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SOIL STRUCTURE INTERACTION ANALYSES BY DIFFERENT METHODS

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The paper is a contribution to the continued discussion on appropriate methods for seismic soil-structure interaction analysis.

A circular PWR-building is analized using a plane strain finite element model, an axisymmetric finite element model, and a lumped parameter model. The structure weighs 1600 MN, it is about 65 meters high, 60 meters in diameter, and very stiff. It is founded 18 meters below the ground surface on alluvial deposits which are several hundred meters thick.

The plane strain finite element analysis is of the type commonly used in the U.S.A., e.g. with the program FLUSH. It utilizes the transmitting boundaries developed by the first author to account for radiation damping. The control motion is assumed at the ground surface in the free field. The seismic input at the base of the model is obtained from the control motion by one-dimensional deconvolution. Strain compatible dynamic soil properties are computed by equivalent linear analysis.

The axisymmetric finite element analysis (with non-axisymmetric loading) is similar to the plane strain analysis. It also uses a transmitting boundary and the same input motion computed by deconvolution.

In the lumped parameter model, the flexibility and damping due to the subgrade is represented by soil springs and dashpots based on halfspace theory. The spring constants are adjusted for embedment. The control motion is directly applied as support acceleration according to common use in Germany.

The lumped parameter model yields structural accelerations much larger than both the finite element models. However, results similar to those of the axisymmetric finite element analysis can be obtained by the lumped parameter model when the control motion is not directly used as support acceleration, but modified using one-dimensional deconvolution to account for the variation of the free field ground motion with depth.

The development of an equivalent two-dimensional finite element model for a basically axisymmetric system is very difficult. At least some advance knowledge of the response of the actual three-dimensional system ist required when the equivalent width and length of the embedded structure is to be selected. In general, it is not possible to match the resonance frequencies of the rigid body modes of the structure as well as their damping values. The quality of the two-dimensional finite element results depends strongly on the availability of three-dimensional solutions to similar problems and on the skill and intuition of the analyst.

1. Introduction

Soil-structure interaction effects during earthquakes are usually analized by one of two methods. In the finite element method the soil surrounding the structure is represented by finite elements, whereas in the spring or lumped parameter method the soil is substituted by singular springs, dashpots and sometimes added soil mass.

The "pros" and "cons" of both methods have been frequently discussed, e.g. /4.6.9/. The major issues are:

- embedment of the structure in the ground influencing the resonant frequencies of the structure and the damping of its motion as well as the effective earthquake input motion;
- layering of the soil influencing the radiation damping in the ground and to some extent the resonant frequencies of the structure;
- representation of the three-dimensional character of the interaction problem;
- effects of nonlinear soil behaviour.

The availability of suitable finite element programs, of analytic or numerical solutions for springs and dashpots and the particular experience of the engineers have affected the arguments used on both sides.

A considerable amount of research during the recent years, however, has improved the state of the art of soil-structure interaction analysis to a point where both methods will lead to a safe design when skillfully used with engineering judgement. The finite element method and the spring method will yield similar results when the basic assumptions with respect to the input motion are compatible and when the stiffness and damping characteristics of the interaction problem at hand are properly modelled /9/. However, several questions regarding the proper modelling still lack a complete answer.

Finite element programs like LUSH and FLUSH, which have been used in earthquake analyses of several nuclear power plants in the U.S.A., are basicly limited to two-dimensional plane strain models. There have been few investigations so far on the adequacy of plane strain models for three-dimensional interaction systems. Luco and Hadjian /10/ found that a plane strain model could only partially reproduce the vibrational behaviour of an axisymmetric structure founded on the surface of a homogeneous halfspace. Kausel and Roesset /6/ and Berger, Lysmer and Seed /1/ obtained fair agreement between the results of a plane strain and an axisymmetric finite element analysis for a stiff heavy structure embedded in a relatively shallow soil deposit.

It ist the purpose of this paper to study the adequacy of a plane strain finite element analysis of a typical German PWR reactor building partly embedded in a deep soil deposit by comparison with an axisymmetric finite element analysis and to demonstrate that a simple lumped parameter model can yield stisfactory results for preliminary analysis and design.

2. Finite Element Analyses

Fig. 1a outlines a heavy circular PWR reactor building founded 18 meters below the ground surface on a moderately stiff soil deposit of great depth. The structure is about 65 meters high, 60 meters in diameter, weighs 1600 MN, and is very stiff.

The earthquake excitation is prescribed at the free ground surface by an acceleration time history matching the US-NRC standard response spectra. The peak horizontal acceleration is 2 m/s^2.

One-dimensional deconvolution is used to compute iteratively by equivalent linear analysis strain compatible shear moduli and damping values in the different soil layers as well as the base acceleration $\ddot{U}_B$ indicated in Fig. 1a. The damping values of the soil are about 10 % throughout the deposit; the shear moduli are given in Fig. 1a.

The right part of Fig. 1a shows the axisymmetric finite element model for the structure and the soil. A transmitting boundary, originally developed by the first author for plane and axisymmetric systems [15] and later extended by Kausel for more general motion [8], represents the lateral soil extending to infinity. It accounts for the dynamic response of the horizontally layered soil deposit including the spring action as well as the radiation and material damping. The transmitting boundary is based on wave propagation theory in a layered elastic or viscoelastic medium and it can be shown to correspond precisely to an infinite number of columns of finite elements surrounding the core region. It significally reduces computational costs and computer storage requirements.

A complete interaction analysis is performed in one step using transfer functions in the frequency domain and fast numerical Fourier transformations to obtain the time history response of the structure to the horizontal base motion $\ddot{U}_B$ computed from the prescribed surface motion $\ddot{U}_S$.

The depth of the rigid base, which is nonexisting in reality, is chosen large enough not to influence the structural response. This is checked by increasing the depth of the rigid base.

Results of the axisymmetric analysis (3-D) are shown in Fig. 2 for the horizontal motion at the top of the external structure and at the foundation level as well as for the rocking motion of the foundation in form of response spectra for 7 % equipment damping. The axisymmetric results are computed before the plane strain analysis is performed.

Fig. 1b shows an equivalent plane strain model which makes use of the symmetry around the center line. The structure is modelled by two shear and bending beams and lumped masses with translational and rotational inertia. The embedded part of the structure is represented by finite elements without mass. All mass is associated with the lumped masses.

The dimensions of the structural model in the plane of motion are equal to the actual dimensions of the structure. The equivalent width of the structure is determined by comparing various solutions for spring constants and damping characteristics of circular and strip footings on the surface of a homogeneous halfspace [11 - 14] and embedded in a homogeneous layer [2,3,5,7]. In spite of a considerable effort to match the known fundamental frequency and the damping of the axisymmetric model by a proper choice of the equivalent width in the very first try, the width had to be varied to obtain the relatively good agreement between the plane strain and axisymmetric results shown in Fig. 2.

Additional adjustments of the plane strain model had to be made in order to eliminate incorrect coupling of the structural beams to the finite elements representing the embedded part of the structure.

Fig. 2a and b show that the plane strain model (2-D) underestimates the rocking motion and overestimates the horizontal motion of the foundation. The effects almost compensate each other at the top of the external structure. The axisymmetric solution (3-D) for the top of the external structure shows a minor peak at 6 Hz due to a natural antiphase bending mode of the external and internal structures with a significant bending contribution of the foundation mat. This mode does not show up in the 2-D results as the flexibility of the foundation mat cannot be adequately represented by the plain strain model. If the plane strain analysis were performed independently without knowledge of the axisymmetric solution, the agreement of the results would likely be less satisfactory.

In order to check the structural beam model shown in Fig. 1 b and Fig. 5 against the finite model of the structure shown in Fig. 1a, the translational and rotational motion of the foundation mat computed by the axisymmetric finite element model is imposed on the beam model. The results for the top of the external structure are also shown in Fig. 2a. They agree well with those of the axisymmetric finite element model. Since smaller changes of the structural model do not change the foundation motion, involved soil- structure interaction analyses need not be repeated when the structural model is slightly altered or refined.

3. Lumped Parameter Analyses

Soil-structure interaction analyses for nuclear power plant structures are commonly performed in Germany using lumped parameter models. Constant soil springs are usually chosen to make modal analysis possible. Modal damping is computed by averaging the structural damping and the radiation and hysteretic damping in the soil according to the distribution of strain energy in each mode. The radiation damping in each mode is either computed under the assumption of viscous soil dashpots or directly from the frequency dependent impedance functions of a rigid footing on an elastic halfspace. The modal damping which may be used according to a German guideline is limited to values not greater than 15 %.

Fig. 3 shows results obtained using a lumped paramter model for the same reactor building analized before. The response spectrum at the top of the external structure is about twice as high as that of the axisymmetric finite element model (3-D) when the modal damping is limited to values less than 15 %. If the modal damping is not limited - 25 % damping is computed for the first mode at 1.8 Hz and 30 % damping for the second mode at 3.4 Hz - the results are still significantly higher than those of the finite element analyses.

One reason for this big difference in the results may be that the actual radiation damping is larger than that computed from halfspace theory due to embedment effects. The main reason, however, is that the free field surface motion $\ddot{U}_S$ is applied as support motion to the lumped parameter model, whereas the effective earthquake excitation in the finite element analysis is much smaller, since it accounts for the variation of the free field motion with depth. Fig. 7 shows that the spectrum of the free field motion at the foundation level $\ddot{U}_F$ is markedly smaller than that of free field motion at the ground surface $\ddot{U}_S$.

In order to obtain for the lumped parameter model an input motion which is compatible with that used in the finite element analysis, it is necessary to consider the kinematic interaction in a first step and the inertial interaction in a second step. (Fig. 4).

The kinematic interaction describes the response of the rigid, massless structure to the input motion. For an embedded foundation this includes both translations and rotations. In the second step the soil-structure system is subjected to fictitious inertia forces computed from the accelerations of the kinematic interaction and the masses of the structure. The result defines the inertial interaction. Superposition of the two steps then yields the total solution [6, 9].

The two steps require, in general, finite element methods. However, reasonable results can also be obtained using approximations. Representing the kinematic interaction, an average acceleration weighted over the soil-structure interface with horizontal and rotational components is computed from the free field motion, considering its variation with depth (Fig. 5, 7). The inertial interaction is computed with a lumped parameter model with constant soil springs and dashpots (Fig. 6).

The response spectra computed according to this method show good agreement with those of the finite element analyses, better than the others computed with surface motion input (Fig. 3). The spectral accelerations still exceed those of finite element analyses but these differences might be further reduced by considering the effects of embedment on damping.

Conclusions

1. The interaction of a partly embedded axisymmetric reactor building with the sur-

rounding soil may be analized by a plane strain two-dimensional finite element model. However, it is very difficult to find an equivalent plane strain model that matches the basic response of the three-dimensional system to be analized. At least some advance knowledge of the response of the actual three-dimensional system is necessary for selecting an equivalent width and length of the structure in a two-dimensional soil-structure interaction model.

2. The coupling of a beam or a three-dimensional structural model to the two-dimensional soil model requires special attention and imposes additional constraints. The flexibility of the foundation mat and the external walls in contact with the soil can at best be approximated.

3. The translational and rotational motion of the foundation mat computed by the axisymmetric finite element model may be applied as input motion to the lumped parameter model with rigid soil springs giving almost the same structural response as the three-dimensional finite element model. Therefore, costly and time consuming soil-structure interaction analyses by finite elements need not be repeated when minor changes of the structural model are necessary or when the structural model has to be refined.

4. The response of the lumped parameter model strongly exceeds that of the three-dimensional finite element model when the free field surface motion is applied as support motion, particularly if the modal damping is limited to values less than 15 % of critical damping according to common practice in Germany.

5. The response of the lumped parameter model agrees well with that of the three-dimensional finite element model when the support motion is the free field soil motion averaged over the soil-structure interface. The translational and rotational components of the support motion account in an approximate manner for the variation of the free field motion with depth and the kinematic interaction. They can be easily derived from the one-dimensional deconvolution of the specified surface motion. The structural response may be computed in the time domain by modal analysis using frequency independent soil springs. The outlined procedure is particularly suited for preliminary analysis and design as it is inexpensive, quick and thus permits extensive parametric studies.

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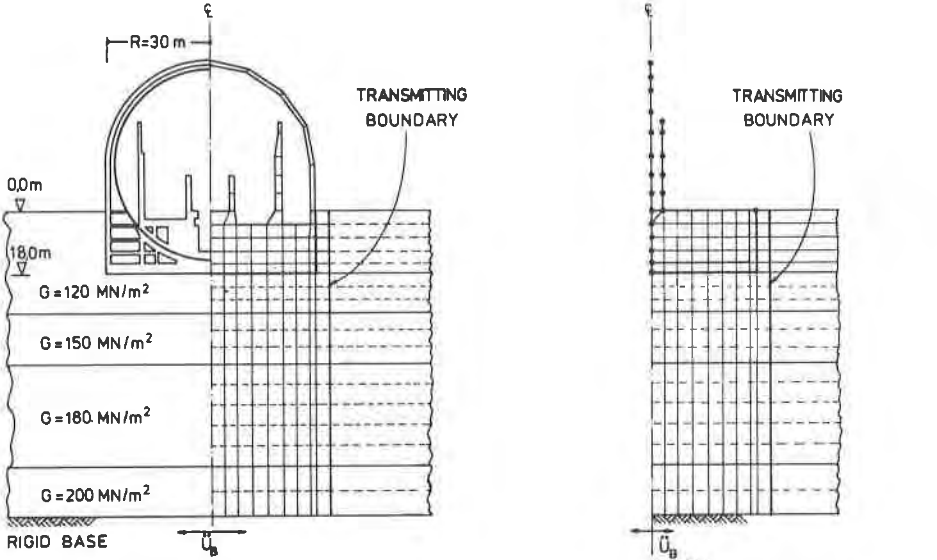

a) AXISYMMETRIC MODEL (3-D)

b) PLAIN STRAIN MODEL (2-D)

Fig. 1 Finite Element Models

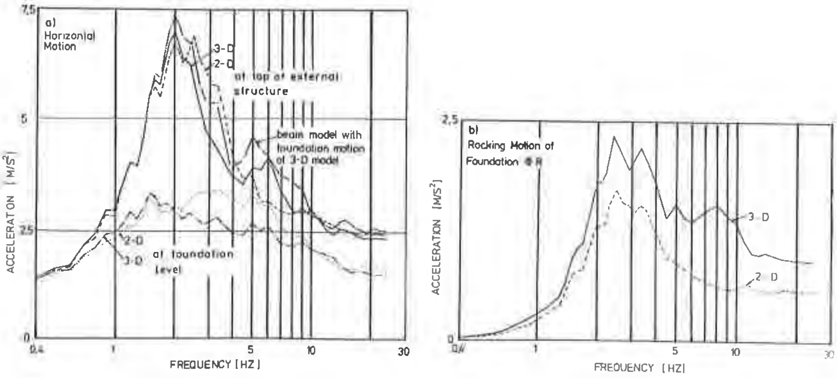

Fig. 2 Response Spectra for 3-D and 2-D Finite Element Models (7 % Damping)

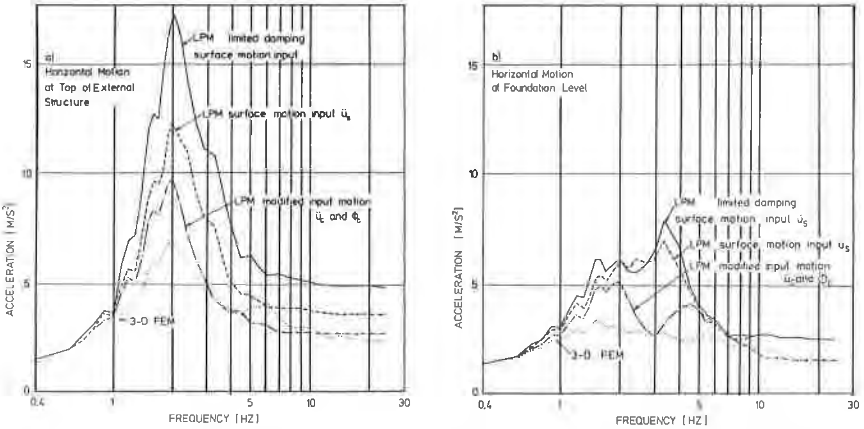

Fig. 3 Response Spectra for Lumped Parameter and Finite Element Models (7 % Damping)

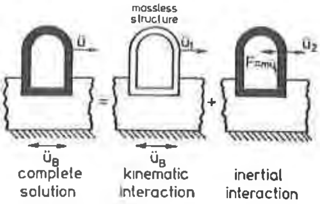

Fig. 4 Superposition Theorem

Fig. 6 Lumped Parameter Model

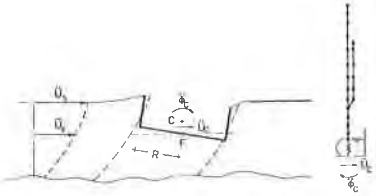

Fig. 5 Kinematic Interaction Problem

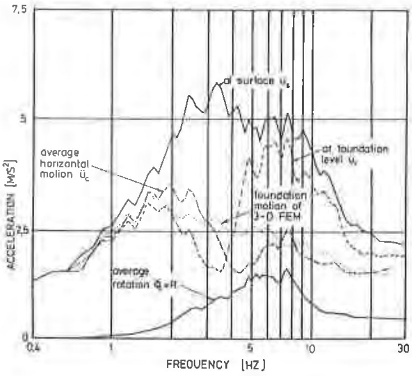

Fig. 7
Response Spectra of Free Field Soil Motion and of Foundation Motion (7 % Damping)