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EFFECT OF FOUNDATION FLEXIBILITY AND EMBEDMENT ON THE SOIL-STRUCTURE INTERACTION RESPONSE

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SUMMARY

The effects of foundation flexibility and embedment on the seismic response of structures are examined. A parametric study is performed to compute and compare the impedances and scattered motions of an embedded square foundation. These effects are demonstrated in actual applications by comparing the soil-structure interaction responses of a containment structure with surface and embedded foundation configurations and an auxiliary building with various degrees of foundation flexibility.

INTRODUCTION

Seismic soil-structure interaction (SSI) effects are important considerations for the seismic analysis and design of critical structures in seismically active regions. A reliable prediction of SSI response requires careful specifications of the design input motion and the dynamic soil and structural properties, and the use of a rigorous analysis method. Currently, there are many methods available to evaluate the SSI effects. All methods are limited by the assumptions made in their formulations; therefore, the applicability of the solutions is also limited by the suitability of these assumptions. Two important parameters that have not yet been adequately considered in the design analysis are the foundation flexibility and embedment effects. It is the purpose of this paper to present the results of studies on the effects of these two parameters on the SSI response. For the foundation embedment effect, the foundation impedances and scattered motions of an embedded square foundation with two embedment depths, and the SSI response of an actual contaiment structure with surface and embedded foundation configurations are presented. For the foundation flexibility effect, the impedances of a flexible surface foundation and the SSI response of an auxiliary building with various foundation flexibility assumptions are presented. All analyses are performed using the linear SSI analysis computer program SASSI (Ref. 1). This program is capable of rigorously handling the SSI problems with surface or embedded, rigid or flexible, arbitrary-shape foundations.

FOUNDATION EMBEDMENT EFFECT

In order to examine the embedment effect, the foundation impedances and scattered motions of an embedded square foundation with dimensions 2ax2a, embedded to a depth h in an elastic halfspace are computed for two embedment ratios of $h/a = 4/3$ and 2, and the results are compared. The Poisson's ratio used for halfspace is 1/3. The impedance functions computed are associated with the degrees-of-freedom at the base center shown in Fig. 1. The stiffness and damping coefficients are normalized with respect to the static stiffnesses of the square surface foundation and expressed in terms of the dimensionless frequency $a_0 = \omega a/V_s$, where ω is angular frequency and V_s is the halfspace shear wave velocity. The results are shown in Figs. 2 through 6 for all modes of vibration. The coupling terms, K_{ht} and C_{ht}, as shown are normalized with respect to the horizontal translation static stiffness of surface foundation. Comparisons of the results show that embedment increases the stiffness and damping of the foundation. This increase is most pronounced in rocking and torsional modes of vibration. The coupling coefficients between the horizontal translation and rocking increases with increasing embedment depth as expected. Figure 7 shows the height from base of the center of stiffness as a function of frequency. As shown, this height is not sensitive to frequency and depth of embedment.

In order to examine the embedment effect on the scattered foundation motions, the ratio of the amplitudes of the scattered foundation horizontal translation at base center and vertical translation at the base edge, normalized with respect to the amplitude of the input motion at grade, are compared in Fig. 8 for the case of vertical SV wave input. As shown, embedment reduces the scattered foundation translation motion and increases the rocking motion, and these variations are not uniform with frequency, neither are monotonical with embedment depth. To demonstrate the effect of embedment in actual applications, the horizontal seismic SSI response of a containment structure on a rock site with surface and embedded foundations are computed and compared. The SASSI model for the foundation used in the analysis is shown in Fig. 9. The foundation is fully embedded in a rock site with the shear wave velocities of 2600 ft/sec near surface and increasing to 4800 ft/sec at depth. For the case of surface foundation, a rigid circular basemat on the surface of the rock site is considered. The rocking impedance functions of the surface and embedded foundations in the direction of shaking are shown in Fig. 10. As shown, the embedment increases the foundation stiffness and the radiation damping. The seismic response in terms of the acceleration response spectra at top of the internal structure are shown and compared with the corresponding fixed-base response in Fig. 11(a). The spectral ratios relative to the fixed-base spectrum are shown in Fig. 11(b). As shown, the frequency shift due to the SSI effect is insignificant for this rock site; however, the reduction in the SSI response amplitude is significant even for the rock site due to the SSI radiation damping effect.

FOUNDATION FLEXIBILITY EFFECT

The effect of foundation flexibility on the seismic response of structures has not been extensively studied mainly due to its complexities and the lack of suitable SSI analysis methods to rigorously handle the problem. For idealized cases, it has been shown (Ref. 2) that the foundation flexibility effect is potentially a significant effect. For a surface square foundation, this is demonstrated by comparing the rocking impedance functions of a flexible foundation with a rigid central core (Fig. 12) with those of a corresponding rigid foundation, as shown in Figs. 13(a) and 13(b). As shown, foundation flexibility reduces the foundation stiffness and damping coefficients, and such reductions are not negligible.

Due to the unique "flexible-volume substructuring" method of SSI modelling and the finite element method of structural modelling that have been implemented in the computer program SASSI, the foundation flexibility effect on the SSI response can be evaluated for actual applications using this program. This is demonstrated by a recent site-specific application for the analysis of the auxiliary building of a nuclear power plant on a rock site. The foundation of the building studied consists of a central core embedded to the depth of 25 ft with two wings extending on both sides of the core. The SASSI model of the foundation used in the study is shown in Fig. 14(a). The foundation and the structure were both modelled using plate elements. Five cases of foundation flexibility, ranging from fixed-base to partly-rigid base-slabs and walls, to fully flexible slabs and walls were considered, as shown in Fig. 14(b). The amplitudes of the seismic response transfer functions at two locations on the top of the building (core east and core west) are compared in Figs. 15(a) and 15(b). As shown, by progressively increasing the foundation flexibility, the SSI frequency gradually decreases and the response amplitude gradually increases. The maximum reduction in frequency (from Case 2 to Case 5) was about 18% and the maximum increase in the response amplitude was 17%. Thus, the foundation flexibility effect was not negligible in this case. Comparisons of the responses shown in Fig. 15 also indicate that the results of Case 4 with partly-rigid base and flexible embedded walls is, for practical purposes, the same as the results of Case 5. This indicates that the flexibility of the embedded foundation walls is a significant parameter that needs to be considered in the analysis.

CONCLUSIONS

The effects of foundation embedment and flexibility on the foundation impedances, scattered foundation motions, and SSI responses of structures have been examined. The embedment was found to increase the foundation stiffness and damping coefficients relative to those of the surface foundation, while it reduced scattered translational motions of the foundation, and increased the rocking motions. The scattering effect was, however, found to be not uniform with frequency and not monotonical with embedment depth. The embedment effect was found to be significant for the seismic SSI response even for structures supported on rock sites. The effect of foundation flexibility on the SSI response was found to be not negligible in the site-specific study presented. Thus, for structures with foundations of large plan dimensions, such as the auxiliary building considered in the site-specific study, the effect of foundation flexibility, especially that due to the embedded foundation walls, may be significant and may have to be considered in the SSI response analysis.

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2. Ostadan, F., Tseng, W. S., Lilhanand, K., "Application of the Flexible Volume Method to Soil-Structure Interaction Analysis of Flexible and Embedded Foundation," 9th SMiRT Conference, Lausanne, Switzerland, August 1987.

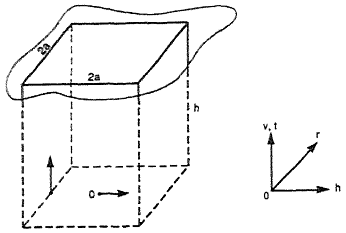

Fig. 1 Embedded Square Foundation Model

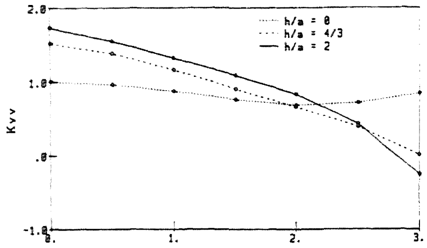

Fig. 2(a) Vertical Stiffness Coefficients

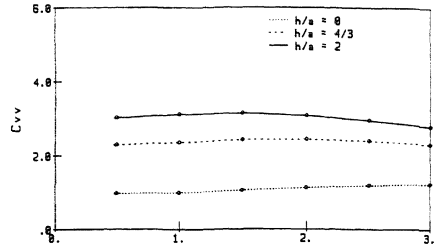

Fig. 2(b) Vertical Damping Coefficients

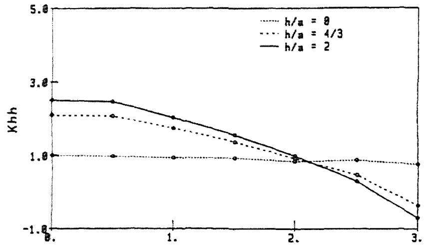

Fig. 3(a) Horizontal Stiffness Coefficients

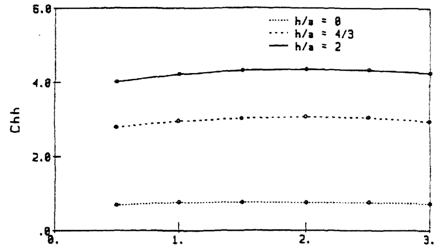

Fig. 3(b) Horizontal Damping Coefficients

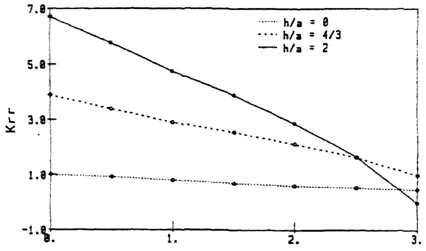

Fig. 4(a) Rocking Stiffness Coefficients

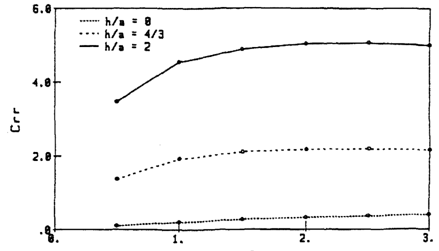

Fig. 4(b) Rocking Damping Coefficients

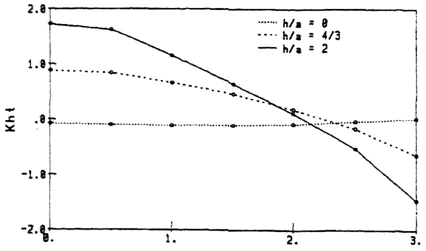

Fig. 5(a) Coupling Stiffness Coefficients

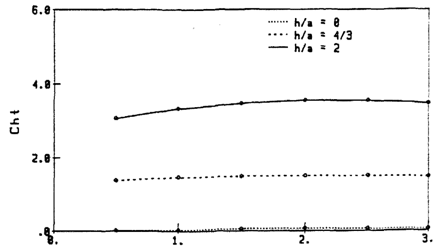

Fig. 5(b) Coupling Damping Coefficients

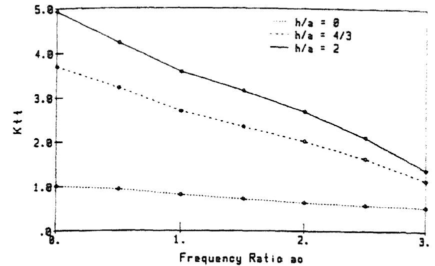

Fig. 6(a) Torsional Stiffness Coefficients

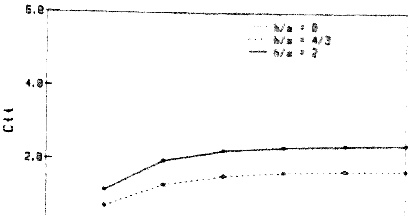

Fig. 6(b) Torsional Damping Coefficients

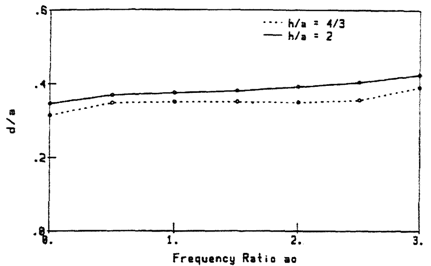

Fig. 7 Height of Center of Stiffness

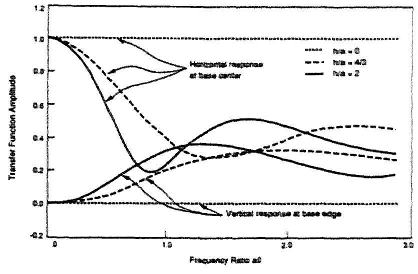

Fig. 8 Scattered Foundation Motion, Vertical SV-Wave Input

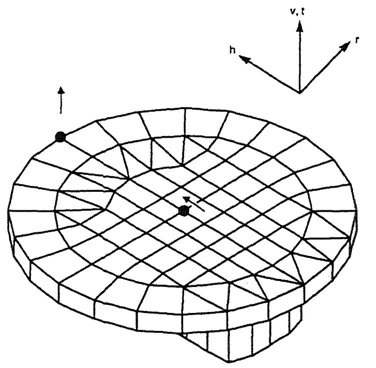

Fig. 9 SASSI Containment Foundation Model

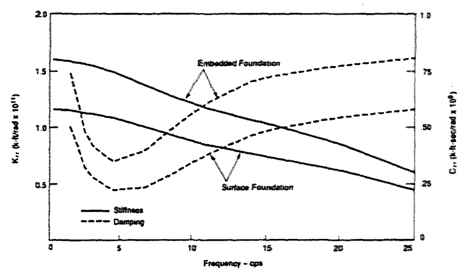

Fig. 10 Rocking Stiffness and Damping Coefficients

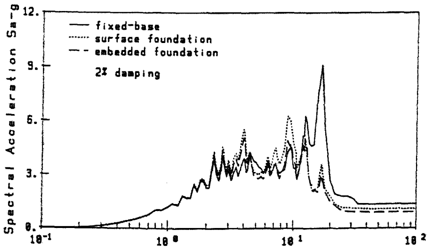

Fig. 11(a) Response At The Top of Internal Structure

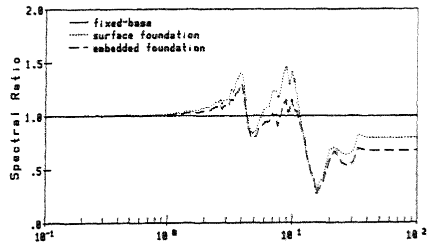

Fig. 11(b) Ratio of The Response At The Internal Structure

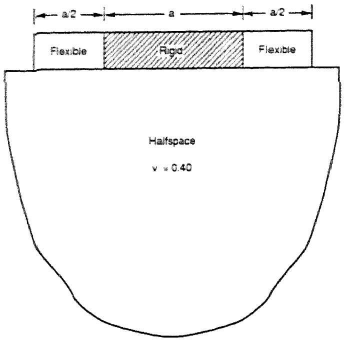

Fig. 12 Rigid-Flexible Foundation

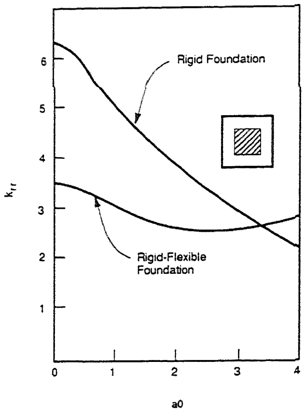

Fig. 13(a) Rocking Stiffness Coefficient

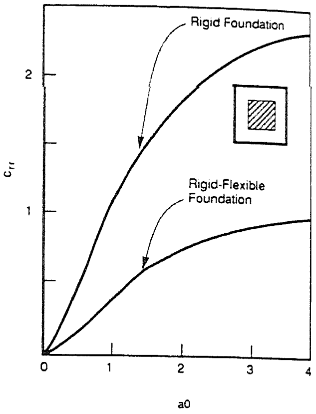

Fig. 13(b) Rocking Damping Coefficient

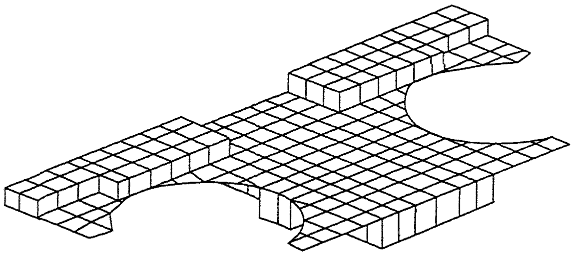

Fig. 14 (a) SASSI Foundation Model for Auxiliary Building

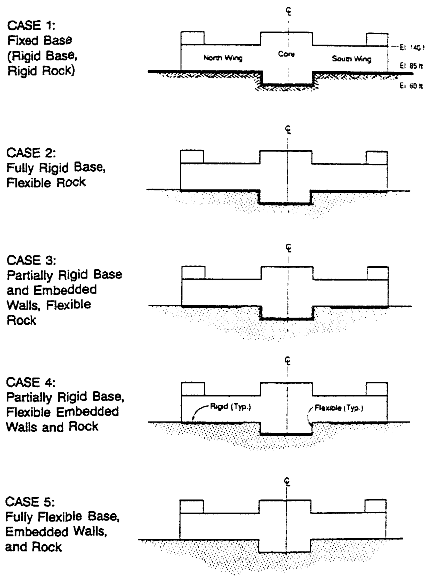

Fig. 14 (b) Various Foundation Basemat Flexibility Assumptions for the Auxiliary Building

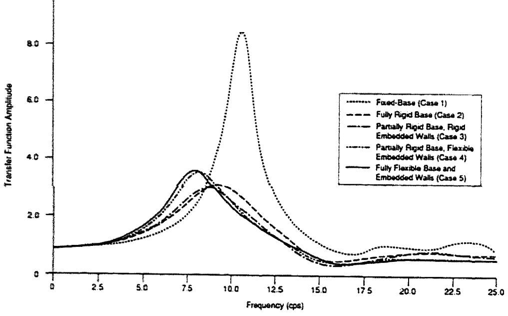

Fig. 15 (a) Transfer Function for EW Response at Core West El. 140′ of the Auxiliary Building

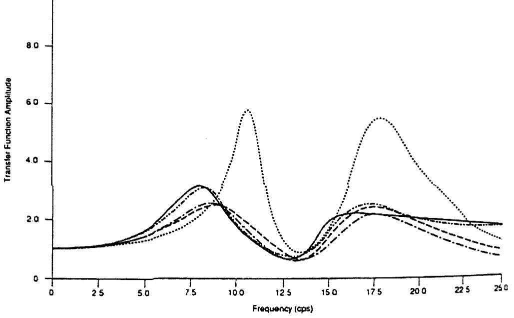

Fig. 15 (b) Transfer Function for EW Response at Core East El. 140′ of the Auxiliary Building