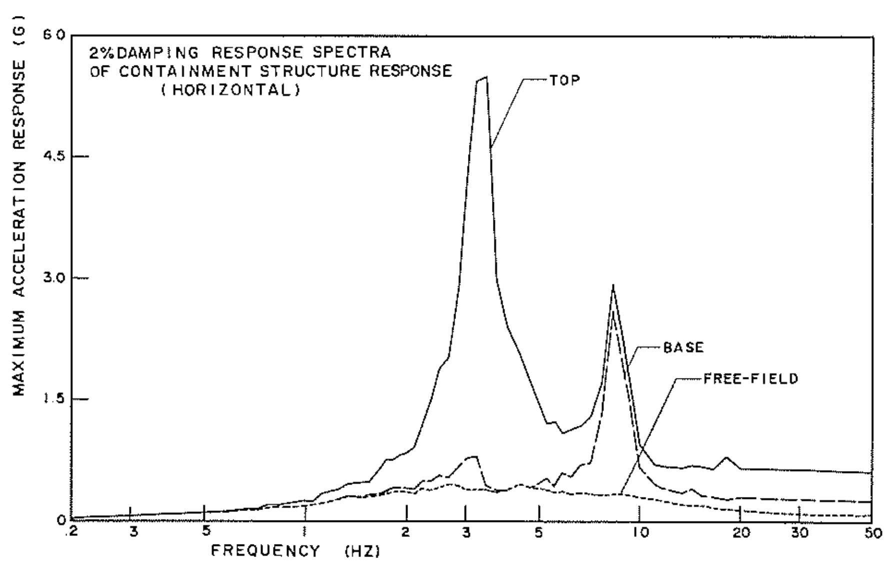

Figure 9. Response in Classical Analysis

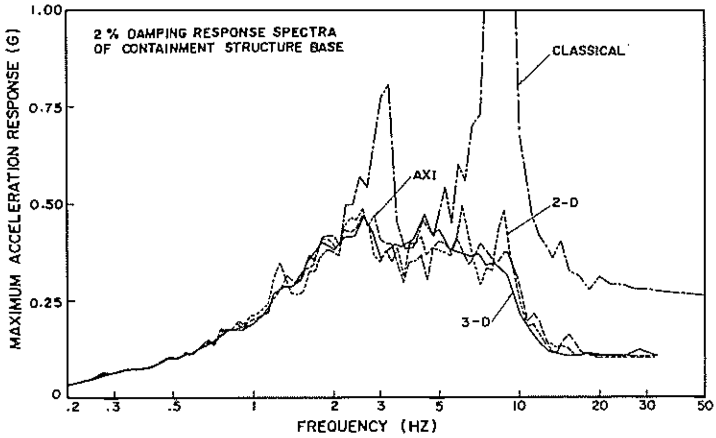

Figure 10. 3-D Effect on Response at Basemat

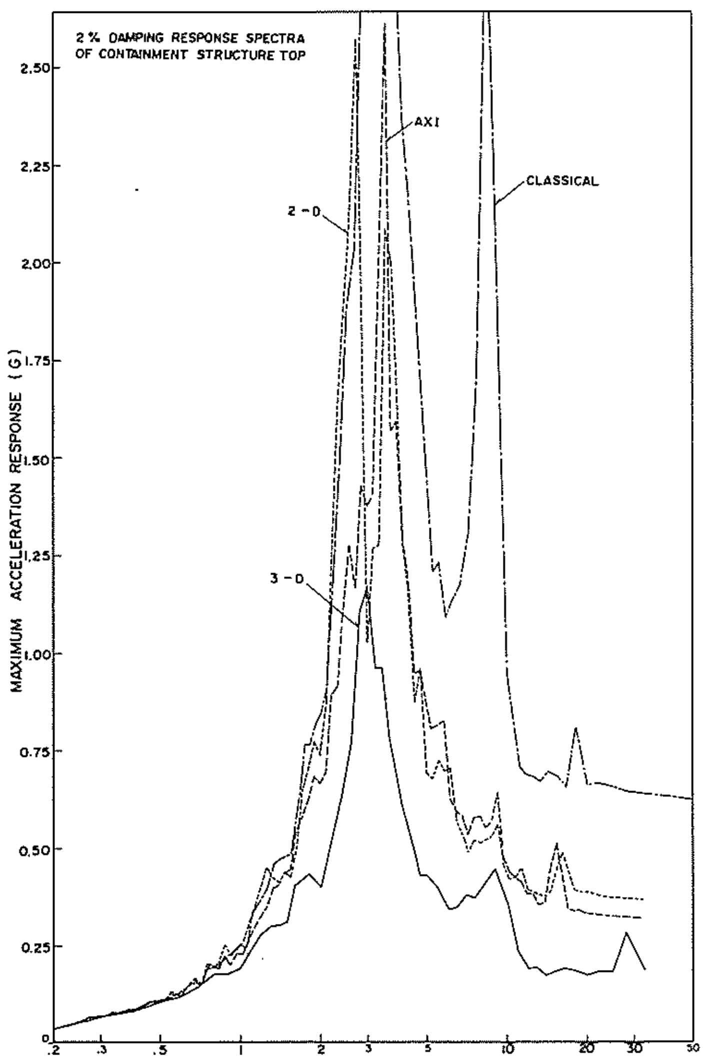

Figure 11. 3-D Effect on Response at Top mass