Application of the flexible volume method to soil-structure interaction analysis of flexible and embedded foundations

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1 INTRODUCTION

The soil-structure interaction (SSI) effect is an important consideration for seismic design of critical structures such as nuclear power plants. Several well-known methods are currently being applied in the industry for the analysis of SSI effect. These methods are, for example, the simple soil-spring method, the more sophisticated half-space continuum impedance method, and the frequently used two-dimensional (2-D) finite element method. Due to limitations resulting from the inherent assumption used in the formulation of each of these commonly-applied methods, the SSI analysis to date still suffer from deficiencies in rigorousness for a truly three-dimensional (3-D) SSI analysis of structures with embedded foundations or foundations with basemat flexibility.

A recently-developed SSI analysis computer program "SASSI" (Ref. 1), which employs the finite element method and the "flexible volume" method of formulation, has, to a great extent, remedied the current deficiencies. In particular, the program is capable of rigorously analyzing SSI responses of structures with embedded and/or flexible foundations. In this paper, the effectiveness of this new computer program for analysis of SSI responses of embedded and flexible foundations is examined by comparing the SASSI solutions with the published solutions for three benchmark problems. In addition, an actual application is demonstrated by applying SASSI for seismic SSI analyses of a PWR containment structure with fixed-base, surface-supported, and embedded foundation conditions and observing the SSI effect and the effect of embedment on the structural response resulting from SASSI analyses.

2 SASSI AND FLEXIBLE VOLUME METHOD

The flexible volume method of formulation used by the SASSI program employs a finite element substructuring technique in which the structure and foundation models are partitioned as shown in Fig.1. The structure model, Fig. 1(c), consists of the finite element models of the superstructure plus the basement minus the excavated soil. The foundation model, Fig. 1(b), consists of the finite element model of the original site, i.e., the excavated soil for the basement is retained with the foundation soil model. With such a partitioning, the foundation medium retains the halfspace (without excavation pit) configuration which greatly simplifies the calculations of the free-field motion and the foundation impedances. The SSI interaction occurs at every interacting nodes within the excavated soil volume, called the flexible volume, as shown in Fig. 1(c). The foundation impedances are calculated for each interacting node within the flexible volume, and then coupled with the structure model, Fig. 1(b), to form the complete SSI system.

The major steps for SSI analysis following this method are: (1) site response analysis which determines the free-field motions within the flexible volume resulting from prescribed seismic wave fields; (2) impedance analysis which calculates the impedance matrix associated with the interacting nodes in the flexible volume; and (3) SSI response analysis which computes the final SSI responses of the assembled SSI system. The SASSI computer program implements the above steps of analysis in modules which allow analyses to be performed and re-started in separate steps. It is capable of analyzing 3-D SSI responses for surface-supported or embedded structures with rigid or flexible basement. The seismic motion can be prescribed in combinations of wave fields of P, SV, SH, Rayleigh, and Love waves (Ref. 1).

3 SASSI ANALYSES OF BENCHMARK PROBLEMS

For the purpose of examining the effectiveness and accuracy of the SASSI program for analysis of SSI responses of embedded and flexible foundations, three benchmark problems were selected from literature and analyzed using SASSI. The results of the SASSI analyses and the comparisons with the published solutions are presented in the following subsections:

3.1 Impedance Analysis of a Rigid-Flexible Foundation (Ref. 2)

The impedances of a rigid-flexible elastic square foundation plate resting on the surface of a uniform elastic half-space have been obtained by Iguchi and Luco (Ref. 2). The configuration of the foundation plate considered is shown in Fig. 2(a). As shown, the middle part of the square plate is rigid; whereas the remaining portion is a flexible elastic plate. This problem with a plate-foundation rigidity ratio of 0.5 as defined in Ref. 2 was analyzed using SASSI for the rocking mode of response. The resulting rocking impedances (stiffness and damping coefficients) are shown and compared with the corresponding solutions from Ref. 2 in Figs. 2(b) and 2(c). In these figures, the solutions for the totally rigid square plate are also presented to show the effect of foundation flexibility on the impedances. As shown by the comparison in Figure 2, the SASSI solution is in good agreement with the solutions of Ref.2. It can also be observed that the foundation flexibility, in this case, has a relatively significant effect on the impedances.

3.2 Compliance Analysis of a Flexible Foundation Plate Subjected to Harmonic Vertical Loads (Ref. 3)

The dynamic responses of a flexible elastic square plate resting on the surface of a uniform elastic half-space subjected to uniform harmonic vertical loads have been solved by Whittaker et al. (Ref. 3). This problem with the same parameters as used in Ref. 3 was analyzed using SASSI for the case of plate-foundation rigidity ratio of 0.004 as defined in Ref. 3. The resulting normalized vertical displacements at three locations in the plate are shown and compared with the corresponding Ref. 3 solutions in Figs. 3(a), 3(b), and 3(c), as a function of dimensionless excitation frequency. As shown by the comparison, the SASSI solutions match closely with the Ref. 3 solutions. It is interesting to note that, for a flexible foundation, not only the displacements vary with locations, the ratios of displacements at different locations also vary with frequency of excitation. This indicates that the dynamic behavior of the flexible-plate-foundation system is different from that of the static behavior. Thus, a rigorous consideration of foundation flexibility in dynamic SSI analysis may be necessary.

3.3 Scattering Analysis of a Rigid Embedded Cube (Ref. 4)

The dynamic responses of a rigid cube fully embedded in an elastic half-space as shown in Fig. 4(a) subjected to the impingement of incidence SH waves have been analyzed by Dominguez (Ref. 4). This problem was analyzed using SASSI for two cases: (1) horizontally propagating SH wave ($\theta=0^{o}$); and (2) inclined SH wave impinging at 45^{o} from the vertical. The resulting responses computed by SASSI are shown and compared with the corresponding solutions by Dominguez in Figs. 4(b), 4(c), and 4(d), for the horizontal translation, torsional, and rocking responses, respectively. The curves shown in these figures have been normalized with respect to the amplitude of the horizontal free-field surface motion ($|U_y|_{ff}$). The comparisons shown indicate that SASSI solutions closely match the published solutions in Ref. 4.

4 SASSI ANALYSES OF A CONTAINMENT STRUCTURE

The results of SASSI analyses of benchmark problems demonstrate the effectiveness of SASSI in solving a variety of SSI problems involving embedded and flexible foundations. For practical applications, the effectiveness of this program is further evaluated by applying the program to analyze the seismic SSI response of a prototype PWR containment structure. For a critical evaluation, the containment on a rock site was selected for analysis since the SSI effect in this case has commonly been ignored. Furthermore, to exemplify the SSI effect on such a site, the analyses have been performed for three foundation conditions, namely, the fixed-base condition (SSI effect ignored), the surface-supported condition (SSI effect considered but embedment effect ignored), and the embedded condition (SSI effect fully considered). The comparisons of results from these three cases show progressive contribution to the SSI effect due to increasing sophistication in the SSI modeling.

The containment with the internal structure and its dynamic two-stick model considered for SASSI analyses are shown in Fig. 5(a). The configuration of the structure and its model properties are cited from Ref.5. The site consists of horizontally-layered rock strata with a varying shear wave velocity of 2500 ft/sec to 3500 ft/sec for the top surface layers, to 5000 ft/sec for the underlying half-space at a depth of 150 ft below grade. The fixed-base analysis assumes the structure is fixed at the basemat; the surface-supported foundation case assumes that the basemat is supported on rock at grade; the embedded foundation case takes into account the embedment of the basemat and reactor cavity pit. The SSI model for SASSI analysis of the embedded case is shown in Fig. 5(b). The seismic input motion used for all three cases is a horizontal synthetic time history compatible with the U.S. NRC Regulatory 1.60 spectra, prescribed at grade assuming vertically propagating shear wave with a peak ground surface acceleration of 0.5g.

The results of all three analyses in terms of 2% damping acceleration response spectra at top of the internal structure are compared in Fig. 6(a). Figure 6(b) shows the ratios of response spectra of Fig. 6(b) relative to the spectrum of the fixed-base case. These ratios clearly show the effect of SSI with and without the embedment effect. As is evident from these results, even for this rock site, the SSI effect significantly reduces the seismic responses. A 20% reduction was achieved by the surface foundation case and a 40% reduction by including the embedment. The effectiveness of SASSI for SSI analysis of an embedded structure has clearly been demonstrated in this application.

5 SUMMARY AND CONCLUSIONS

The capability and effectiveness of the newly-developed SASSI program and the flexible volume method of SSI analysis for embedded and flexible foundations have been examined through comparisons of SASSI solutions with three published benchmark solutions. The results show that SASSI solutions closely match the published solutions. The effectiveness of SASSI for solving practical SSI problems with embedment has also been demonstrated by the application example presented. Evidence from recorded forced vibration and earthquake response data in actual structures has revealed potential importance of embedment and foundation basement flexibility effects on SSI responses (Refs. 6 and 7). With the advent of the new SASSI program, such effects can now be more rigorously analyzed for engineering design purposes, as have been demonstrated in this paper.

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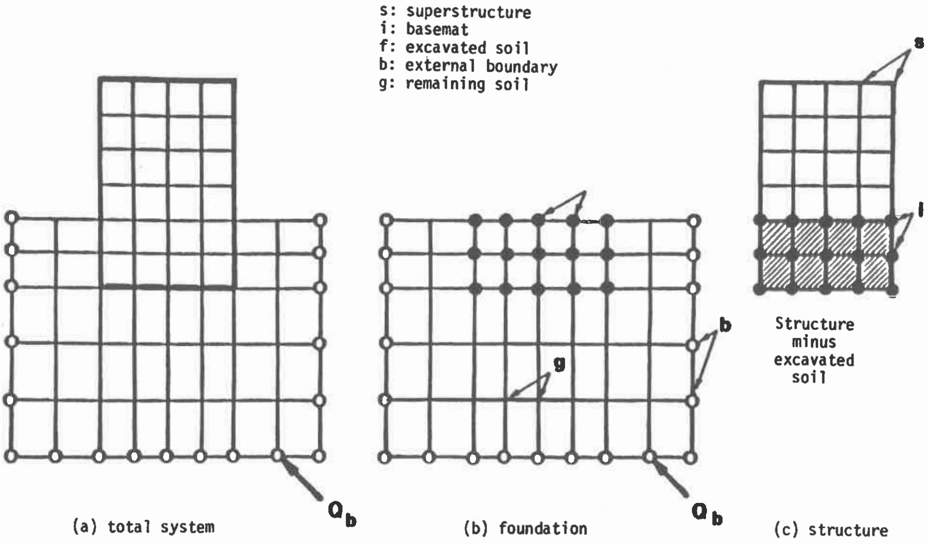

Figure 1. Substructuring in the Flexible Volume Method

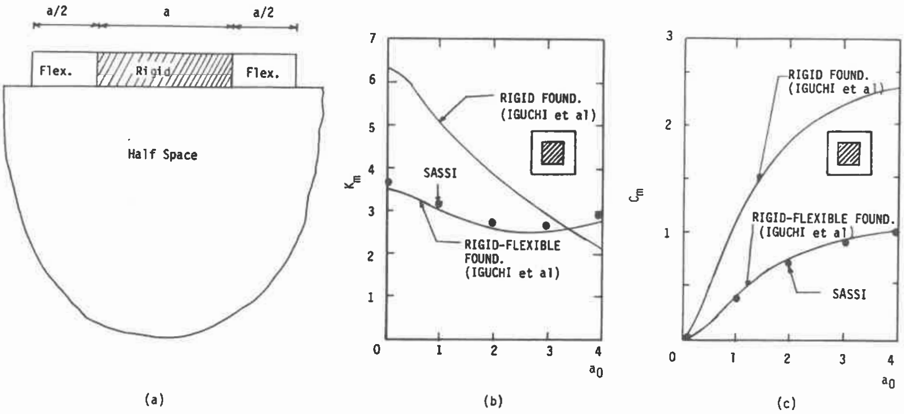

Figure 2. (a) Rigid-Flexible Foundation Model, (b) Stiffness Coeff., (c) Damping Coeff.

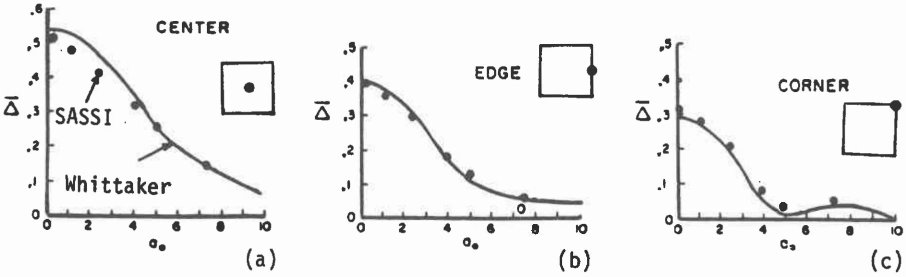

Figure 3. Normalized Displacement due to Uniform Harmonic Vertical Load

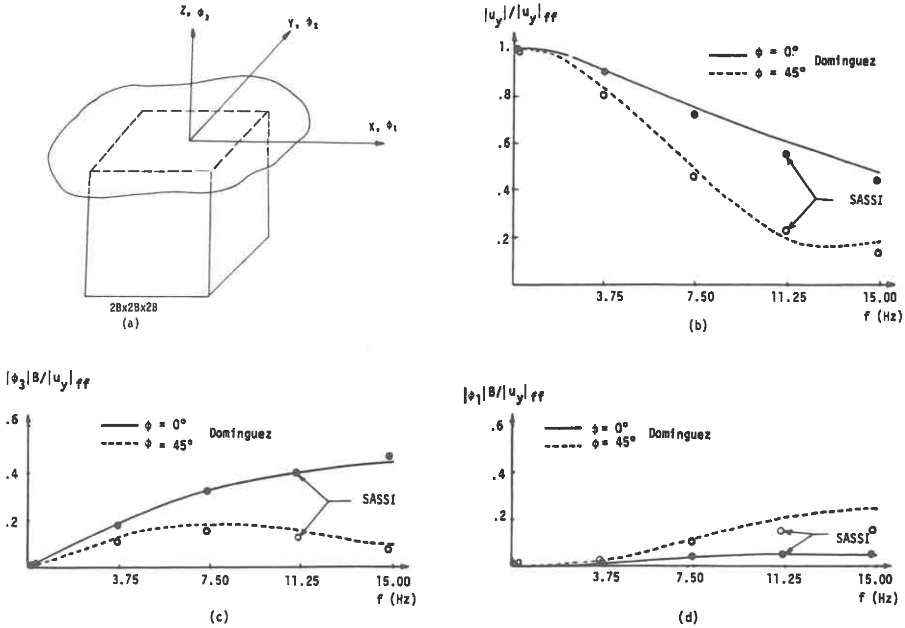

Figure 4. (a) Rigid Embedded Cube Model, (b) Translational Response, (c) Torsional Response, (d) Rocking Response,

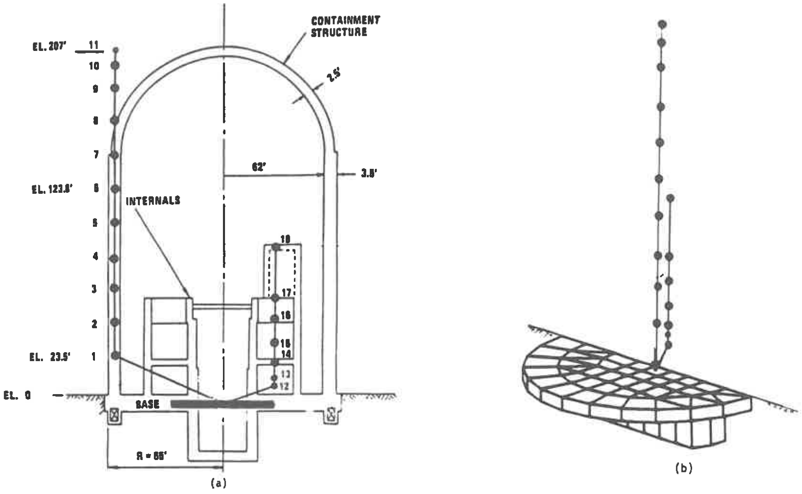

Figure 5. (a) Fixed Base Containment Model, (b) SASSI SSI Model

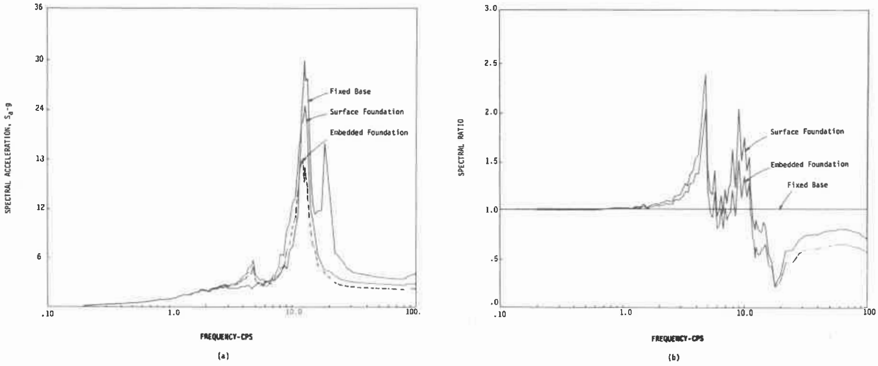

Figure 6. Response at the top of Internal Structure
(a) Absolute Acceleration Response Spectrum,
(b) Spectral Ratio