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Computational Simulation Procedure for Soil-Structure Interaction Modeling in Building Seismic Damage Response

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ABSTRACT

A finite element based computational procedure is presented for soil-structure interaction modeling in building seismic damage response. Attention is focused on a combination of contact surfaces at the soil-foundation interface, nonlinear soil material response, and infinite elements as transmitting boundary conditions. A rationale for efficient mesh design is offered for the detailed building/foundation/soil system model based on computational wave propagation studies using infinite elements. As a first study of the proposed procedure, a comparison is made between results of eigen mode analysis of two models for a 3-story office building, one with the conventional treatment of the foundation and soil as discrete linear springs [3], and the other incorporating the proposed procedure.

INTRODUCTION

Statement of the problem

Case studies of structure seismic response on the campus of the University of Mississippi have highlighted the importance of interaction between structure foundations and soil deposits. A structure with finite dimensions is embedded in deformable soil of infinite dimensions. The time-dependent load can either act directly on the structure, arising for instance from rotating machines or be introduced into the dynamic system through incident waves as from earthquakes.
In order to model this problem using computational simulation procedures, two main difficulties should be taken into consideration: 1) t\ransmitting boundary conditions, 2) soil/structure interface.

(1) Transmitting Boundary Conditions. The most common analytical Soil-Structure Interaction models are based on the assumptions that the soil domain may be represented by an elastic half space and that dashpots may be used to represent the transmitting boundary conditions [6]. These boundary conditions are required to model both radiation damping of the foundation motion as waves propagate outward into the infinite domain and to prevent reflections back into the foundation from any artificially introduced finite domain of the half-space. A recent study shows some disadvantages for these dashpots especially with large computational models [6].

(2) Soil / Structure Interface. A number of recent research studies have provided insight into the seismic response characteristics of structures. Application of system identification techniques to measured earthquake response data for structures has indicated that structure foundations and the surrounding soil constitute a strongly coupled system. The dynamic behavior of the structure foundations and the surrounding soil has a first order influence on the dynamic response of the structure. Analysis of measured strong motion response data has also indicated that local nonlinear behavior of soil can result in significant nonlinear global behavior of the entire system, even when the structure remains linear. This local nonlinear behavior should be taken into consideration in any modeling procedure.

WAVE PROPAGATION STUDIES

(1) Transmitting Boundary Conditions

Infinite Elements versus Dashpots. The Infinite Element type $1/r^n$ [8] available in the ABAQUS [4] commercial software package has been investigated as a transmitting boundary condition in place of the traditional ones (dashpots) for 1-D, 2-D and, 3-D FE models. Two FE models have been developed for the 1-D wave propagation in semi-infinite rod problem, one with dashpots and the other one with infinite elements. The dashpot coefficient and infinite element density have the following relation: [5]

$$\rho_{inf} = d^2 / A^2 E \quad (1)$$

A pulse with unit amplitude for 0.02 sec has been applied as a dynamic concentrated load on the first three nodes at the beginning of the rod. The responses of the two models were found to be nearly the same, and the response in case of infinite elements is more regular in absorbing the wave [5].

A strip of foundation with rectangular cross section embedded in half-plane of soil [15], has also been investigated as a 2-D case. In this case, since we have two degrees of freedom per node, the following two dashpot coefficients [15], one in the normal direction of the model, and the other in the tangential one, are employed:

$$d_n = \rho\, c_p \quad \text{(Normal direction)} \quad (2)$$

$$d_t = \rho\, c_s \quad \text{(Tangential direction)} \quad (3)$$

Two different ABAQUS models have been used to study this problem, one with dashpots and the other with Infinite Elements, as shown in Figure 1 and 2, respectively. It was difficult to find a complete analytical solution for a 3-D problem with dashpots, so the 2-D model case has been extended to a 3-D situation and the same results were obtained [5].

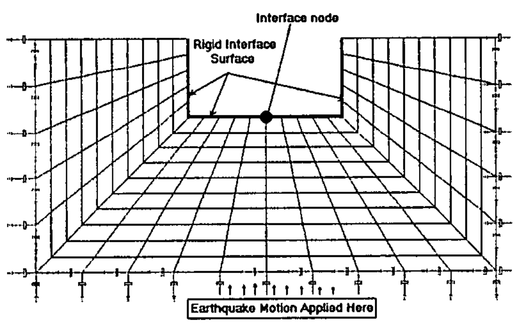

Fig. 1. 2-D FE Model with Dashpots.

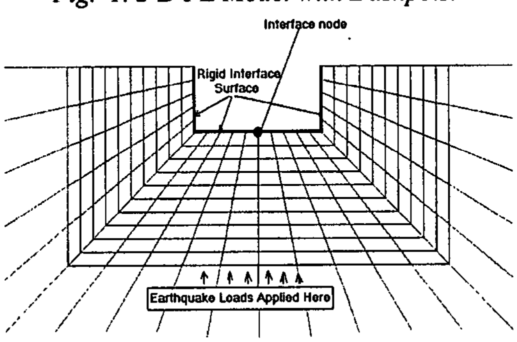

Fig. 2. 2-D FE Model with Infinite Elements.

Lamb Problem. It is well known that a vertical vibrating source produces surface waves (Rayleigh waves) that propagate with horizontal velocity. The wave amplitude decays rapidly with depth; in effect, it is confined to a thin layer near the surface. Radiation damping performance of the Infinite Elements for Rayleigh waves is examined for the well-known Lamb problem with a harmonic normal point load applied to a rigid disc on a 3-D half-space [14]. The semi-infinite half space of soil has been modeled using ABAQUS 8-noded continuum elements, and the infinite elements have been used at transmitting boundaries, as shown in Figure 5.

A harmonic load with frequency 3.33 Hz has been applied at the center of the model and time history analysis of response computed.

Taking the far field radius (r_f) [15] as a reference value, a comparison between the FE and theoretical solution [15] is presented in Figure 6. The values of the FE solution are the peaks of the steady state solution. . The solution has been normalized to the solution at the edge of the disc.

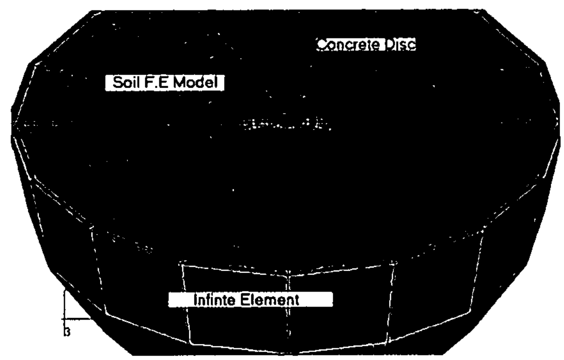

Fig. 5. 3-D Model of Point Load on Half-Space with Rigid Disc.

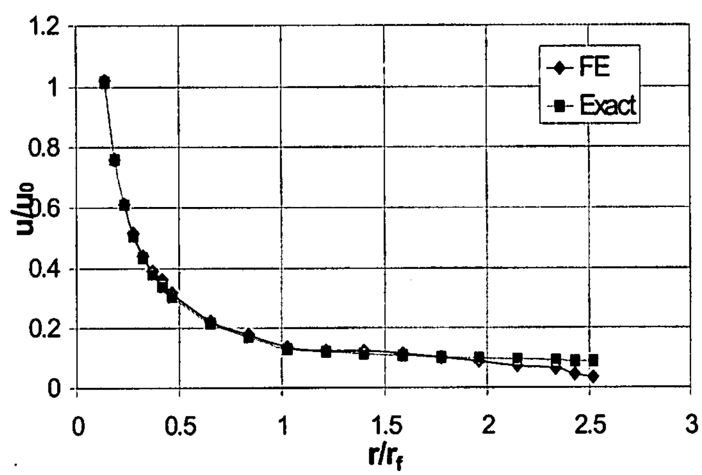

Fig. 6. A comparison between FE and Theoretical solution for 3-D Lamb Problem.

From Figure 6, it is clear that both exact and FE solutions are nearly the same until $r/r_f = 1.7$ and then the FE solution starts to be stiffer. Which means, both exact and FE results were the same for 60% of the distance away from the point dynamic load.

(2) Soil / Structure Interface.

Evaluating the interaction of soil / structure system subjected to a seismic load is an important step in any dynamic analysis. One of the most important problems in this kind of analysis is the local nonlinear behavior between the soil and the structure foundation.

Contact Surface Approach. One of the contact surface modeling procedures available in ABAQUS is the Master-Slave technique. In this technique, the model is divided into two sub-models, one called the Master and the other called the Slave [4]. The two sub-models interact along a user-defined contact surface. By virtue of this surface, it is not necessary to have compatibility of the meshes at the interface. By using the standard sub-structural approach [6], the program determines the displacement for the Master nodes on the contact surface, then the Slave ones.

Application to a Gravity Retaining Wall. A finite element analytical model developed by Alhamoud [1] to analyze the seismic response of rigid highway bridge abutments has been reconstructed using the contact surface approach in ABAQUS. The soil has been taken as Master sub-model, the abutment as Slave sub-model, and the Infinite Elements as transmitting boundary. Figure 7 shows the response of this model to an earthquake loading of moderate intensity. Concentrating on the interface region, we can see that the important local nonlinear behaviors, including vertical and horizontal sliding and over - turning of the abutment, have been captured by this technique.

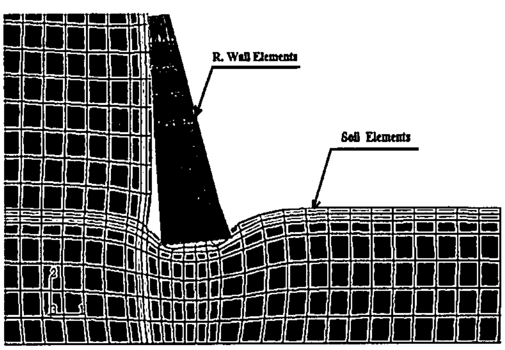

Fig. 7. 2-D Deformed FE Model of Bridge Abutment

Application to a Spread Footing for a Building. A 3-D FE model has been developed for one of the isolated footings of Stockard-Martin Hall dormitory building located on the University Of Mississippi campus[11]. The footing detail model includes the infinite elements as transmitting boundary conditions. The column connecting to this footing has been modeled with the static forces from the building applied to the top of the rigid column. The cap model [4] has been employed as a nonlinear material for the soil. The master sub-model is the soil and the slave sub-model is the footing. The earthquake loading has been applied at the base of the soil. The deformed shape of the model showed in Figure 8. It is clear from the figure that this technique has captured most of the local nonlinear behavior in the interface between soil and footing.

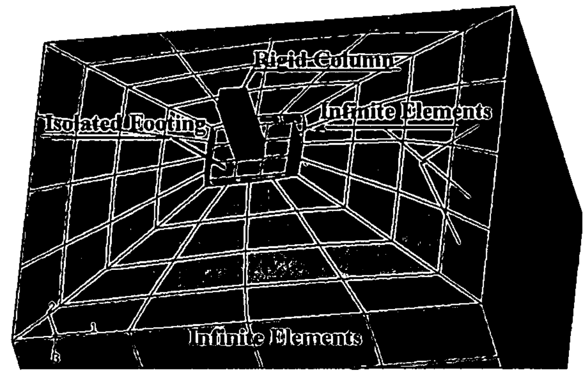

Fig. 8. 3-D Deformed FE Model of Isolated Footing

Advantages of Contact Surface Approach

We may summarize the findings of the nonlinear response studies as follows:
1. No interface elements are required which reduces the total number of elements in the model.
2. The two meshes of the slave sub-model and master sub-model are completely different which means, for example, if we are interesting in the slave sub-model behavior, we can make its mesh finer than the master sub-model one.

PROPOSED FE MODELING PROCEDURE

Based on the preliminary study for the two main problems of the SSI modeling, the following FE model has been developed by FE code ABAQUS for a typical three-story reinforced concrete building.

Specifications of the Building. A three-story office building located in north Mississippi has out side dimensions of 72 ft x 40 ft. It consists of three panels of 24 ft; by two bays with panels of 20 ft are to be designed in accordance with the Standard Building Code [10].

Building SSI Model. ABAQUS FE models were developed as shown in figure 9 using a Patran graphical user interface for the building and the surrounding geology. The mesh for the complete model has 11155 elements. For the sake of convenience in modeling, the model is broadly classified into the following groups:

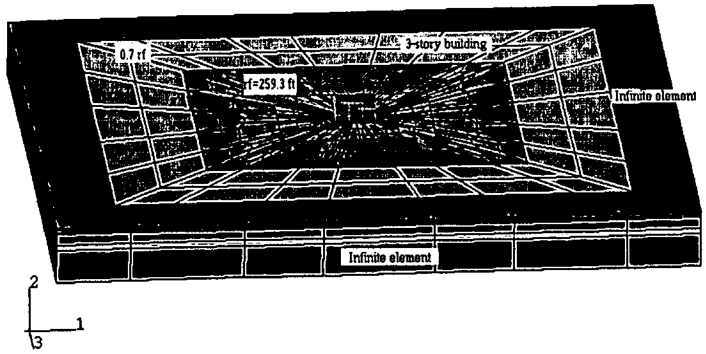

Fig. 9. 3-D Detailed FE Model of 3-Story Building

Floor Slabs. The floor slabs, which are 7.5 inches in thick, are modeled using four nodded bending elements. The slab mesh is finer near the edges and courser in the center.

Beams and Columns. The beams and columns are modeled with beam element, which has 6 degrees of freedom per node. Due to the fact that 1-D modeling is used for the columns and beams, there is a difference in elevation between the tops of the columns and the beams. Hence a fictitious beam-column element is used to provide a rigid connection between them. These elements are given in-plane flexural rigidity values about ten times of the topmost elements of the columns to more closely resemble the stiffness of the haunches.

Footings. All the footing in the building is isolated reinforced concrete footing, each footing modeled by eight 3-D rectangular prism elements in two layers each layer is four elements.

Soil. The soil underneath and around the building, are modeled using 3-D rectangular prism elements. The depth of the modeled soil is 100 feet [3] with three layers. The properties of the soil layers and the equivalent one as shown in table 1.

***Table 1.** Soil Properties*

Layer	Thickness (ft)	Density (Kips/ft^3)	V_s (ft/s)	Poisson's ratio	E (Kips/ft^2)
1	30	0.12	554.0	0.33	1939.03
2	10	0.11	986.92	0.317	9056.37
3	60	0.12	1233.0	0.35	15023.5
Equiv. layer	100	0.12	885.38	0.341	7356.79

Soil-Structure Interface. Based on the preliminary study the contact-surface approach has been used to model the soil-structure interface, The footing and the surrounding soil were modeled as master and slave sub-models as in figure 10. The mesh of the footing and the soil are different. Based on the soil properties a friction coefficient of 0.2 has been applied between the soil and the footing. Very rigid fictitious four nodded shell elements are used at the middle of the footing thickness connected to the column to provide a rigid connection between the column and the footing.

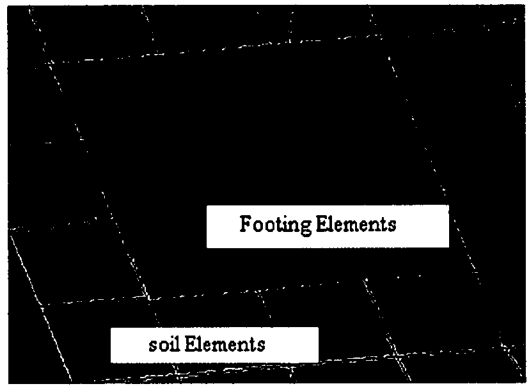

Fig. 10. SSI modeling for One of the Footings

Infinite Elements. Based on the properties of the equivalent soil layer the r_f of the model is 259.3 feet. According to the results of the preliminary study and in order to have a well performance from the infinite elements as transmitting boundary conditions, soil should be modeled up to 450 feet from the center of the building in the all directions.

Linear Springs Model. According to FEMA guidelines [3], the SSI analysis can be performed for the structure seismic analysis by replacing the foundation and the soil by six linear springs, three for the translation degrees of freedom and three for the rotation ones. These Linear spring coefficients depend on the geometry of the footing and soil properties. Another model with FEMA linear springs has been developed for the same building.

EIGEN MODE ANALYSIS OF 3-STORY BUILDING

Upon completion of the structural model, a check for stability with a fixed-base static (self-weight) analysis was performed. After verification of the adequacy of the model, an eigen value (natural frequency) extraction was performed in order to obtain an idea of the behavior of the first three modes. Then, a comparison between the eigen values of the fixed-base model, the model with linear springs and the detailed model with the soil layers.

The results of the first three eigen modes for the three models are shown in table 2. From this table it is clear that the fundamental frequency of the fixed-base structure was found to be 1.34 Hz, giving the structure a natural period of 0.74 sec. Also, the natural frequencies of the spring model are nearly the same as fixed base one, which means there is no effect of the SSI in the spring model. The big difference in the natural frequencies between the detailed model with the soil layers and the other ones are due to the big mass of the soil in the model. Figure 11 and figure 12 show the first modes of the spring model and the detailed model respectively.

Table 2. Eigen Mode Analysis

Model	Mode	Frequency (Hz)	Description
Fixed-base	1	1.34	Translation in X-dir.
	2	1.69	Torsion
	3	1.75	Translation in Y-dir.
Linear Spring	1	1.30	Translation in X-dir.
	2	1.65	Torsion
	3	1.70	Translation in Y-dir
Detailed with soil	1	1.20	Translation in X-dir.
	2	1.38	Torsion
	3	1.39	Translation in Y-dir

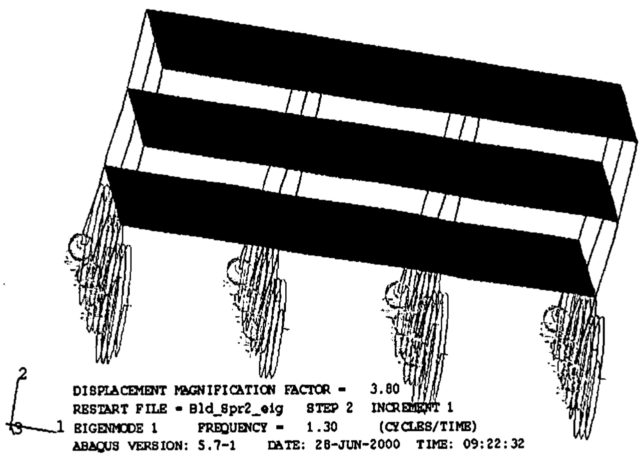

Fig. 11. First Eigen Mode of Spring Model

Fig. 12. First Eigen Mode of Spring Model

CONCLUSIONS

A computational procedure for modeling soil-structure interaction has been proposed based on wave propagation studies of footing type problems with large scale finite element models of building systems in mind where mesh design is a critical aspect of the analysis. The effective use of the procedure is demonstrated for a 3-D model of a typical building system.

The proposed procedure includes radiation damping through infinite elements, contact surfaces at footing / soil interfaces, and local nonlinear material response of the soil around the footing. These features are only approximately incorporated in conventional analysis with linear discrete springs.

Results of eigen mode analysis show reasonable agreement with the conventional approach for the undamaged state of the system. Subsequent time history analysis will demonstrate the utility of the proposed procedure for damaging seismic loading.

NOMENCLATURE

The following symbols are used in this paper:

A = Cross sectional area of the rod .
c = Wave velocity in the rod.
c_p = Dilatational wave velocity.
c_s = Shear wave velocity .
d = Dashpot coefficient..
d_n = Dashpot coefficient in normal direction.
d_t = Dashpot coefficient in tangential direction.
E = Material Young's modulus of the rod.
r_f = Far field radius.
u = Displacement of the rod
U = Displacement of Lamb problem.
U_0 = Displacement at disc radius of Lamb problem.
ρ = Material density.
ρ_{rod} = Material density of the rod.
ρ_{inf} = Material density of the Infinite Element

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