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THREE-DIMENSIONAL EFFECTS ON SOIL-STRUCTURE INTERACTION SYSTEMS

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SUMMARY

An effiecient solution technique, "Mixed Flexible Volume/Boundary Method", is introduced for solving general three-dimensional soil-structure interaction problems. The method uses a complex response finite element method based on the substructure approach and utilizes major advantages of both the flexible volume method and the flexible boundary method. The accuracy and adequacy of the proposed method are evaluated by comparing the computed impedance matrices to the previously published data. A realistic problem has been solved to evaluate three-dimensional effects in the soil-structure interaction system. Remarkable response differences are obeserved between three-and two-dimensional analyses both in an earthquake response problem and in a forced vibration problem.

INTRODUCTION

In the analyses of soil-structure interaction (SSI) systems, due attention must be given to the evaluation of the effects of the direction of the incident seismic waves, the irregularity and semi-infinite nature of soil layers, and possible embedment of the structure. This is possible only if three-dimensional SSI analyses are utilized. A sizable literature exists for the various solution techniques for SSI problems. The discretized numerical solutions implemented in the finite element programs, however, appear to be the most appropriate for solving general SSI problems involving complex geometry and soil properties.

The "complete" method and "substructure" method are the most commonly available methods for SSI analyses. Although the complete method is straightforward, it requires large computer memories and running times. The substructure method on the other hand handles reasonable amount of degrees of freedom at one time by separating the problem into several steps. The substructure method, therefore is considered to be the best candidate for three-dimensional SSI analyses.

An efficient solution technique based on the substructure method is introduced in this paper and is implemented into the computer program "SuperFLUSH/3D" (Ref. 1). The method used for handling soil-structure interaction effects is basically the flexible boundary method, but impedance and scattering characteristics are computed using the flexible volume method. This approach is thus called "Mixed Flexible Volume/Boundary Method".

The efficiency and accuracy of the method are examined and evaluated by comparing the dynamic stiffness and damping coefficients of typical surface and embedded foundations to those obtained from the published literatures (Refs. 2, 3, 4, 5). Subsequently, a realistic problem is used to understand three-dimensional effects in SSI system. Both the earthquake response analyses and forced vibration analyses have been performed for this purpose.

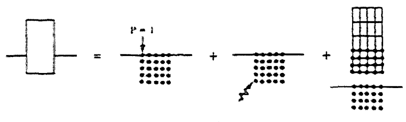
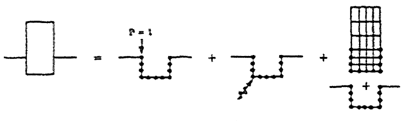
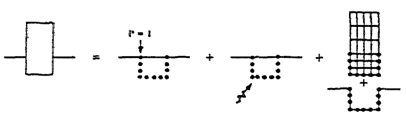
	SSI	Impedance Problem	Scattering Problem	Structural Analysis	Merit/Demerit
Flexible Volume Method	 Layered System				Merit : Impedance & Scattering Problems in horizontally layered system. Demerit : Larger impedance matrix because of the increase of Interaction nodes.
Flexible Boundary Method	 Not Layered System				Merit : Smaller impedance matrix because of the minimum amount of the interaction nodes. Demerit : Extremely complicated impedance and scattering problems.
Mixed Flexible Vol./Bound. Method (Super FLUSH/3D)	 Layered System				Merit : Impedance & Scattering problems in horizontally layered system. minimum amount of interaction nodes.

Fig.1 Comparsions of Various Substructure Methods

THEORETICAL BACKGROUND

The comparisons of the flexible volume method, the flexible boundary method and the mixed flexible volume/boundary method are described and summarized in Fig. 1. The advantage of the flexible volume method is that the scattering and impedance problems can be greatly simplified. The impedance problem, in particular, is reduced to the problem where only a limited number of forced vibration cases is required in a horizontally layered system (Ref. 6). The size of the impedance matrix, however, becomes larger for the flexible volume method due to the increase of interaction nodes between structure and surrounding soil, while it is smaller for the flexible boundary method. The scattering and impedance problems are extremely complicated in the flexible boundary method. The proposed mixed flexible volume /boundary method utilizes major advantages of both the flexible volume method and the flexible boundary method. The approach itself is based on the flexible boundary method, but the flexible volume method is used to compute scattering and impedance matrices. The detailed description of the derivation of the equation of motion is available in Refs. 1 and 7.

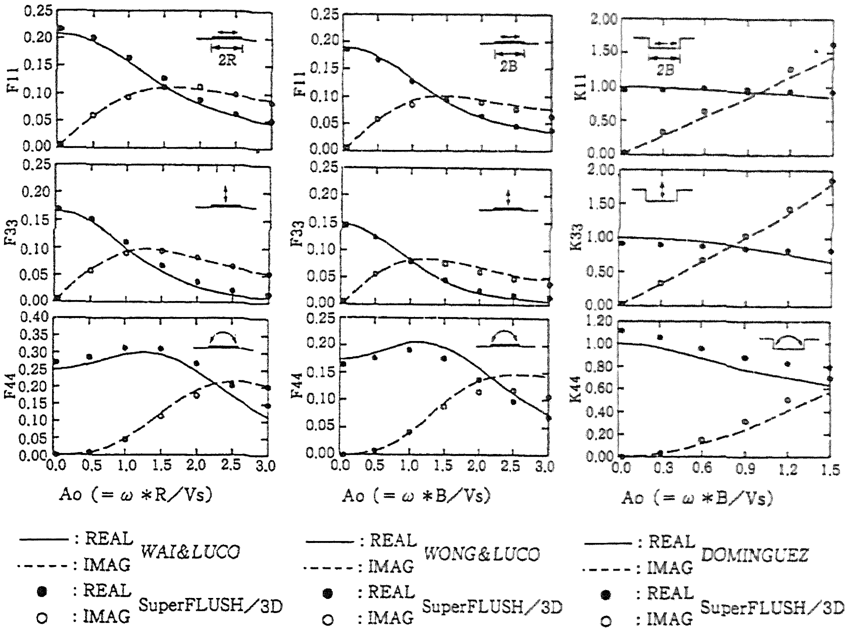
EVALUATION OF THE MIXED FLEXIBLE VOLUME/BOUNDARY METHOD

In oder to evaluate the accuracy and adequacy of the proposed method, the impedance matrices or flexibility matrices are computed and compared to those previously published. The comparisons are only made for the rigid circular and rectangular foundations.

The results of the study are presented in Fig. 2 in terms of normalized flexibility matrices for frequency range of interest in SSI analyses. At least one-sixth of wave length rule is applied as a criterion of determination of the dimension of elements in order to assure the accuracy of the results of the calculation. It is easily seen that excellent agreement is obtained. It should be noted, however, that the violation of the wave length of one-sixth leads to inaccurate results.

EVALUATION OF THREE-DIMENSIONAL EFFECTS ON SOIL-STRUCTURE INTERACTION SYSTEMS

Description of The Problem Two-dimensional and three-dimensional analyses are performed using the computer programs "SuperFLUSH" (Refs. 8, 9) and "SuperFLUSH/3D" in oder to evaluate three-dimensional effects on SSI systems. A caisson type of structure is selected



(a) Flexibility Coefficients (Circular Foundation)

(b) Flexibility Coefficients (Square Foundation)

(c) Impedance Functions (Embedded Square Foundation)

Fig.2 Dynamic Stiffness and Damping Coefficients
(ν =0.33, G=1.0, ρ =1.0, h=0%)

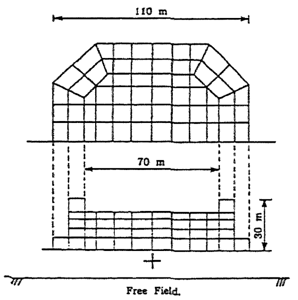


Fig.3 FEM Model Used for 3−Dimensional Substructure Method.

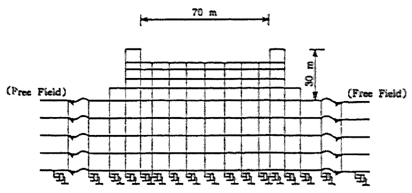


Fig.4 2−Dimensional FEM Model.

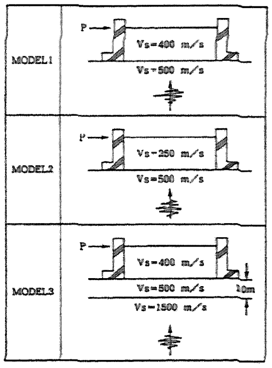


Fig.5 Cases Analized
(ν =0.33, ρ =2.0, h=10%)

as an example case study. The caisson is constructed of reinforced concrete and its base has an octagonal shape. The plane view at foundation level and side view of three−dimensional finite element model are shown in Fig. 3. The sand as core material is assumed at the central portion of the model. The finite element model used in two−dimensional analyses is shown in Fig. 4. A semi−infinite half space was assumed at the bottom of the FEM model and the energy transmitting boundaries are attached at the lateral boundaries to simulate the existance of semi−infinite soil layers. Total of three cases of different material properties are used for the studies and are illustrated in Fig. 5. Both earthquake response and forced vibration analyses are performed in this series of study.

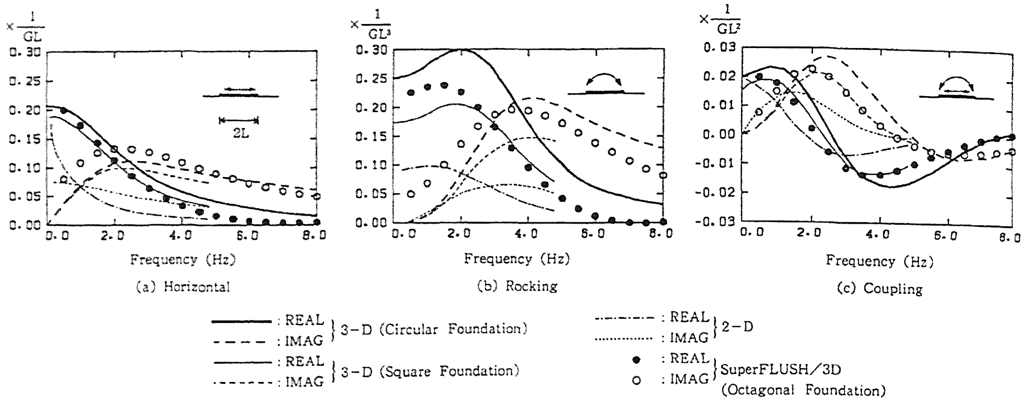


Fig.6 Comparisons of Flexibility Coefficients between 3–D and 2–D Analyses.
(G : Shear Modulus, L : Half Side Length)

Impedance Functions In oder to obtain a clear picture and to better understand three–dimensional effects, the computed impedance functions are re–calculated with rigid foundation. Impedance functions computed in the three–dimensional system are plotted in Fig. 6 and compared to those of two–dimensional system. The impedance functions for the circular and rectangular surface foundations (Refs. 2, 3, 4) are also plotted for comparative purpose. The comparisons between computed and published data show excellent agreement. On the other hand, the clear differences are observed in the low frequency responses between the flexibility matrices of three–and two–dimensional systems.

Earthquake Rasponse Analyses The N–S component of El Centro Earthquake recorded on May 18, 1940 with a maximum acceleration of 342 gal is used as a control motion. The motion is specified at the free field ground surface. The analyses have been performed up to 8.0 Hz. The computed response spectra with 5% damping at selected nodal points are shown in Fig. 7. The solid lines are for three–dimensional analyses and the broken lines are for two–dimensional analyses. For the comparative purpose, the response spectrum of control motion given at the free field ground surface is shown as the long–short broken lines. The results show that the responses obtained from three–dimensional analyses are higher than those obtained from two–dimensional analyses. The transfer functions from the control point to the top and bottom at the center line of the core are shown in Fig. 8. The difference from unity indicates the effects of the presence of the caisson. The comparisons show the SSI effects approximately at frequencies of 2.3 Hz and 5.0 Hz. While no clear peak is observed at frequency of 2.3 Hz, the clear reduction of the computed values are observed before the frequency of 5.0 Hz in the two–dimensional analyses. The comparisons of the computed responses obtained from three–and two–dimensional analyses show the noticeable response differences. Those differences imply that representation of three–dimensional problems by two–dimensional analyses is not always possible.

Forced Vibration Analyses The trapezoidal shaped input force time history as shown in Fig. 9 is assumed as the excitation in this series of studies. The force time history is scaled up to have maximum of 100 tons/m. All the analyses have been performed up to the frequency of 8.0 Hz. The responses are summarized in terms of maximum accelerations and shear stresses, and are shown in Figs. 10 and 11. It is clearly observed that the responses from the three–dimensional analyses are higher than those from the two–dimensional analyses. Approximately one half to one quater of the two–dimensional responses is computed in the three–dimensional analyses. It should be noted that responses obtained in the forced vibration analyses show the completely opposite trend compared to those in the earthquake response.

Since the control motion is applied only on one side of the caisson wall, the energy can only propagate through the core material in the two–dimensional analyses. On the other hand, the energy can propagate through both the core and side concrete caisson in the three–dimensional analyses. It is therefore unavoidable to obtain certain degree of response

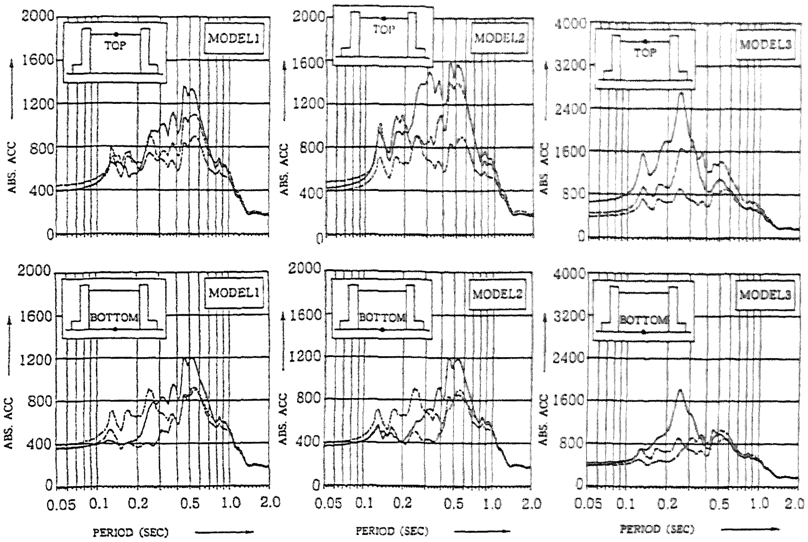


Fig.7 Comparisions of Response Spectra between 3−D and 2−D Analyses.(h=5%)

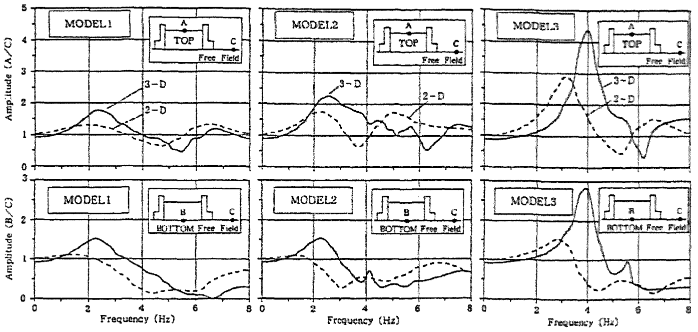


Fig.8 Comparisions of Transfer Functions between 3−D and 2−D Analyses.

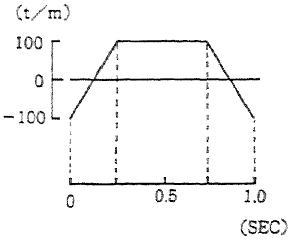


Fig.9 Input Force Time History

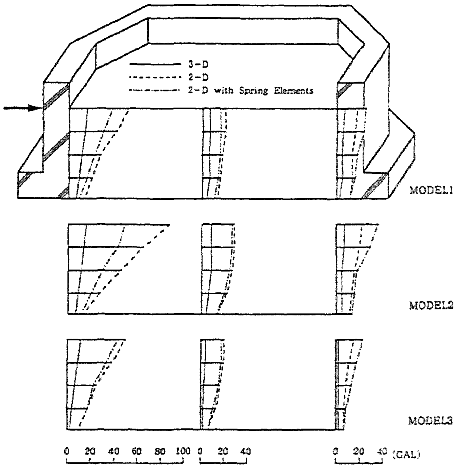


Fig.10 Distribution of Maximum Accelerations

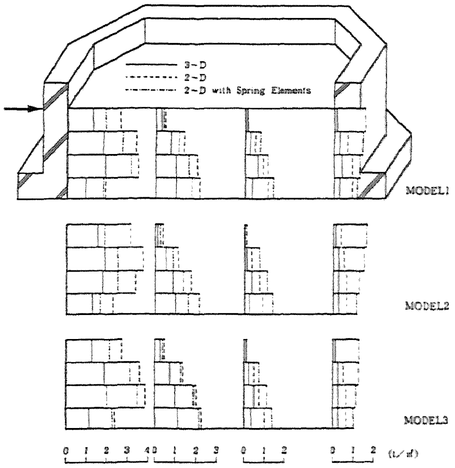


Fig.11 Distribution of Maximum Shear Stresses

differences between three-and two-dimensional analyses. In the next analyses, spring elements are added to simulate lateral concrete caisson effects in two-dimensional analyses.
The computed responses are shown as long-short broken lines in Figs. 10 and 11. The use of the equivalent spring elements produces somewhat different distribution of the maximun responses compared to that without spring elements. The modeling technique in the FEM analyses may be an another important problem in two-dimensional systems.

CONCLUSION

An effective approach based on the substructure method is introduced to solve three-dimensional soil-structure interaction problems, The method utilizes the major advantages of both the flexible boundary method and the flexible volume method, such as reduction of the size of the impedance matrix and elimination of the scattering problem, resulting in the remarkable reduction of the computational cost. The method is called "Mixed Flexible Volume/Boundary Method". The computer program "SuperFLUSH/3D" is devoloped based on the proposed approach.

The computed responses for the rigid surface and embedded foundation are compared with the data previously published. Excellent agreement is observed between the computed results and published data.

The reinforced concrete caisson with an octagonal foundation is used to evaluate three-dimensional effects on the soil-structure interaction systems. The computed results from the three-dimensional analyses are compared to those from the two-dimensional analyses. The noticeable response differences are observed between three- and two-dimensional analyses.

This series of studies indicates that the three-dimensional dynamic analyses may be essential in order to understand realistic behavior of the structures and that two-dimensional analyses may occasionally produce quantitatively poor results.

It is not always possible for two-dimensional analyses to consistently represent the dynamic characteristics of the three-dimensional soil-structure interaction systems over the complete frequency range. More extensive comparative studies may be necessary to better define and understand the range of applicability of two-dimensional solutions.

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