An Assessment of Soil-Structure Interaction Effects Based On Simple Models

A.J. Philippacopoulos
Department of Nuclear Energy, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

C.A. Miller
Department of Civil Engineering, City College of New York, Convent Avenue at 138th Str., New York, N.Y. 10031, U.S.A.

Soil-structure interaction effects are investigated using a simple mathematical model which employs three degrees-of-freedom. The foundation is approximated by a homogeneous, isotropic, elastic half-space. Harmonic functions and a recorded earthquake are used to represent the free-field input motion. Variations of the response characteristics due to structural and interaction parameters are demonstrated. Response spectra are presented that display the magnitude of the maximum structural response for a range of fixed-base structural frequencies, interaction frequencies and damping. Conclusions are obtained regarding the behavior of the response of the soil-structure system. The findings reported herein can be used for the interpretation of the results of soil-structure interaction analyses of nuclear plant structures that are performed with available computer codes.

1. Introduction

The soil-structure interaction analysis of nuclear power plant-structures is usually determined by relatively large models that represent the soil-structure system. Numerical results are obtained utilizing available computer codes. The difficulty with this approach is that, due to the large amount of data involved in the analysis, the analyst engineer cannot have a direct appreciation of the various parameters that influence the structural response. One way to assess the significance of these parameters is to use simplified mathematical models to describe the motion of the soil-structure system. Such models have been employed in previous studies.

In this paper, the interaction problem is treated with a three degree-of-freedom model for simplicity. It incorporates a single flexural mode and two rigid body modes. Typical foundation characteristics have been assigned to the model which account for conditions met in practice. This model allows a close-up examination of the system frequencies and response amplitudes. Variations of these items are demonstrated, based on analytical solutions for transfer functions. The free-field input is represented by harmonic functions as well as by a recorded earthquake. Acceleration response spectra are generated for a representative range of structural and interaction parameters. The results reported herein can be used in the modeling of soil-structure systems. Furthermore, they can be used for the interpretation of the numerical results from analyses of complex systems obtained by computer solutions.

2. Model Considered

The mathematical model considered to treat the interaction problem represents a flexible superstructure (fixed-base structure) resting on a deformable foundation. The structural part is represented by a single flexural mode having natural frequency and viscous damping ratio f_o and ξ_o, respectively. The foundation is approximated by a homogeneous, isotropic, elastic half-space. Impedance functions for such foundations are available in the literature, i.e., Ritchart et al, [1]. In general, these functions are frequency dependent, however, it has been suggested by Parmelee [2], Tsai [3] and others that these dynamic properties of the foundation may be considered to be constant.

For horizontal motion, the degrees-of-freedom of the model are represented by the translation of the superstructure, the translation and the rocking of the foundation. Furthermore, by neglecting the flexibility of the superstructure, a set of interaction quantities can be defined. Specifically, when $f_o = 0$ and for translation motion without rocking the interaction frequency is

$$f_t = \frac{1}{2\pi}\sqrt{\frac{k_t}{m}} \tag{1}$$

k_t = translational soil spring constant; m = total mass of superstructure plus foundation. Also, when $f_o = 0$ and for rocking motion without translation, the interaction frequency is

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k_t}{I}} \tag{2}$$

k_r = rocking soil spring constant; I = rotatory moment of inertia with respect to the interaction axis. The corresponding interaction damping values in translation and rocking are:

$$\xi_t = \frac{c_t}{2\sqrt{k_t m}} \quad ; \quad \xi_r = \frac{c_r}{2\sqrt{k_r I}} \qquad (3)$$

c_t, c_r = soil dampers. From eqs. (1)-(3), it is observed that two soil-structure interaction systems with identical foundations will have different interaction parameters f_t, f_r, ξ_t, ξ_r if their masses and rotatory moments of inertia are different.

The motion of the soil-structure model described above can be expressed by a system of three second order linear differential equations. Formulation of these equations and solutions for transfer functions have been obtained by the first author [4]. Transfer functions between the free-field and the structural translation and acceleration are expressed in terms of eight parameters. The latter include three frequencies f_o, f_t, f_r three damping ratios ξ_o, ξ_t, ξ_r and two mass ratios r_1, r_2. Ratio r_1 is equal to the total mass of the system (i.e., structure plus foundation) over the structural mass. Ratio r_2 is equal to the rotatory inertia of the system with respect to the interaction axis over the product of the structural mass times the square of its height above the foundation. The effect of these parameters on the system frequencies and response amplitudes is demonstrated next.

3. Variations of System Frequencies

Frequency variations were obtained using the transfer functions of the soil-structure system. The frequency at which the maximum modulus of the transfer function between the free-field and the response of the superstructure occurs is denoted by f^*. For rigid foundations $f^* = f_o$. Variations of the ratio f^*/f_o are illustrated in Fig. 1. Fixed-base frequencies in the range of 2-15 cps were considered. For simplicity, the interaction frequencies f_t, f_r were taken to be equal and are denoted by f_s. It was concluded that the curves shown in this figure do not change significantly for small differences between f_t and f_r.

From Fig. 1, it is observed that at low values of f_o/f_s the frequency of the soil-structure system approaches the fixed-base frequency, while at other values of this ratio: $f^* < f_o$. Furthermore, the frequency of the soil-structure system is shown not to be sensitive to the mass ratios r_1, r_2. Two values were considered for these ratios, namely 1 and 2. Ratio r_1 is equal to one when the mass of the foundation is neglected as compared to the mass of the superstructure. On the other hand, the ratio r_2 is equal to one when the rotatory moment of inertial of both the foundation and the superstructure are neglected. The values of r_1, r_2 for nuclear plant structures are usually below two. For example, the models considered by Tsai [4] have mass ratios in the range of 1.0 to 1.5.

4. Harmonic Motion

Harmonic responses for the relative translation and the total acceleratión of the superstructure were obtained numerically using small frequency increment. Harmonic free-field excitations with unit amplitudes are considered. The results are presented in terms of the peak amplitudes D^* and A^*. D^* is the maximum of the modulus of the transfer function between the free-field and relative translation of the superstructure. A^* is the corresponding maximum for the absolute acceleration. Variations of the peak amplitudes due to structural and interaction parameters are described next.

Variations of D^* are shown in Fig. 2 for fixed-base frequencies in the range of 2 to 7 cps and for two values of the structural damping, i.e., ξ_o = 2% and 10%. It can be seen that the peak amplitude D^* is sensitive to the structural damping especially at high interaction frequencies f_s. It is also noted that peak amplitude variations are more promounced for soil-structure systems associated with superstructures having low fixed-base frequencies. Usually, higher interaction frequencies result in higher amplitudes D^*. However, from the same figure, it can be seen that at higher structural damping, i.e., ξ_o = 10% higher interaction frequencies produce lower amplitudes. While the curves shown in Fig. 2 were computed with ξ_t = 30% and ξ_r = 5%, results obtained with fifty percent higher interaction damping indicated that the effect is small. Furthermore, D^* was found not to be sensitive to the mass ratios r_1, r_2.

Variations of the peak amplitude A^* are given in Fig. 3 for different structural and interaction damping values most commonly used. Note, that while interaction damping does not effect significantly the amplitudes, the structural damping reduces considerably the amplitudes especially at low values of f_o/f_s. For $f_o > 2f_s$, practically no variations of A^* are observed. An investigation of the effect of the mass ratios r_1, r_2 lead to the conclusion that these ratios do not effect the amplitude A^*.

5. Response to Earthquake Motion

In order to demonstrate response variations of the soil-structure system considered here due to multifrequency excitations, the concept of the response spectrum is used. Conventionally, response spectra are represented by a set of curves which correspond to different structural damping. In the present study, the spectral curves are assigned to the structural and interaction damping as well as interaction frequency. The acceleration record of the El Centro 1940 earthquake is used as free-field motion. Maximum absolute acceleration responses of the superstructure due to this earthquake were computed for different structural and interaction parameters. Frequency domain solutions were carried out. Small frequency increments were used in order to make sure that the peaks of the transfer functions for all the soil-structure system parameters considered were taken into account during the computation. Acceleration spectra were generated for soil-structure systems with associated fixed-base frequencies ranging from 0.2 to 33.0 cps.

From spectra generated with typical interaction damping values, it was concluded that the spectral curves do not change significantly with the interaction damping. This result is demonstrated in Fig. 4 for two pairs of values of ξ_t and ξ_r. Spectral curves for interaction frequencies greater than 5 cps were found practically unchangeable due to the interaction damping. Similar behavior was found due to variations of the mass ratios. Based on these observations and in order to simplify the presentation of this section, results with ξ_t = 30%, ξ_r = 5% and r_1, r_2 = 1, are demonstrated. Acceleration spectra for soil-structure systems due to the El Centro earthquake are given in Figs. 5(a)-5(d). The frequency axis represents the fixed-based frequency f_o of the superstructure. Four curves are displayed per spectrum corresponding to interaction frequencies f_s = 1, 5, 20 and ∞ cps. Spectral curves for f_s greater than 20 cps were found to be very close to the rigid foundation solution. From these figures, it can be seen that flexible foundations can attenuate or amplify the response of fixed-base structures. It is noted also that at higher structural damping, the spectral curves converge faster to the rigid foundation case.

6. Conclusions

The behavior of the response of soil-structure systems is examined using a three degree-of-freedom model. Based on the results presented, it is concluded that:

1. Higher interaction frequencies result in higher soil-structure system frequencies. As the foundation rigidity increases, the soil-structure system frequencies converge from lower values to the fixed-base frequencies.

2. Soil-structure system frequencies and responses due to harmonic and earthquake excitations are not sensitive to the mass ratios r_1, r_2.
3. Variations of the interaction damping have practically no effect on the response amplitudes. The latter, however, generally depend on the structural damping.
4. Both maximum harmonic and earthquake responses of the soil-structure system represent attenuations or amplifications of the corresponding fixed-base system responses. Also, as the rigidity of the foundation increases, the convergence of the soil-structure system maximum responses to the fixed-base case may not be a monotonic process. Faster convergence occurs at higher structural damping.

Acknowledgements

Any opinions, findings and conclusions or recommendations expressed in this paper, are those of the authors and do not necessarily reflect the views of either the Brookhaven National Laboratory nor any agency of the U. S. Government.

References

[1] RITCHART, F.E., et al., Vibrations of Soils and Foundations, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1970.

[2] PARMELEE, R.A., et al., "Seismic Response of Multiple-Story Structures on Flexible Foundations," Bulletin of the Seismological Society of America, 59 (3), pp. 1060-1070 (1969).

[3] TSAI, N.C., et al., "The Use of Frequency-Independent Soil-Structure Interaction Systems," Nucl. Eng. Design 31, pp. 168-183 (1974).

[4] PHILIPPACOPOULOS, A.J., "Behavior of Basic Soil-Structure Interaction Parameters," (to be published).

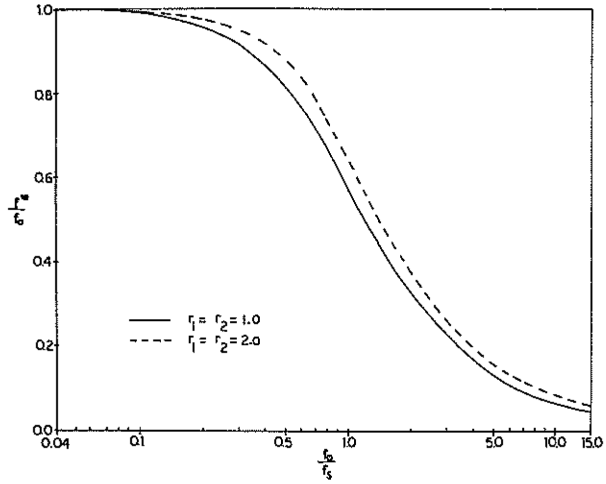

Figure 1 - Variation of Soil-Structure System Frequencies.

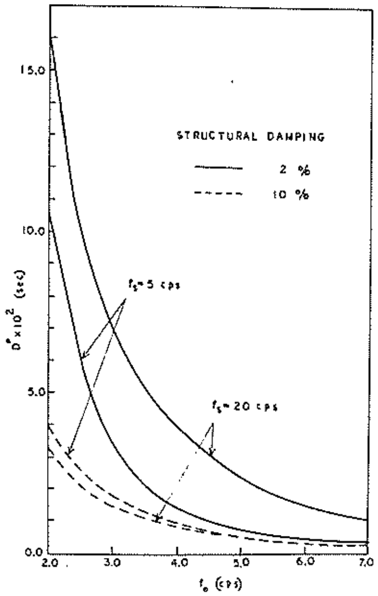

Figure 2 - Variations of Peak Amplitude D^*.

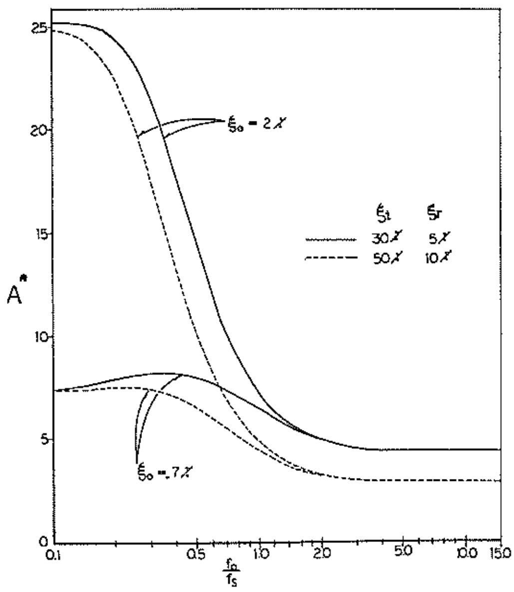

Figure 3 - Variations of Peak Amplitude A^*.

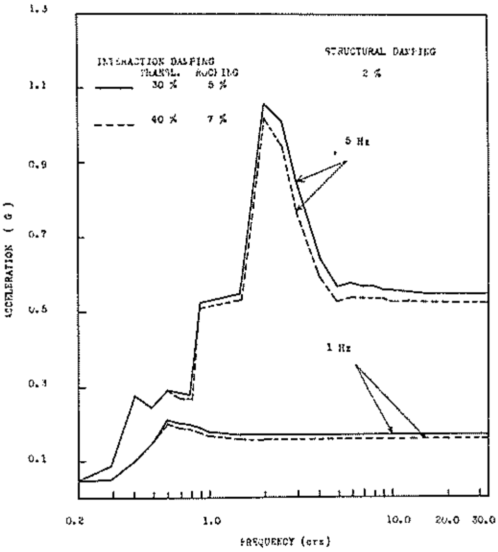

Figure 4 - Effect of Interaction Damping.

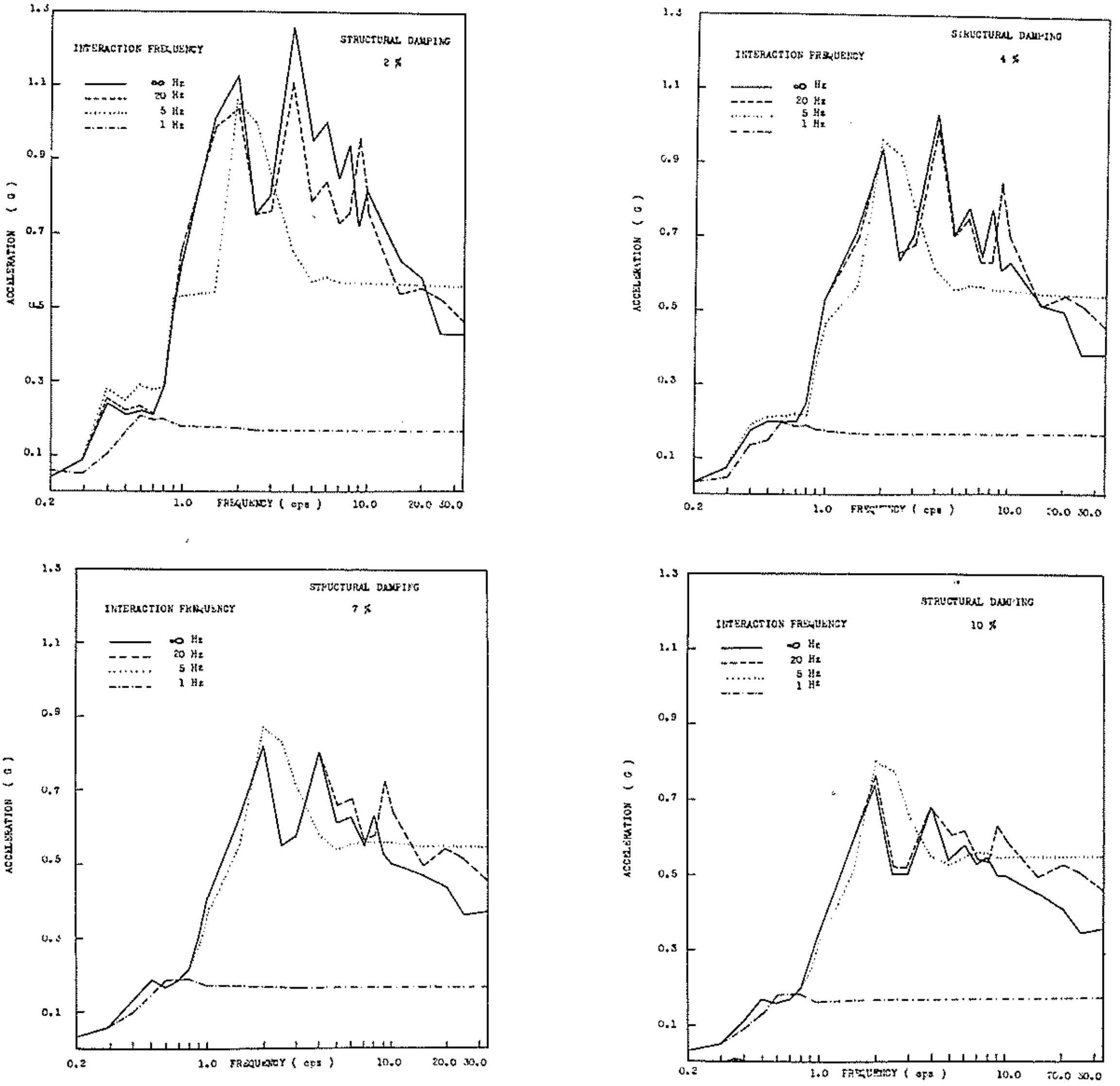

Figure 5 - Acceleration Spectra for Soil-Structure Systems.