UCRL-JC-124372
Preprint

# Effects of Foundation Modeling on Dynamic Response of a Soil-Structure System

J.C. Chen
Lawrence Livermore National Laboratory

Mansour Tabatabaie
Kleinfelder, Inc.

This paper was prepared for submittal to:
ASME Pressure Vessels and Piping and ICPVT- 8th Conference
Montreal, Canada

July 21-26, 1996

July 1996

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

# EFFECTS OF FOUNDATION MODELING ON DYNAMIC RESPONSE OF A SOIL-STRUCTURE SYSTEM

**J.C. Chen**
Fission Energy and Systems Safety Program
Lawrence Livermore National Laboratory
PO Box 808, MS: L-631
Livermore, California

**Mansour Tabatabaie**
Kleinfelder, Inc.
7133 Koll Center Parkway, Suite 100
Pleasanton, California

## ABSTRACT

This paper presents the results of our investigation to evaluate the effectiveness of different foundation modeling techniques used in soil-structure interaction analyses. The study involved analysis of three different modeling techniques applied to two different foundation configurations (one with a circular and one with square shape). The results of dynamic response of a typical nuclear power plant structure supported on such foundations are presented.

## INTRODUCTION

The seismic evaluation of nuclear power plant structure usually includes a soil-structure interaction (SSI) analysis to account for effects of the soil media and the major structures on the response of the reactor core. The SSI analysis provides the input motion to be used in detailed analysis of the reactor core to evaluate the response of the core safety system. Therefore, the evaluation of the core safety system is significantly affected by the input motion. However, the results of the SSI analysis are subject to certain uncertainties involved in the modeling of the soil-structure system and the analysis methods, chen, et al., 1984.

Because of the uncertainties involving the modeling technique of the N-reactor foundation basement in the SSI analysis, we performed investigations to evaluate the effects of the different foundation modeling techniques on the overall SSI response.

Three techniques used to model a rigid circular/rectangular basemat fully bonded to the surface of the soil mass are described:

- The basemat is modeled as an assemblage of rigid solid elements bonded to the surface of the soil medium.
- The basemat is modeled by a number of rigid beam elements, connected to the soil only at the beam end locations.
- The basemat is modeled by a number of rigid beam elements in a ring type configuration. The rigid beams and the soil mass are connected at the beam end locations. This model is believed to best represent a ring-shaped basemat.

## STRUCTURE MODEL

The structure selected for this study consists of a simplified model of a typical nuclear power plant building, as shown in Figure 1.

The superstructure is modeled as cantilever beams with masses lumped at the beam ends. The section and material properties of the beam elements are given in Table 1; the nodal masses of the structure, in Table 2. It is assumed that the superstructure stick model is connected to the center of the basemat at ground surface elevation. A circular and a rectangular basemat configuration were used in this study. The basemat is assumed to be very stiff; its mass and rotational inertia are lumped at the center of the mat.

The foundation soil consists of a uniform soil medium with properties as given in Figure 1.

The model is assumed to be subjected to a seismic wave environment consisting of vertically propagating shear waves with the control motion specified at the ground surface. the acceleration time history of the free-field control motion is

* This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

shown in Figure 2. A peak ground acceleration of 0.5g is used in this study.

## METHODS OF ANALYSES

Two sets of analyses were performed:

- The circular foundation was investigated using the computer code SASSI (Ref. 2). SASSI (SASSI (System for Analysis of Soil-Structure Interaction) was developed at the University of California at Berkeley, and is based on a new substructuring procedure, called the Flexible Volume Method. The new method differs from other substructuring methods in the manner in which the mass and stiffness matrices of the structure are partitioned from those of the soil; as a result, the procedure allows the solution of two- or three-dimensional structures supported on foundations with arbitrary shapes founded on or embedded in a layered viscoelastic halfspace. The entire analysis is performed in the complex frequency domain.
- The rectangular foundation was analyzed using the computer code CLASSI (Ref. 3). CLASSI (Continuum Linear Analysis of Soil-Structure Interaction) was developed at the University of California at San Diego and the University of Southern California; it performs numerical integration of the Green's functions to calculate the impedance and scattering properties of the foundation. This information is then input to the dynamic finite element analysis of the structure. The calculation of the impedance properties of the foundation is done in the complex frequency domain.

### SASSI Analysis

SASSI was used to calculate the foundation compliance functions and the SSI response of the soil-structure system, as described earlier. The three cases analyzed include the same superstructure model; but they use different foundation models to simulate a rigid circular basemat foundation as described.

#### Foundation Models

Model 1 - The foundation is modeled using six-node solid elements with very stiff properties as shown in Figure 3a. The connection between the superstructure and the basemat is provided by several rigid beams which connect the base of the superstructure model to the center and several other nodes at the bottom of the basemat.

Model 2 - In this model, the foundation consists of a number of rigid beam elements simulating the rigid basemat; the superstructure model is connected directly to the center of the beam foundation. This model, as shown in Figure 3b, may be selected for convenience in model set up only and does not offer any advantage over the previous model. therefore, it is considered equivalent to Model 1.

Model 3 - This model is shown in Figure 3c. It consists of a number of rigid beams connecting the outside boundary of the foundation mat as well as connecting this boundary directly to the center of the mat. The center node, which is not connected to the soil, provides a connection between the superstructure and the rigid foundation ring models. This model is not considered exactly equivalent to Models 1 or 2, but its use may offer significant savings in computer time and storage over those of the previous two models. The main purpose of the present investigation is to assess the effectiveness of this type of modeling.

In Models 1 and 2 described above, the basemat and the soil are discretized into a number of finite elements, and the two are then connected at all the nodal points over the entire mat area. By satisfying the compatibility criteria between the mat and soil elements, these two models are then capable to simulate the effects of a rigid mat bonded to the surface of a soil medium. Model 3, on the other hand, only provides connection between the soil and mat on the outside perimeter of the mat; therefore, it can best be used to simulate the effects of a rigid circular ring bonded to the surface of a halfspace.

**Foundation Compliance Functions**. The compliance functions of the foundation basemat are obtained by the computer code SASSI (complex frequency response analysis). The real and imaginary components of the sliding and rocking compliance functions obtained for the three models are shown in Figures 4 and 5, respectively, for frequencies ranging from 0 to 20 Hz. As seen in Figures 4 and 5, the results of Models 1 and 2 show good agreement except for the real part of the rocking compliance obtained from Model 2. This difference, which is more significant at frequencies about 10 Hz, is attributed to the fact that the foundation beams are not longer capable of modeling the rigidity of the basement at high frequencies. The results obtained using Model 3 show relatively good agreement with those of Models 1 and 2 for frequencies below 5 Hz. However, as frequency increases for all four components of Model 3 show evidence of oscillating. The amplitude of these oscillations becomes very pronounced above 15 Hz. These peaks are caused by the constructive interference of the waves inside the ring, a phenomenon which is not observed in other cases. In summary, we conclude that the compliance functions obtained using Model 3 do not represent those of a rigid circular solid mat bonded to the surface of a uniform halfspace at frequencies about 5 Hz. This frequency corresponds to a wave-length-to-disk-radius ratio of about 3 (VS=1000 fps and R = 65 ft).

**SSI Response of the Structure**. The seismic response of the total soil-structure system was evaluated at several nodes on the superstructure and at the base of the foundation mat using the three models, as described above. Since the compliance functions of the foundation basemat show little difference between Model 1 and Model 2, the structural response of the two models were almost the same. Hence, comparison of the structural response was only made between Model 2 and Model 3. The comparisons are shown in Figures 6a and 6b. The response of Model 3 (ring foundation) is 29% higher than that of Model 2 around 8.5 Hz. The maximum acceleration is about 3% higher for the ring foundation. The dominant frequency shifts from 2 Hz to about 1.6 Hz, while the spectral amplitude at the dominant frequency increases about 7% from Model 2 to Model 3. The response at Node 11 shows about an 11% difference in maximum acceleration. The difference in the dominant frequency is not significant for this structure.

Generally, the ring type of foundation model tends to give a higher response than that of the solid type of foundation model for most frequencies.

### CLASSI Analysis

Because the foundation configuration of the N-reactor structures is basically rectangular, it was decided to perform a similar investigation using the same superstructure model, as shown in Figure 1, resting on a rectangular foundation basemat. The computer code CLASSI was used to analyze three cases involving the same superstructure model but different foundation models, as described.

**Foundation Models**. Two different foundation models of rectangular basemat. They were analyzed by the CLASSI code. They are described as follows:

Model 1 - As shown in Figure 7a, the foundation (130 ft by 130 ft) is modeled by a massless solid plate. The plate is assumed to be perfectly rigid. The structure is supported at the center of the basemat.

Model 2 - As shown in Figure 7b, the foundation is modeled by a massless strip plate connecting the outside boundary of the foundation mat. The foundation is again assumed to be perfectly rigid. The impedance is computed with respect to the center of foundation.

**Foundation Impedance Functions**. The impedance functions of the foundation basemat are obtained by the computer code CLASSI. The results for the two foundation configurations investigated are presented in Figures 8a and 8b. Comparison of the impedance obtained using two different foundation models shows similar behavior as was found in the SASSI analysis. The translational components of the impedance function obtained from the two cases begin to deviate from each other at approximately 3 Hz, while the rocking components start deviating at 5 Hz. Furthermore, at higher frequencies, the translational and rocking components of the impedance function of the ring foundation begin oscillating. The result is that the stiffness parts of the impedance function of the ring foundation becomes larger, while the damping parts become smaller than those of the solid foundation.

**SSI Response of the Structure**. The seismic response of the total soil-structure system was evaluated at the same nodal locations, as described above. The response spectra between the two cases are compared at the foundation level at node 11 (Figures 9a and 9b). Note that the higher responses are observed from the case corresponding to the ring foundation. The difference in the maximum acceleration is about 8.5% at the foundation level and about 24% at the top of the structure. The frequency shift in the dominant frequency of the SSI response is not very different between the two models. This is because the impedance functions of the two solid foundation and the ring foundation are not significantly different at the low-frequency range, and that the first mode of the fixed-base response of the structure is below 5 Hz. However, the foundation modeling will have a more profound effect on the predicted SSI response if the dominant modes of the structure are above 6 Hz. Nevertheless, based on the study of the simple structural model presented herein, the ring type of foundation modeling tends to result in higher predicted SSI responses than those obtained from the solid type of foundation modeling over most of the frequency range considered. Hence, the results of the ring foundation much be considered conservative.

## CONCLUSIONS

Based on our investigations using two different methods of analysis and two different foundation configurations, we have reached the following conclusions:

- The compliance/impedance functions obtained using rigid beam elements located at the perimeter of the basemat and connected to the soil along the perimeter do not represent those of a rigid solid basemat bonded to the surface of uniform halfspace at frequencies above 5 Hz. This frequency corresponds to a wave-length-to-disk-radius ratio of about 3.
- In general, at high frequencies, the impedance of the ring foundation begins to oscillate such that the stiffness parts become larger, but the damping parts become smaller than those corresponding to the solid foundation.
- As the damping part of the foundation impedance is reduced, the dynamic response tends to become larger. Thus, the dynamic SSI responses calculated for the case of the ring foundation are conservative.

The impact on SSI response of using different foundation models depends significantly on the type of structure.

## REFERENCES

Chen, J.C., Chun, R.C., Goudreau, G.L., Maslenikov, O.R., and Johnson, J.J., 1984, "Uncertainty in Soil-Structure Interaction Analysis of a Nuclear Powerplant due to Different Analytical Techniques, 8th World Conf. on Earthquake Engineering, Vol. III, San Francisco, July 21-28, 1984

Lysmer, J., Tabatabaie, M., Tajirian, F., Vahdani, S., and Ostadan, F., 1981, "SASSI - A System for Analysis of Soil-Structure Interaction," Report No. UCB/GT/81-02, Geotechnical Engineering University of California, Berkeley, California, April, 1981

Wong, H.L., and Luco, J.E., 1980, Soil-Structure Interaction: A Linear Continuum Mechanics Approach (CLASSI), Dept. of Civil Engineering, University of Southern California, Los Angeles, California, CE79-03, 1980

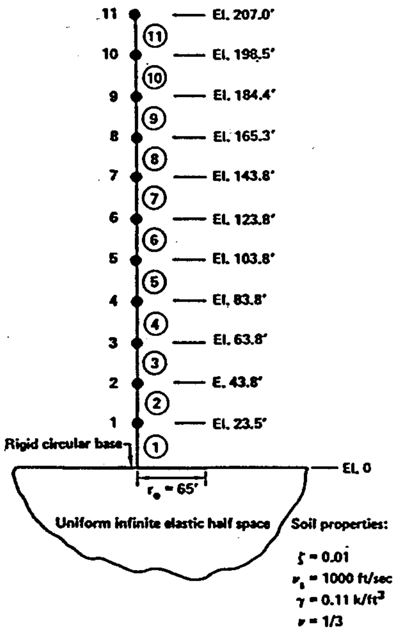


Fig. 1 Soil-Structure System

TABLE 1
BEAM ELEMENT PROPERTIES OF THE STRUCTURE

| Element No. | Section Area ($ft^2$) | Shear Area ($ft^2$) | Moment of Inertia ($ft^2$) |
|---|---|---|---|
| 1-7 | 1400 | 700 | $2.8 \times 10^6$ |
| 8 | 990 | 500 | $1.9 \times 10^6$ |
| 9 | 990 | 500 | $1.5 \times 10^6$ |
| 10 | 990 | 500 | $0.8 \times 10^6$ |
| 11 | 990 | 500 | $0.2 \times 10^6$ |

TABLE 2
NODAL MASSES OF THE STRUCTURE

| Node No. | Nodal Mass (Kips) |
|---|---|
| 1 | 4,600 |
| 2 | 4,200 |
| 3 | 4,200 |
| 4 | 4,200 |
| 5 | 4,200 |
| 6 | 4,200 |
| 7 | 4,610 |
| 8 | 3,020 |
| 9 | 2,470 |
| 10 | 2,120 |
| 11 | 190 |
| Base | 20,000 |

$I_{base} = 4.5 \times 10^6$ kip-ft²

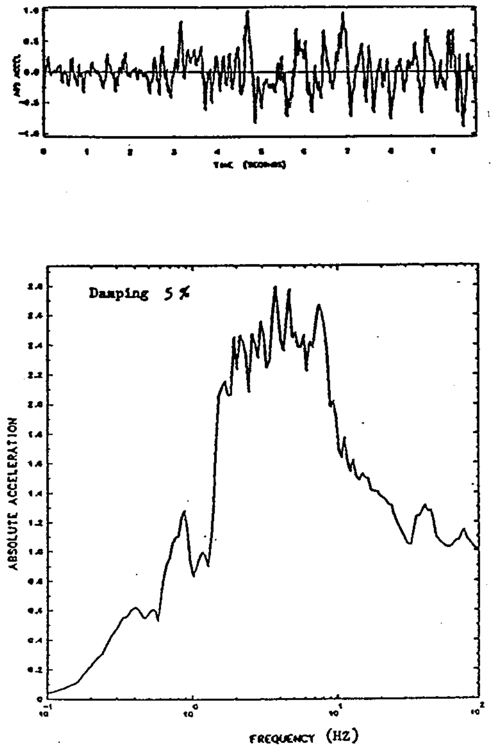


Fig. 2 Free-Field Control Motion: Acceleration Time History and Response Spectrum with 5% Damping

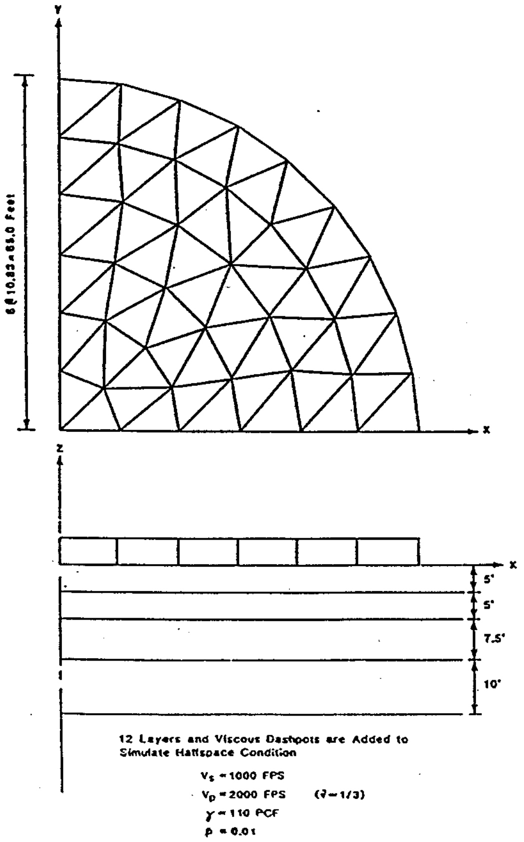


Fig. 3a SASSI Foundation Model 1 - Solid Elements with Very Stiff Properties

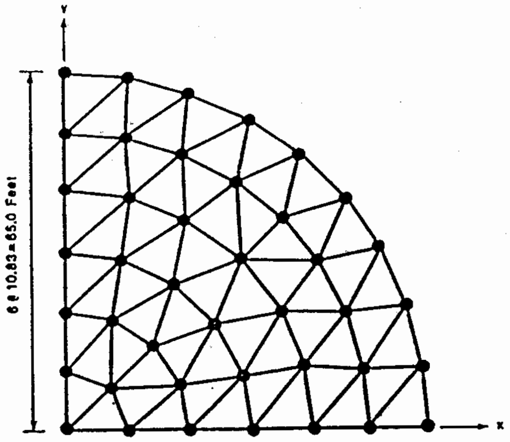


Fig. 3b SASSI Foundation Model 2 - Use Rigid Beam Elements

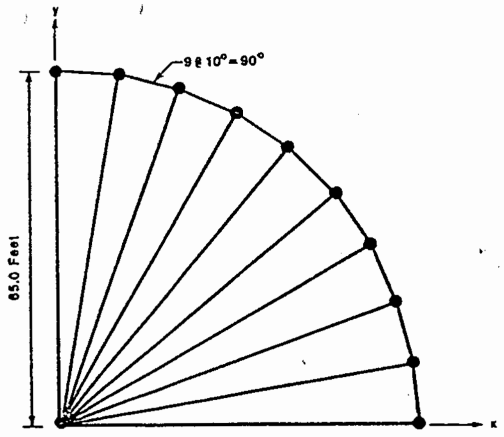


Fig. 3c SASSI Foundation Model 3 - Use Rigid Beam Elements

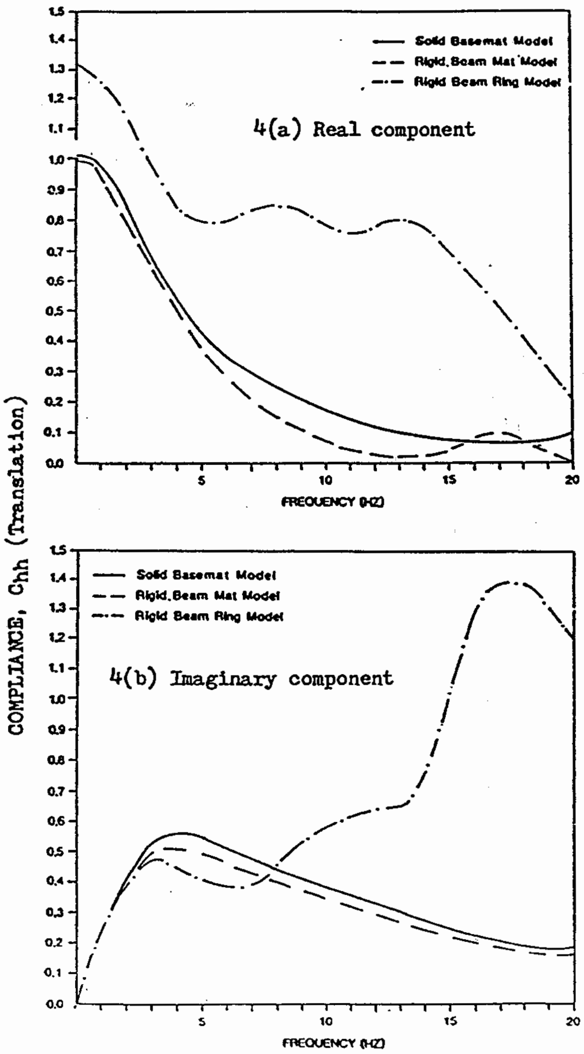


Fig. 4 Compliance Functions of Circular Foundation - Translation Component

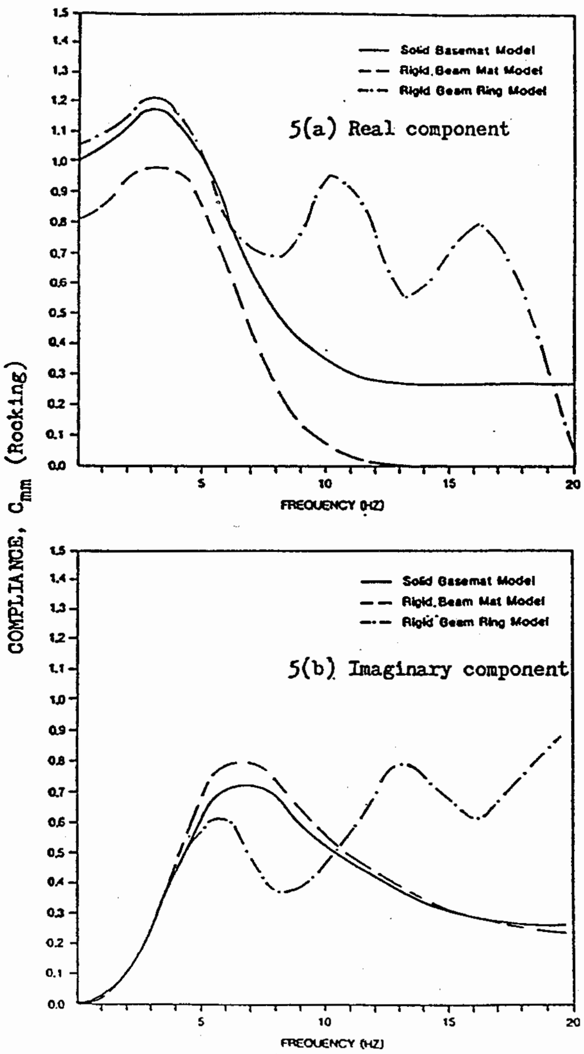


Fig. 5 Compliance Function of Circular Foundation - Rocking Component

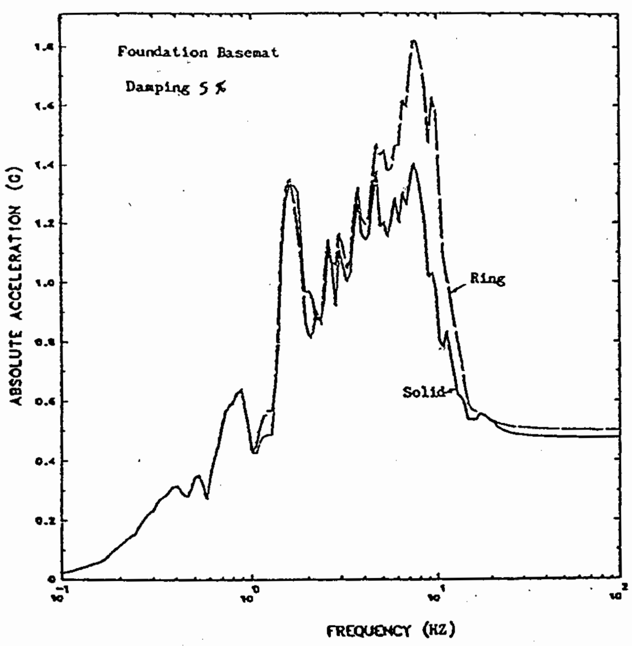


Fig. 6a The Effect of Foundation Modeling on Dynamic Response at Foundation Basement - SASSI Analysis

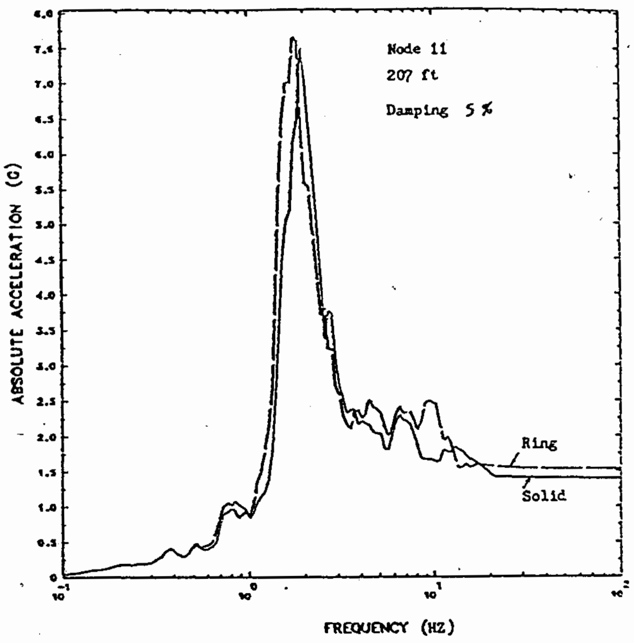


Fig. 6b The Effect of Foundation Modeling on Dynamic Response at Foundation Node 11 - SASSI Analysis

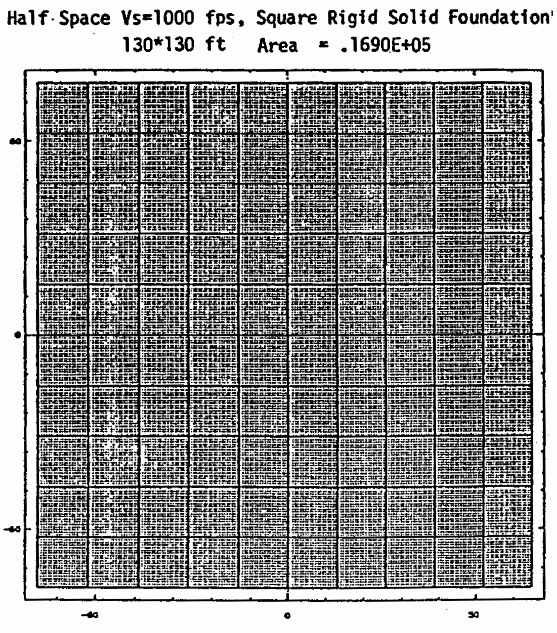


Fig. 7a Square Solid Foundation on Elastic Halfspace with Shear Wave Velocity 1000 fps

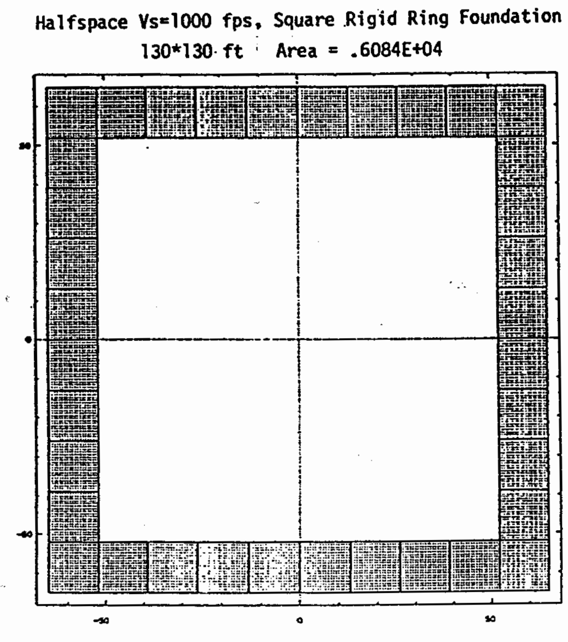


Fig. 7b Square Rigid Ring-plate Foundation on Elastic Halfspace with Shear Wave Velocity 1000 fps

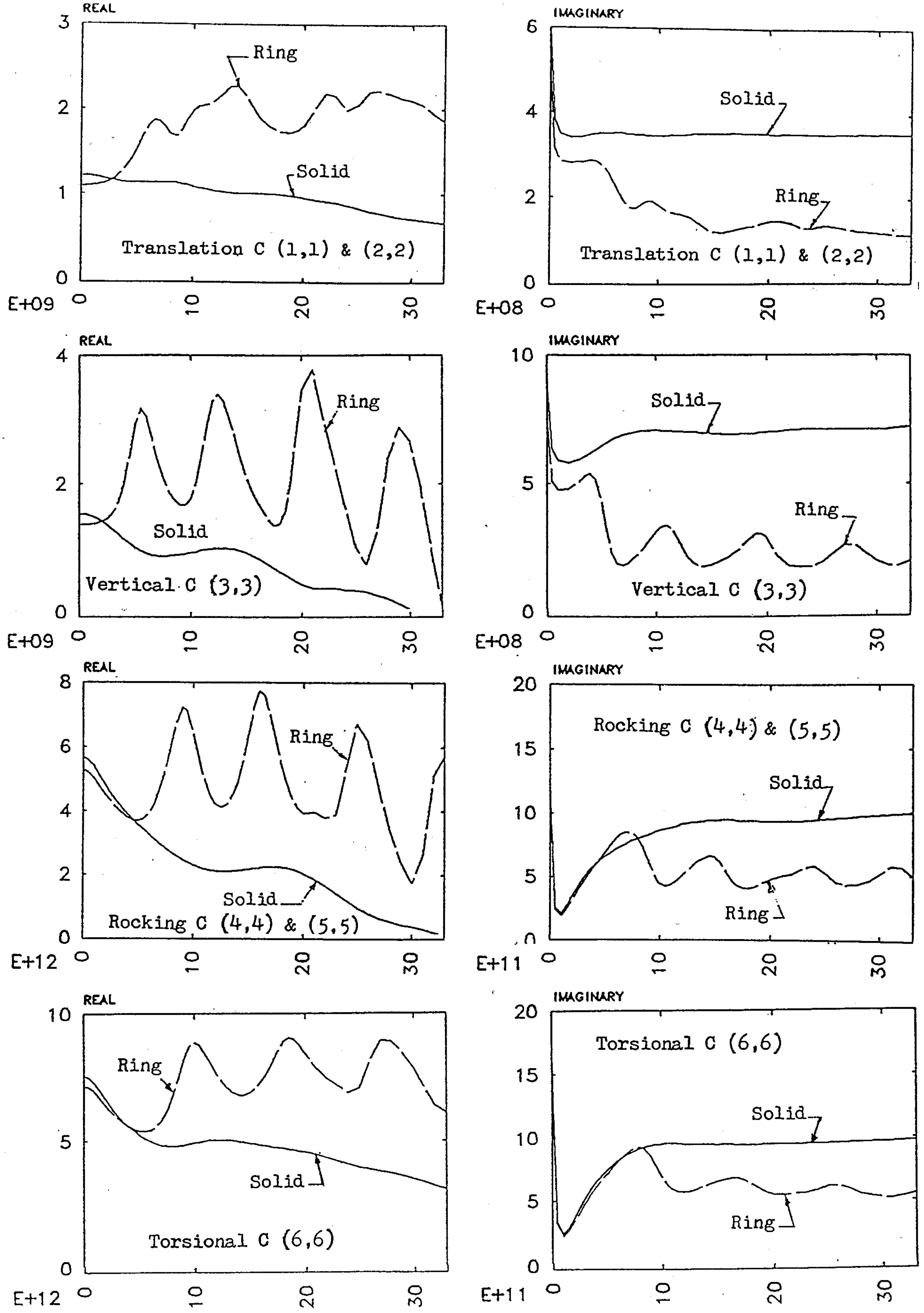


Fig. 8a Comparison of Impedance between Square Solid and Square Ring Foundation - Translation, Rocking and Torsional Component, CLASSI

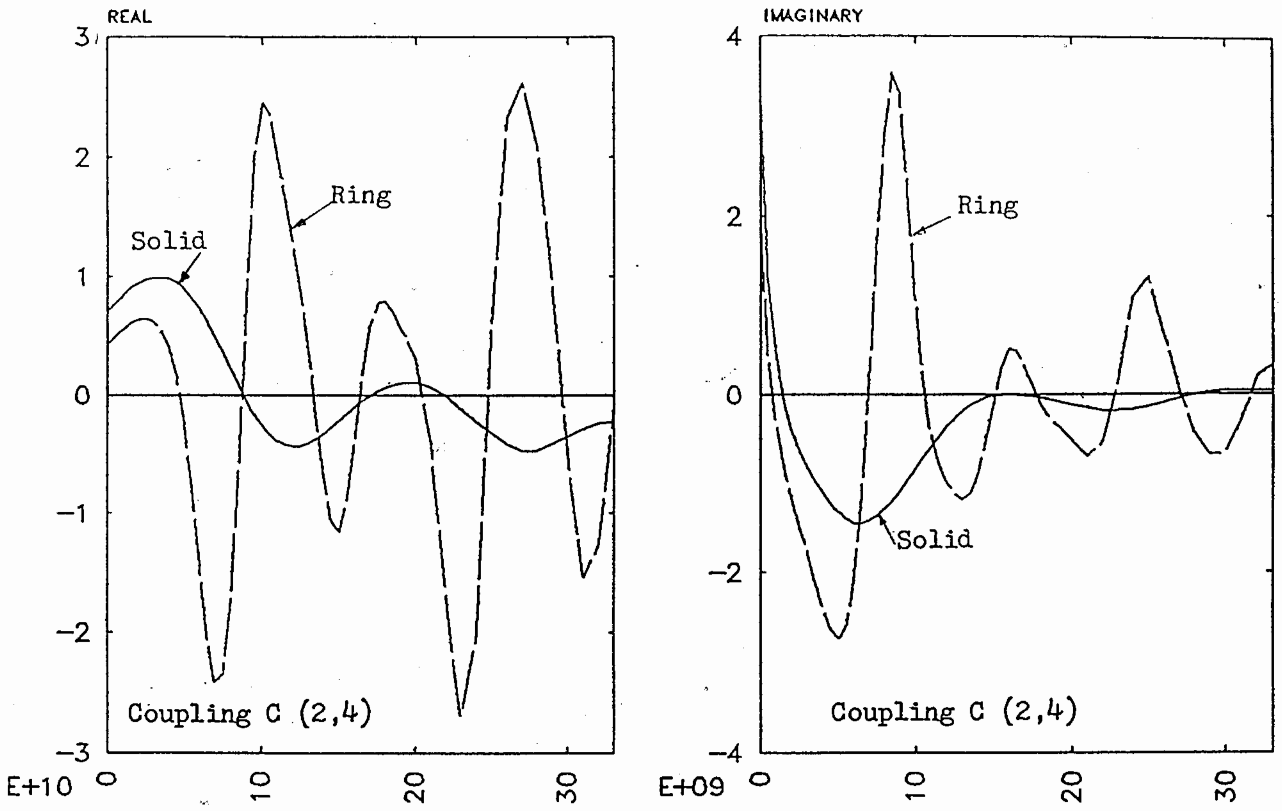


Fig. 8b Comparison of Impedance between Square Solid and Square Ring Foundation - Coupling Component, CLASSI

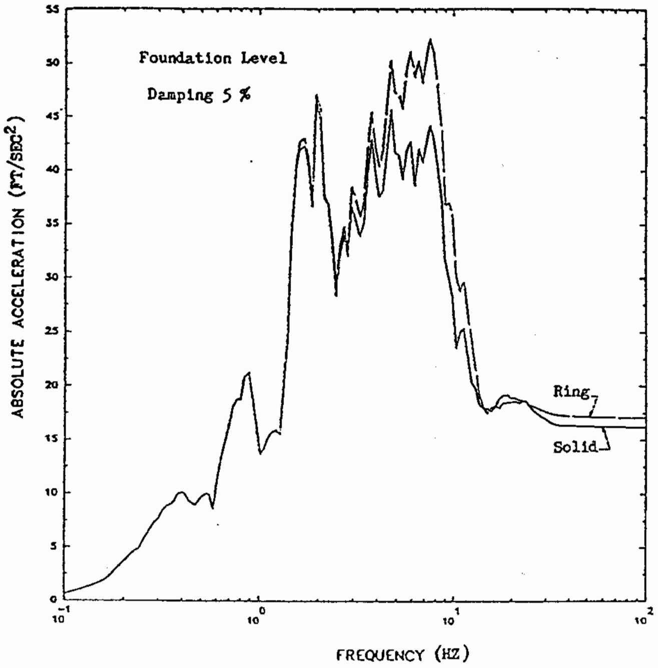


Fig. 9a The Effect of Foundation Modeling on Dynamic Response at Foundation Level, CLASSI

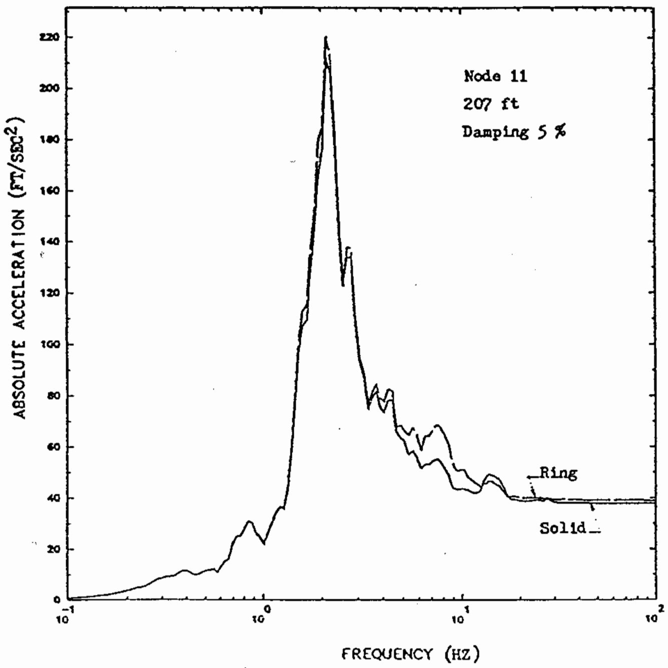


Fig. 9b The Effect of Foundation Modeling on Dynamic Response at Node 11, CLASSI