COMPARISON OF ANALYSIS METHOD FOR SEISMIC SOIL-STRUCTURE INTERACTION

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SUMMARY

Seismic soil-structure interaction analyses were performed using the direct finite element method (FLUSH), the frequency-independent soil spring approach, and the impedance approach for an embedded reinforced concrete reactor building. The responses of the reactor building are compared in terms of peak acceleration and floor response spectra. It was found that the direct finite element method and the impedance approach predict comparable peak horizontal and rocking accelerations. Overall, the agreement between the FLUSH and the impedance approach spectra is quite good. The lumped parameter frequency-independent soil spring approach gives much higher response than those obtained from FLUSH and the impedance approach analyses.

INTRODUCTION

The interaction effects between structures and soil play an important role in the seismic response of structures. One particularly important aspect of the aseismic design of the embedded nuclear power plant is the effect of the motion of a massive, stiff structure on the soil. The soil-structure interaction effect can initiate rocking and result in different soil motions compared to the free-field motion, thus significantly affecting the structural response. Also, the soil-structure interaction affects a structure by lowering the apparent fundamental frequency of the structure. The interaction is especially significant for embedded structures, where the increased contact area causes a further modification of the structural frequencies and increases the radiated energy.

Two basic methods are presently available to solve the interaction problem: The direct finite element method (FLUSH, Ref. 1,) and the impedance or substructure approach. Soil-structure interaction analyses to investigate the aseismic behavior of an embedded reinforced concrete reactor building have been performed using the lumped-parameter frequency-independent soil spring approach, the direct finite element method and the impedance approach. An overall comparison of the reactor building response results is presented in this paper.

METHOD FOR SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS

The Direct Finite Element Method

The finite element FLUSH analysis is one of the well established methods used to perform the soil-structure interaction analysis. In this method, the entire soil-structure system is modelled by a finite element model.

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The advantage of the finite element analysis is that the non-linear soil properties and other types of material behavior can be approximately included in the analysis. One of the limitations of the FLUSH analysis is that, although an attempt is made to simulate the three-dimensional effect, the model is basically a two-dimensional model. The direct finite element method (FLUSH) in its present form cannot study the torsional response of a soil-structure system as a result of the nonvertically incident seismic waves, or the lack of symmetry of the structural configuration. Above all, the two-dimensional characteristics of FLUSH analysis may result in underestimation of the response of an isolated structure, while exaggerating the interaction effect of multi-structures. It has been shown that for containment type structures, the maximum spectral response at the top obtained by use of a two-dimensional model can be 30% lower than that obtained by a more realistic three-dimensional model (Refs. 2 and 3).

The Lumped Parameter Frequency-Independent Soil-Spring Approach

In this approach, the effect of the foundation medium is represented by the frequency-independent foundation impedance. The foundation impedance can be simulated by a mechanical analog composed of equivalent springs and dampers. The equivalent dampers represent the effect of radiation damping. The material damping of the foundation medium is generally neglected since it is small compared with the radiation damping. The lumped-parameter soil spring approach is generally used for structures supported at or near the surface of a uniform elastic half space. The foundation input motions, which characterize the process by which the seismic waves are scattered by the presence of embedded foundations, are usually not considered in the analysis.

*For a surface foundation on a uniform elastic half-space, the dynamic stif*fness and damping characteristics of the foundation medium is determined using the formula suggested by Whitman and Richart (Ref. 4). To account for the embedment effect, the half-space frequency-independent impedances are modified according to the procedure described by Niehoff (Ref. 5).

The Impedance Approach

In this method, the complete soil-structural analysis problem can be separated into the following basic problems: 1) determination of the free-field motion in absence of the foundation, 2) evaluation of the response of the rigid and massless foundation to the free-field motion excitation, 3) evaluation of the base forces and moments that the superstructure exerts on the foundation expressed in terms of the foundation motion, 4) evaluation of the forces that the foundation exerts on the soil in terms of the foundation motion by considering the equation of motion of the foundation including its mass, and 5) determination of the foundation motion caused by the forces that the foundation exerts on the soil (Ref. 6). The advantage of the substructure approach is that the most appropriate solution for each subproblem can be used in the analysis. The approach allows engineers to have a better understanding of the physical behavior of each subproblem. At present, for foundation with backfill material and embedded in layered media, a time domain finite element approach is used to obtain the frequency-dependent foundation impedance functions and input motions (Ref. 7). Recently, the integral equation formulation used in conjunction with the Green's function for layered viscoelastic media have been used to evaluate the foundation impedance function. The method resolves two prevailing shortcomings in restricting the soil model to be a homogeneous, non-dissipative elastic half-space and constraining the analysis to the case of flat foundation (Ref. 8).

POWER PLANT DESCRIPTION AND SOIL PROPERTIES

The nuclear power plant analyzed is embedded in soil media and is potentially subjected to a strong earthquake. The reactor building is 265.7 ft square in plan, 213.3 ft high and 65.5 ft embedded. The design earthquake is a 30 sec artificial time history with a peak acceleration of 0.30 g. In the free field, a fine sand layer (v_s = 656 ft/sec) extends from the surface to elevation -13 ft. The mudstone layer (v_s = 3,280 ft/sec) then extends to elevation -183 ft. Backfill material (v_s = 656 ft/sec) is placed in the excavation of the sides of the reactor building down to elevation -65.5 ft. The standard Seed and Idriss strain-dependent shear modulus and damping curves are used in the analysis for the backfill fine sand (Ref. 10). The properties of the mudstone is assumed to be elastic.

SEISMIC SOIL-STRUCTURE INTERACTION ANALYSIS

The Direct Finite Element Soil-Structure Interaction Analysis

The soil-structure model of the reactor building consists of 533 nodal points, 389 solid elements and 99 beam elements. The transmitting boundary is used to model the effect of a semi-infinite halfspace. Viscous boundaries are used by FLUSH to model the out-of-plane energy dissipation through the soil. The viscous dampers extend up to the ground level, and their damping properties are based on the free-field soild properties.

The Lumped Parameter Frequency-Independent Soil-Spring Approach

As shown in Figure 1, four sticks have been modeled to represent the Reactor Building, PCV (primary containment vessel), RSW (reactor shield wall) and RPV (reactor pressure vessel). These four sticks are connected by infinitively rigid members at the bottom and by three simulated horizontal springs.

There are a total of 25 mass points and 24 beam elements in this model. The Reactor Building stick consists of 10 mass points and 9 beam elements. K_x and C_x represent the equivalent spring and radiation damping respectively due to the horizontal motion of the basemat; K_z and C_z for the vertical motion of the basemat; K_ψ and C_ψ for the rocking motion of the basemat.

The Impedance Approach Soil-Structure Interaction Analysis

The method proposed by Day (Ref. 7) to obtain the dynamic response of embedded rigid foundations is used. The computed impedance functions and input motions are combined with the structural parameters to obtain the total interaction foundation motions. These foundation motions are then used as superstructure base excitation to obtain the dynamic structural response using the procedure described by Lee and Wesley (Ref. 9).

The soil-foundation model used to evaluate the impedance functions and input motions consists of 2501 elements and 2604 nodal points. The model assumes axisymmetry and only half of the soil-foundation system is considered. The iterated soil properties obtained from in the horizontal FLUSH analysis are employed in the present investigation. The computed rocking, coupling and horizontal stiffness and radiation damping coefficients for the embedded reactor building foundation are plotted in Figures 2 to 4. These coefficients show a strong dependency on frequency. This strong frequency-dependence is associated with the presence of Rayleigh or surface waves. As Figures 2 and 4 show, the surface foundation has lower rocking and horizontal foundation impedance functions (Ref. 11).

Figures 5 and 6 show the numerical values obtained for horizontal and rocking input motions, ΔU and $\Delta\phi_r$, as functions of the dimensionless frequency a_o. For a surface foundation, the horizontal input motion would simply be equal to the free-field amplitude U_o at all frequencies and the rocking input motion $\Delta\phi_r$ would be zero. However, Figure 5 indicates that the amplitude of ΔU for an embedded foundation is significnatly reduced, especially at high frequencies, as a result of foundation embedment. On the other hand, Figure 6 indicates that foundation embedment introduces a significant component of rocking. The effect of soil layering introduces a marked frequency dependence.

COMPARISON OF RESULTS

Horizontal seismic soil-structure interaction analysis results obtained using the direct finite element method, the frequency-independent soil spring approach, and the impedance approach are compared in terms of peak acceleration and 5% floor response spectra. Both FLUSH and impedance analyses give comparable dynamic response of the Reactor Building. However, the structural responses obtained from soil spring approach are quite conservative as compared to those obtained from both FLUSH and impedance approach analyses.

Figure 7b is the comparison of the 5% dampiong floor response spectrum for the top of the Reactor Building obtained from the soil spring approach and the impedance analyses. The maximum spectral accelerations predicted by soil spring approach are much higher than those calculated by the impedance approach. In Figure 7a the horizontal 5% response spectra obtained from the impedance analysis are compared with those obtained from FLUSH. At the top of the Reactor Building, the FLUSH analysis predicts a maximum spectral acceleration 26% lower than that predicted by the impedance approach.

The differences in the spectral amplitudes between the soil spring approach and impedance approach analyses can be attributed to two causes: 1) foundation input motions, which characterize the process by which the seismic waves are scattered by the presence of the embedded foundation, are not included in the soil spring approach analysis, and 2) the seismic criteria for modal analysis requires that the upper limit of the first composite modal damping be limited to a maximum of 10%. The use of free field input motions in the seismic soil-structure interaction analysis will result in much more conservative structural responses as compared with those obtained using embedded input motion. The differences in the spectral accelerations between the FLUSH and the impedance approach can be attributed to three causes: 1) material damping is included in the impedance approach solution only in an approximate fashion (Refs. 12 and 13), 2) the foundation is assumed to be rigid in the impedance approach analysis, and 13) the two dimensional characteristics of the FLUSH model may reduce the spectral response (Ref. 2 and 3). Overall, however, the agreement between the FLUSH and the impedance approach response spectra is quite good.

CONCLUSIONS

1. The foundation embedment increases the horizontal, coupling, and rocking stiffnesses and radiation dampings.

2. The amplitude of the horizontal input motion at the foundation base is reduced due to the presence of the embedded, rigid foundation. The amplitude of rocking input motion (which is zero for surface foundations) attains a fraction of the free-field amplitude as a result of the foundation embedment.

3. FLUSH and the impedance approach predict comparable peak horizontal and rocking accelerations. The spectral acceleration at the top of the Reactor Building obtained by FLUSH is approximately 26% lower than that obtained from the impedance approach. Overall, the agreement between the FLUSH and impedance approach spectra is quite good. The lumped-parameter frequency-independent soil spring approach gives much higher response than those obtained from FLUSH and the impedance approach analyses.

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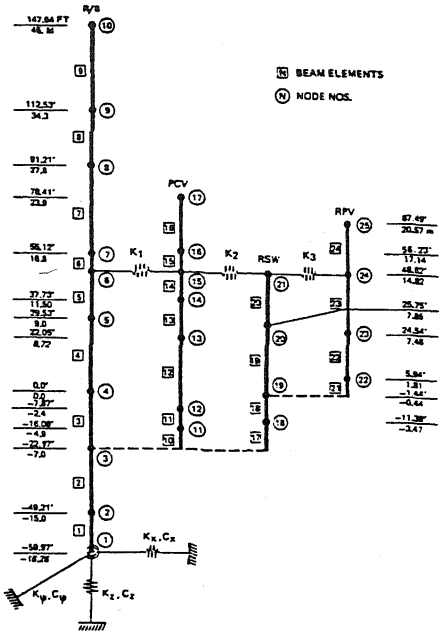

FIGURE 1

HORIZONTAL STICK MODEL
(REACTOR BUILDING)

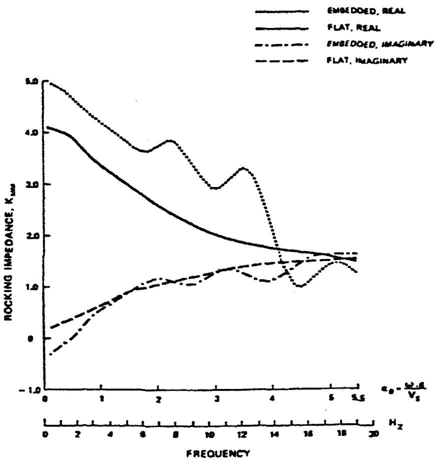

FIGURE 2

ROCKING IMPEDANCE

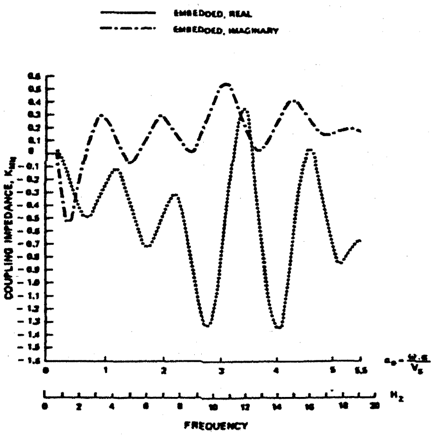

FIGURE 3

COUPLING IMPEDANCE

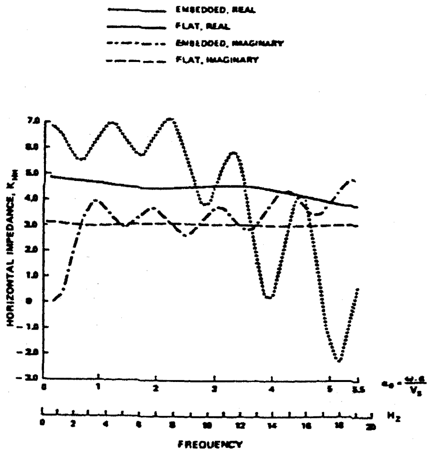

FIGURE 4
HORIZONTAL IMPEDANCE

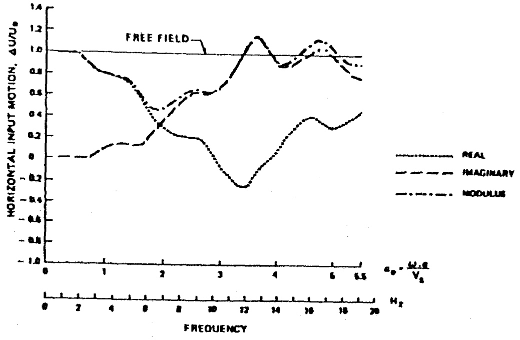

FIGURE 5 HORIZONTAL INPUT MOTION

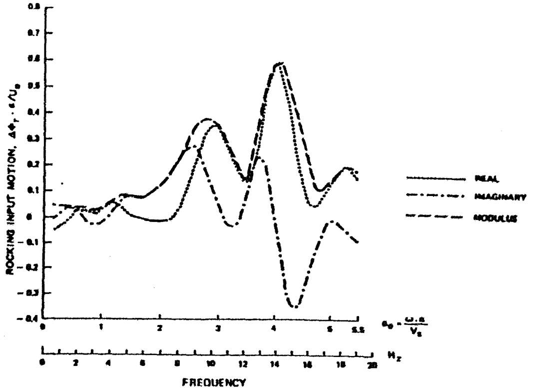

FIGURE 6 ROCKING INPUT MOTION

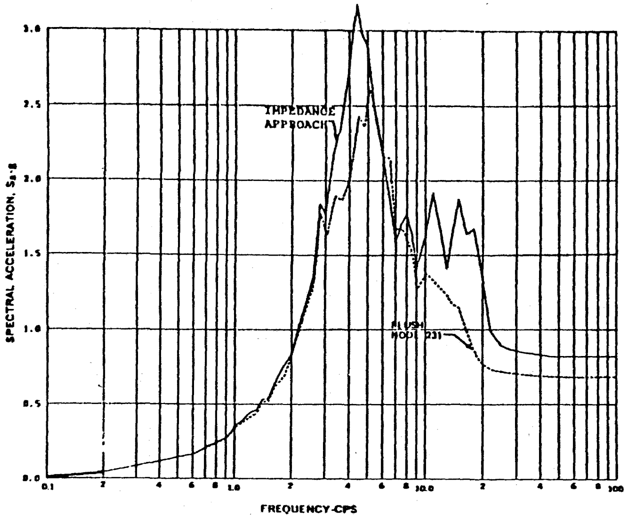

FIGURE 7a COMPARISON OF RESPONSE SPECTRUM

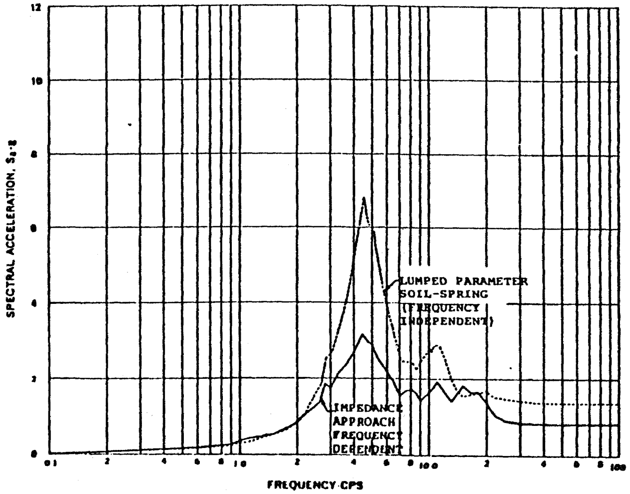

FIGURE 7b COMPARISON OF RESPONSE SPECTRUM