Soil-Structure Interaction Analyses for Varying Seismic Environments and Boundary Conditions

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SUMMARY

A new computer program, SuperFLUSH, has been developed based on the existing program FLUSH, which utilizes the complex response method and the finite element method. The new program can accomodate a variety of boundary conditions and seismic input environments, provide even more versatility and flexibility and perhaps also more cost-effective measures for seismic soil-structure interaction analyses. The boundary conditions considered in this paper are as follows:

(1) energy transmitting boundary on the rigid base,
(2) energy transmitting boundary on the half-space,
(3) lateral viscous dashpot boundary,
(4) rigid base boundary,
(5) base viscous dashpot boundary to simulate half-space, and
(6) viscous dashpot boundary to simulate approximate 3-D effects.

The seismic input environments considered are as follows:

(1) vertically propagating body waves and
(2) traveling seismic waves.

The computed response shows the importance of the selection of boundary conditions and input forms. It is believed that the inclusion of the various features accomodated in the program should facilitate intelligent applications of the results in practice with good engineering judgment and an intimate knowledge of the technical details.

1. INTRODUCTION

The finite element method provides a powerful tool for the solution of seismic soil-structure interaction problems especially when there are complicated boundary conditions. It is a relatively expensive tool, however, continuing research on the application of the method has generated many new ideas for special seismic input environments and boundary conditions can made use of the finite element method even more versatile and perhaps also more cost-effective for seismic soil-structure interaction analyses. This does not mean that all finite element analyses of soil-structure interaction provide adequate evaluation of response. Like all analyses, they can be performed with different degrees of approximation or sophistication. A good analytical procedure should consider the following as summarized below:

(1) Soil compliance effects on the earthquake response of the important structures should be treated as semi-infinite zones.

(2) The analyses should be able to take into account the three dimensional nature of the problem.

(3) The analyses should consider the nonlinear characteristics of the soils.

(4) Since the wave propagation in soil deposits is very complex, the analyses should be capable to handle appropriate seismic input environments, such as vertically propagating body waves, traveling seismic waves, surface waves, etc.

In order to overcome the above mentioned difficulties, some of the ideas have been incorporated into a new computer program, SuperFLUSH, which is a further development of the well known program FLUSH [5,6]. It is the purpose of this paper to compare the effects on computed responses of variations in boundary conditions and input environments. As in the various boundary conditions, the following are considered:

(1) Energy transmitting boundary on the rigid base.

(2) Energy transmitting boundary on the half-space.

(3) Lateral viscous dashpot boundary.

(4) Rigid base boundary.

(5) Base viscous dashpot boundary to simulate half-space.

(6) Viscous dashpots boundary to simulate approximate 3-D effects.

As the various seismic input environments the following are considered:

(1) Vertically propagating body waves.

(2) Traveling seismic waves.

2. SOIL-STRUCTURE INTERACTION ANALYSES

2.1 Control Motion

An artifical accelerogram with a peak acceleration of 0.3g was used as the control motion for horizontal excitation at the ground surface of free-field. The accelerogram has a duration of 24 seconds and is digitized at a time step of 0.02 seconds and is filtered to exclude all frequency above 15 HZ. The time history and response spectrum at 5% damping are shown in Figures 1 and 2, respectively. The response spectrum has a relatively flat range of response from 0.15 to 0.5 second to cover all the possible motions expected at a nuclear power plant site.

2.2 Geometry and Material Properties

The hypothetical nuclear power plant shown in Figure 3 was chosen for soil-structure interaction study as an example case. The foundation for the containment structure consists of uniform sand with a relative density of 75%. A unit weight of 2.0 ton/m^3 and Poisson's ratio of 0.33 were used, as representative values for soil. The hypothetical containment structure of the nuclear power plant is embedded in the sand deposit of 24.0 m and extends 30 m above the ground surface. The top part of the building is considered to be a light shell structure, while the embedded part of the building is assumed to be relatively heavy and stiff. The different structural properties corresponding to these conditions are shown in Figure 3.

The equation suggested by Seed[7] was used to evaluate shear moduli at low-strain levels. The properties are then iterated in the free-field until strain compatible shear moduli and damping values are obtained. The properties obtained from the free-field analysis were assigned to the main mesh and used for the response computations, ignoring secondary nonlinear effects due to soil-structure interaction.

2.3 Finite Element Models

Total of six finite element models are used for the soil-structure interaction study. The points A to F in the models show the output points for response spectra. All the response spectra in the paper were obtained using 5% damping.

MODEL 1 (Figure 4) - MODEL 1 was chosen as the standard model in this paper. Only half of the entire model is used to take advantage of geometrical symmetry. The base of the model is extended 14.4 m from the base of the structure and is only extended up to 24 m from the center line of the structure.

MODEL 2 (Figure 5) - MODEL 2 is identical to MODEL 1 except that MODEL 2 is extended a distance of 96 m from the center line of the structure (4 times of the half structure). The MODEL 2 is used to evaluate the efficiency of the energy transmitting boundary [3.9].

MODEL 3 - (Figure 7) - MODEL 3 is also identical to MODEL 1 except that the base of the soil deposits are assumed to be 81.6 m below the ground surface to evaluate the efficiency of viscous dashpot for simulating half space [1,2].

MODEL 4 (Figure 7) - MODEL 4 is used to evaluate the efficiency of the base viscous dashpot as an extreme case by setting the base of the model only 2.4 m from the base of the structure.

MODEL 5 (Figure 8) - MODEL 5 is used to evaluate the effects on the response due to an unbalanced free-field condition which is defined as the system whose right and left hand side free-fields are not identical.

MODEL 6 (Figure 9) - The finite element model for the traveling wave analysis is shown in Figure 9. Since the loading condition is not symmetric, it is not possible to take advantage of the symmetry of the structure about its center line.

2.4 Results of Discussions

Efficiency of Energy Transmitting Boundary

In order to simulate the existance of horizontal soil layers outside the vertical boundaries, it is necessary to impose special boundary conditions on these boundaries. The boundary could be placed further away from the structures where there is no disturbances due to the existance of the structures. It is, however, not the best approach to solve the problems because the high computational costs. Energy transmitting boundaries [8,9] are used at the right hand side of the vertical boundaries of MODEL 1 and MODEL 2 to evaluate the efficiency of the energy transmitting boundary. The control motion shown in Figure 1 is given at the ground surface in the free-field. The three-dimensional simulation [6] is also introduced for these analyses assuming the width of the structure in the third-dimension is 38.4 m.

The comparison of the acceleration response spectra at nodal point A obtained from MODEL 1 and MODEL 2 is shown in Figure 10. The response obtained shows excellent agreement and differences in computed responses are negligible for practical purposes. The energy transmitting boundary, therefore, is a very useful and accurate tool to reduce mesh size which in turn results in reduced computational time. The ratio of computational times of MODEL 1 to MODEL 2 is approximately 3/5.

Efficiency of Lateral Viscous Dashpot Boundary

The response using the energy transmitting boundary and lateral viscous dashpot boundary [4] are compared in MODEL 1. The comparison of the acceleration response spectra at nodal point A is shown in Figure 11. The result shows good agreement between the computed responses, provided that the use of a lateral viscous dashpot boundary produces only a few percent of errors on the responses. This is because (1) the viscous dashpot boundary is designed to absorb body waves only and the waves generated by the soil-structure interaction consist primarily of surface waves and (2) the absorption cannot be made perfect over the whole range of incident angles of waves. However, the response differences are neglible for practical purposes. It seems that the lateral viscous dashpot boundary is also a very effective tool to simulate extended soil systems. The time required for the computation of the responses using the side viscous dashpot boundary is reduced to 50% to 70% of that using the energy transmitting boundary.

Incident Wave vs Rigid Base Approach

The model used in soil-structure interaction analyses should be deep enough to account for the effects of radiational damping in the actual field system so that responses of the structure is not significantly affected by the depth of the model used, unless very hard rock formation is found near the structure and considered as a rigid base. The determination of the depth of the model is one of the important decisions of the analyses. However, there is no reliable method available to determine the base where no interaction effect can be reached.

It is not currently possible to specify the control motion at the surface with a non-linear site response problem. However, the control motion can be specified at an outcrop with the assumption of the special case where nonlinear layered system overlies a uniform linear elastic half space [1,2]. The technique can be applied to separate incident and reflected components of the wave at any depth of the layers. The input specifications accomplished by determining incident waves at the base of the model can be called an incident wave approach. In this model the mesh is supported on a Lysmer-Kuhlemeyer dashpot [4] and excited by a force at the base proportional to the known outcrop velocity time history.

MODEL 1, MODEL 3, and MODEL 4 are used and the responses on the structure are computed by both incident wave and rigid base approaches. The distribution maximum accelerations along the center line of the structure are shown in Figure 12. The results show that the location of the model base have the significant effect on the responses with the rigid base approach. However, it seems that the use of the incident wave approach minimizes the response differences due to the variations of the model bases. Figures 13 and 14 show the response spectra at nodal point A of the MODEL 1, MODEL 3, and MODEL 4 based on the rigid base approach and incident wave approach, respectively. It is noted that the responses based on the rigid base approach show the significant variations depending on the location of the base. On the other hand the responses based on the incident wave approach shows the good agreement with each other even on the extreme case where the base was placed only 2.4 m below the structure foundation (MODEL 4). It is also noted that the responses on MODEL 3 based on the rigid base and incident wave approaches show the perfect agreement.

It seems to be that the incident wave approach will be a very powerful and cost effective tool to eliminate the difficulty of the determination of the base location. For the readers' information, the ratio of computational time of the responses between the incident wave approach on MODEL 1 to the rigid base approach on MODEL 3 is about 0.6.

Sloping Soil Site

It is not always possible to build an important structure on perfectly horizontal layered soil, especially in mountainous areas. The sloping ground surface might be found near the structure. To overcome the difficulty of the boundary condition at the sloping ground surface, the idea of unbalanced free-field site shown in Figure 8 is introduced as one of the special boundary conditions.

The responses obtained from MODEL 5 shown in Figure 8 and MODEL 1 shown in Figure 4 are compared so as to study the effect of the sloping ground surface on the structure responses. Figure 15 shows the comparison of response spectra at nodal point A due to the locally sloping and horizontal soil surface conditions.

The result indicates that the sloping soil surface condition tends to produce a higher response than the horizontal soil surface condition, in the order of 5 to 10% at the peak of the response spectrum. The results may imply that the response differences may be insignificant, however, ignoring them would lead to a dangerously unconversative conclusion.

Traveling Waves vs Vertically Propagating Waves

Most currently available procedures assumed that the ground at some depth below vibrates in phase at all the time, which is called the vertically propagating wave analysis. However, this assumption cannot be considered valid for a wide structure as surface ground motion is the combined result of a number of complex traveling waves. The traveling seismic wave • which assumes differences in phases between motion at a different base point [8] is examined with respect to the vertically propagating wave in this section. MODEL 6 shown in Figure 9 is used for the traveling wave analysis and responses are compared with those obtained for the vertically propagating wave in MODEL 1.

Figure 16 shows the comparative plot of the acceleration spectra of motions at nodal point A. Generally speaking, less conservative horizontal responses are obtained from the traveling wave analysis by reducing the responses at the higher frequency components of the response spectra has been called the 'self-cancelling' effect.

3. CONCLUSIONS

A new computer program, SuperFLUSH, for evaluating the seismic response of soil-structure interaction systems has been developed based on the existing program FLUSH [5,6], which utilizes the complex response finite element method. The results obtained from the hypothetical nuclear power plant site are compared to study the effects of variations in boundary conditions and input environments on computer response. The results of this study lead to the following conclusions:

(1) The energy transmitting boundary is a very useful and powerful tool to simulate semi-infinite layered zones.

(2) The lateral viscous dashpot boundary results in reducing computational time in comparison with the energy transmitting boundary. This boundary also provides the considerably accuracte response by absorbing energy from the structure.

(3) Base viscous dashpot boundary is a very powerful tool to simulate half space below the mesh. Consequently the base boundary can be placed closer to the structure analyzed.

(4) The effect of the geometry of the soil deposit such as a sloping ground surface may have an important effect to the response of the structure.

(5) The dynamic behavior of structures are considerably effected by the input environment,such as the traveling wave case.

In the light of the above conclusions, the results show the importance of the selection of boundary conditions and input forms and it is believed that inclusion of the various features described above in the program should facilitate intelligent application of these findings in practice with good engineering judgment and an intimate knowledge of the technical details.

4. REFERENCES

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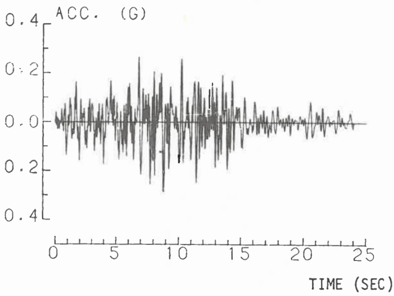

Fig.1 Time History of Control Motion.

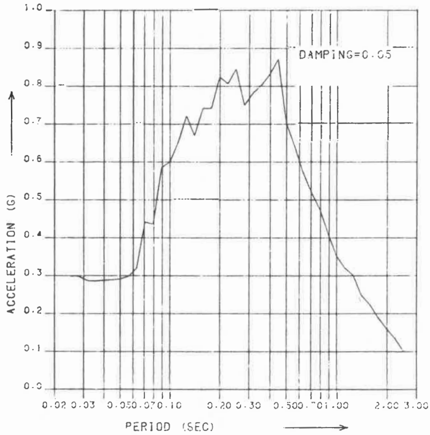

Fig.2 Response Spectram of Control Motion.

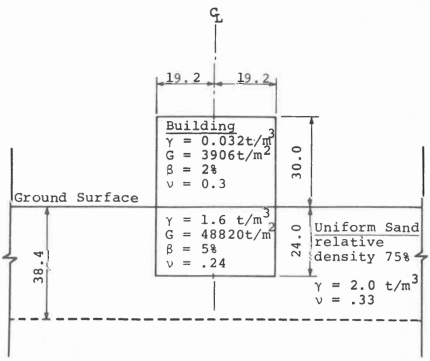

Fig.3 Geometry and Properties of Hypothetical Nuclear Power Plant.

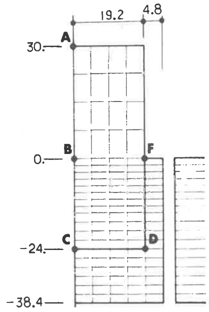

Fig.4 Model 1

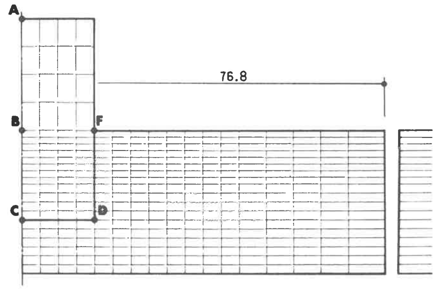

Fig.5 Model 2

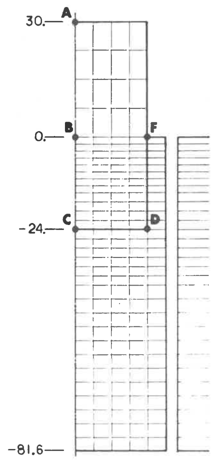

Fig.6 Model 3

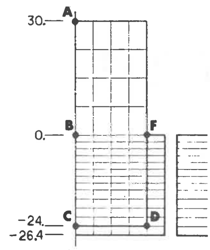

Fig.7 Model 4

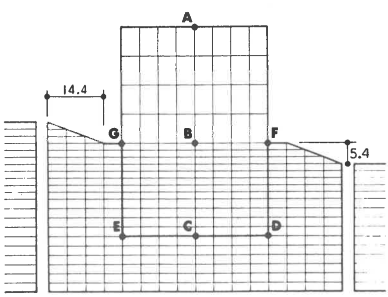

Fig.8 Model 5

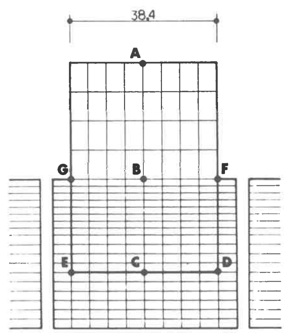

Fig.9 Model 6

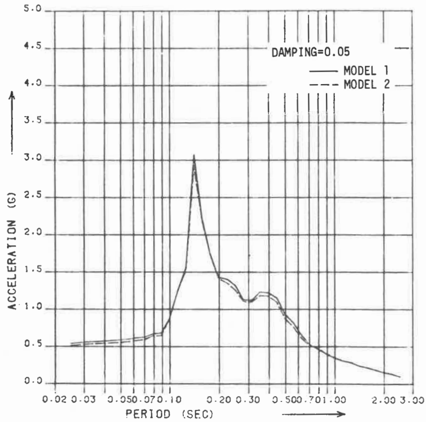

Fig.10 Efficiency of Energy Transmitting Boundary.

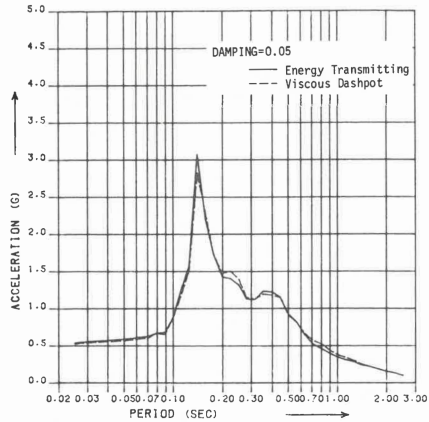

Fig.11 Energy Transmitting Boundary Vs. Viscous Dashpot.

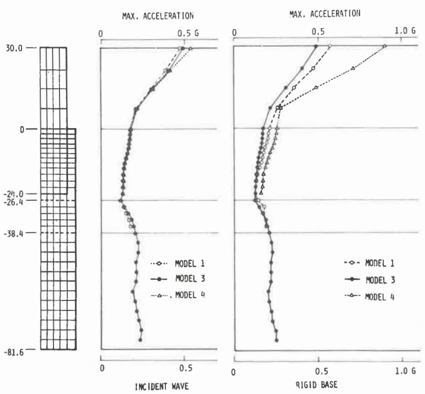

Fig.12 Max. Acceleration Distribution.

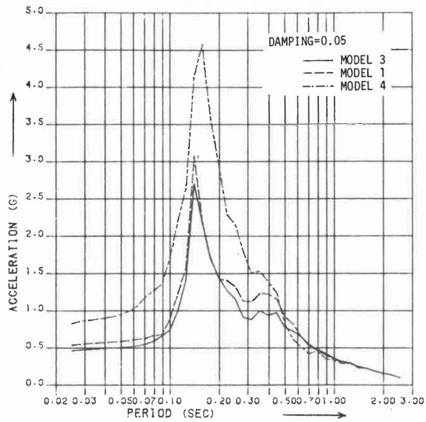

Fig.13 Rigid Base Analysis

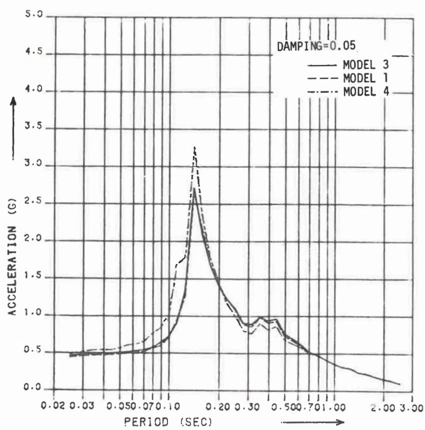

Fig.14 Incident Wave Analysis.

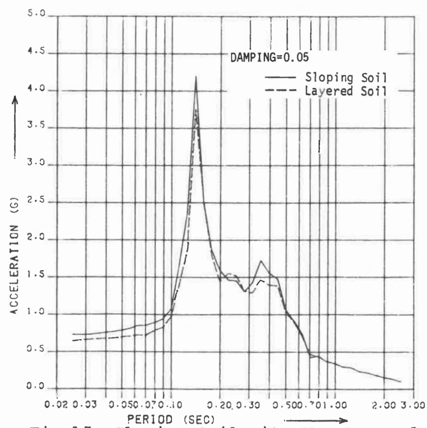

Fig.15 Sloping Soil Site Vs. Layered Soil Site.

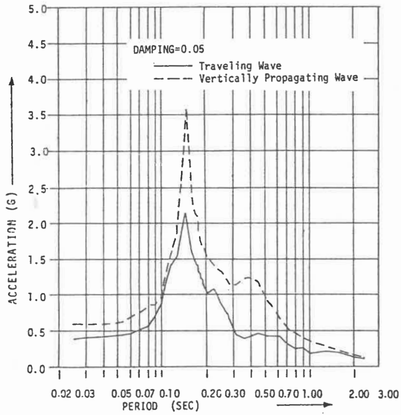

Fig.16 Traveling Wave Vs. Vertically Propagating Wave.