SOIL-STRUCTURE INTERACTION ANALYSIS
BY FINITE ELEMENT METHODS
STATE-OF-THE-ART

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SUMMARY

Analyses of soil-structure interaction effects during earthquakes for nuclear power plant structures are usually made by one of two methods—either by means of an idealized complete interaction analysis involving consideration of a compatible variation of motions in the structure and the adjacent soil, or by means of an inertial interaction analysis in which the motions in the adjacent soil are assumed to be the same at all points above the foundation depth. For surface structures, the distribution of free-field motions with depth in the underlying soils has no influence on the structural response and thus, provided the analyses are made in accordance with good practice, good results may be obtained by either method of approach. For embedded structures, however, consideration of the variation of motions with depth is essential if adequate evaluations of soil and structural response are to be obtained without undue conservatism.

The finite element analysis procedure is particularly well suited for evaluating the response of embedded structures since it can readily provide consideration of the variation of soil characteristics with depth, the different non-linear deformation and energy absorbing capacities of the various soil strata, the variation of motions with depth in accordance with the general principles of engineering mechanics, the three-dimensional nature of the problem and the effects of adjacent structures on each other.

At the present time analyses incorporating the above considerations may be made for (1) an axi-symmetric structure in an extensive soil deposit; (2) an axi-symmetric structure where the extensive soil deposit is represented by a relatively small mesh equipped with transmitting boundaries; (3) a plane strain analysis of a structure in a soil deposit equipped with transmitting boundaries; (4) an approximate three-dimensional analysis of multiple structures where radiation damping effects are represented by transmitting and viscous boundaries; (5) a probabilistic three-dimensional analysis of multiple structures using a relatively small mesh with transmitting and viscous boundaries. All of the above analyses are customarily made for vertically propagating waves. However consideration can now be given to non-vertically incident waves and to horizontally propagating waves in the analysis procedures.

While the cost of such analyses has been high in the past, the development of increasingly efficient computer programs now seems to have overcome this limitation.

It is believed that these procedures provide a powerful tool for use in the design of nuclear plants. However like all such procedures they must be used with an intimate knowledge of the technical details which can be built into the various computer programs and which are necessary for adequate modelling of soil-structure systems. Used in this way and in conjunction with good engineering judgment they can provide evaluations of response with a level of accuracy entirely adequate for engineering design, as evidenced by the recent completed study of the strong motions developed at the Humboldt Bay Power Plant in the Ferndale earthquake of June 1975.
Introduction

Analyses of soil-structure interaction effects during earthquakes for nuclear power plant structures are usually made by one of two methods—either by means of a complete interaction analysis involving consideration of the variation of motions in the structure and the adjacent soil, or by an inertial analysis in which the motions in the adjacent soil are assumed to be the same at all points above foundation depth. For surface structures, the distribution of free field motions with depth in the underlying soils has no influence on the structural response and thus, provided the analyses are made in accordance with good practice, good results may be obtained using either method of approach. For embedded structures, however, consideration of the variation of ground motions with depth is essential if adequate evaluations of soil and structural response are to be obtained without undue conservatism.

At the present time, a variety of methods of analysis including these effects have been developed using finite element techniques. Not only do finite element methods provide an excellent tool by means of which the significant aspects of an idealized complete interaction analysis for embedded structures may be considered with a high degree of accuracy on theoretical grounds, but recent observations of the response of the Humboldt Bay Nuclear Power Station to strong shaking induced by the Ferndale, California earthquake of June, 1975 show that this method of approach provides response evaluations which are in good accord with those observed under field conditions.

This does not mean that all finite element analyses of soil-structure interaction provide adequate evaluations of response. Like all analyses, they can be performed with different degrees of approximation or sophistication. The basic requirements for a good analytical procedure may be summarized as follows:

1. The analysis should consider the variation of soil characteristics with depth for the soil profile existing at the proposed site.
2. The analysis should consider the non-linear and energy-absorbing characteristics of the different soil strata comprising the soil deposit.
3. For embedded structures, the analysis should consider the variation of ground motions with depth; this variation should be consistent with established theories of engineering mechanics for evaluating the response of the continuous soil-structure system and be in reasonable accord with available knowledge concerning the variation of ground motion characteristics with depth during earthquakes.
4. The analysis should be capable of taking into account the three-dimensional nature of the problem.
5. The analysis should be capable of considering the effects of adjacent structures on each other.

It is not always necessary to meet all of these requirements—for example, where a simple structure is involved, accurate evaluations of the motions at the base of a structure can be obtained using a two-dimensional analytical model—but, in general, all of the requirements listed above should be taken into account.

One of the primary arguments against the use of finite element methods of analysis is their high cost. This of course depends on the efficiency of the computer program used but it is true that in the recent past, analyses of this type have been substantially more costly.
than analyses using the inertial interaction approach in conjunction with half space theories. This limitation now seems to have been overcome through the development of more efficient computer techniques.

It is the purpose of this paper to review the current level of accomplishment which may be achieved using finite element techniques for the performance of complete interaction analyses. It is hoped to show that they provide an efficient procedure for evaluating translational, vertical, and rocking modes of excitation in accordance with all the desirable requirements listed above without incurring excessive costs for design and analysis.

Two-dimensional Finite Element Analyses

A complete analysis of the soil-structure interaction problem would involve a determination of the response of a structure when it is subjected to earthquake ground motions which vary from point to point in the soil and rock around and underlying the structure and travel in some unknown way across the base of the structure (see Fig. 1).

This admittedly complex problem is usually idealized for purposes of analysis so that motions in the vicinity of the structure are considered to be due to vertical propagation of body waves from underlying stiffer formations. This is clearly an approximation and is justified on the grounds that (1) it is believed to be sufficiently accurate for engineering purposes; (2) there is a growing body of evidence to show that variations of motions with depth computed in this way are in reasonable accord with field observations of ground response during actual earthquakes; and (3) for computations of translational, vertical and rocking modes of structural response, the assumption that all ground motions are due to vertically propagating shear waves is conservative (Lusco, 1977).

On the basis of the above approximation, finite element analysis procedures satisfying the first three of the basic requirements for an adequate procedure have been available for a number of years (Seed et al, 1974 and 1975). A control motion, specified at some point in the free-field soil profile, can be deconvolved to determine the corresponding motions at some depth, such as a soil-rock interface. One dimensional amplification theory can be used for this purpose (Schnabel et al, 1972a and 1972b). Then the motion computed at this depth is used as input to a finite element model of the soil-structure system, and the response computed at points of special interest. Another method of approach is to compute transfer functions relating the motions and forces at desired points in the soil or structure to the control motion applied at a point on the surface of the soil well away from the structure (Kausel and Roesset, 1974). In either case, the analysis should be performed iteratively to allow for the strain dependent nature of the nonlinear soil characteristics (Seed and Idriss, 1969; Schnabel et al, 1972). In each iteration the analysis is linear but the soil properties are adjusted from iteration to iteration until the computed strains are compatible with the soil properties used in the analysis.

Using this approach, different soil properties may be assigned to every element, if desired, so that there is no difficulty in considering the variation of soil characteristics with depth, while the iteration procedure permits consideration of the non-linear stress-strain and damping characteristics of the soils. In order to control the damping ratios to the desired values it has been found desirable to use the complex response method of analysis,
and the computer program LUSH (Lysmer et al., 1974) has been widely used for analyses of this type. Other methods of analysis (modal analyses, methods using Rayleigh damping, etc.) do not provide the necessary freedom to adjust damping ratios to specified values in each element.

In the LUSH-approach the soil-structure system is represented as a two-dimensional finite element model. It has been shown that such two-dimensional representations of the soil-structure system can provide good evaluations of the response at the base of the structure (Berger et al., 1975) but, not necessarily within the structure. Thus in order to obtain adequate evaluations of response using this approach it has been necessary to compute the overall response of structures which cannot be considered plane in two stages: (1) a two-dimensional analysis of the soil-structure system to determine the motions in the portion of the structure below the ground surface and (2) a three-dimensional analysis of the structure to determine its response to the base motions computed in stage (1).

Clearly the main limitations of this approach are that it fails to satisfy fully the last two requirements listed on page 2, i.e. full consideration of the three-dimensional nature of the problem and the ability to satisfactorily evaluate the effects of adjacent structures. In addition, computer costs for extensive systems have been very considerable. Accordingly, the following modifications have been made to remedy these deficiencies, leading to a more versatile and efficient analysis procedure.

Three-dimensional Effects

In recognition of the need to consider the three-dimensional nature of the soil-structure system, finite element analysis procedures for axisymmetric structures have been developed by several investigators (Ghosh and Wilson, 1969; Agrawal et al., 1973; Kausel and Hoesset, 1974; Berger et al., 1975). The analytical problem involved is illustrated schematically in Fig. 2. In making such analyses it is necessary to ensure that the boundaries of the finite element model are sufficiently far removed from the structure that the full effects of radiation damping are correctly represented (Berger et al., 1975). Alternatively, the analytical model may be provided with transmitting boundaries which absorb any wave effects emanating from the structure and thus simulate the effects of an extensive soil deposit (Kausel and Hoesset, 1974).

While some three-dimensional effects may be considered in this way, solutions cannot be obtained once the axi-symmetric nature of the structure ceases to exist; this might occur, for example, in the simple case of two adjacent structures, each axi-symmetric but the combined system no longer having axi-symmetric characteristics. In a nuclear plant involving many different types of structures, axi-symmetric situations are the exception rather than the rule and other methods of approach are required. Never-the-less the axi-symmetric solutions provide an essential standard by means of which the validity of other approaches may be judged and in this respect represent a vital aspect of the development of analytical techniques.

An alternative method of approach for including the three-dimensional features of a soil-structure system is that suggested by Hwang et al. (1975). The method involves the use of viscous boundaries along the planar surfaces of a slice of soil on which one or more structures are located. This idealization of the soil-structure system is illustrated schematically in Fig. 3.
If the soil slice is made sufficiently long, then wave energy radiating along the axis of the slice will be absorbed by material damping while energy radiating in a direction normal to the axis of the slice will be absorbed by the viscous boundaries. It has been shown that this form of analytical model for a single structure provides essentially the same response values as an analysis for an axi-symmetric system such as that shown in Fig. 3 (Hwang et al., 1975). The method also has the advantage that it is considerably faster than the axi-symmetric analysis because it uses only two as opposed to three degrees of freedom per nodal point.

The dimensions of the finite element mesh illustrated in Fig. 3 may be drastically reduced if the model is provided with transmitting boundaries at the ends, as shown schematically in Fig. 4. The analytical model illustrated in Fig. 4 has the added advantage that it can be used to compute the combined response of multiple structures having the same width as the soil slice. This might involve, for example, two rectangular structures of approximately equal widths standing side by side. Such a system could not be analyzed using an axi-symmetric analysis formulation but the three-dimensional effects for adjacent structures can readily be included using the model formulation shown in Fig. 4.

**Effects of Building-Building Interaction**

The necessity of considering the interaction between adjacent structures in evaluations of structural response has also been demonstrated using finite element techniques (Lysmer et al., 1975). In one case examined, it was found that the presence of the adjacent structures increased the maximum response of the containment building by about 60 percent, a substantial effect, but considerably less than that which would be indicated by a two-dimensional analysis of the soil-structure system, thereby confirming the need for consideration of the effects of adjacent structures but only by procedures which can give consideration to the three-dimensional nature of the problem.

Three-dimensional analyses of the type illustrated in Fig. 2 may be performed by such computer programs as ALUSH (Burger, 1975) while analyses of the type illustrated in Figs. 3 and 4 can be performed using the computer program FLUSH (Lysmer et al., 1975). This latter program incorporates the following features:

1. Viscous boundaries are provided to represent three-dimensional effects.
2. Transmitting boundaries are provided to minimize the required number of finite elements.
3. An out-of-core equation solver is available, making it possible to solve large problems on a relatively small computer.
4. Linear bending elements are provided for better modelling of basement walls and structural frames.
5. A capability to perform the deconvolution of near surface motions within the program using the same finite element mesh as that used for the soil-structure interaction analysis.

Since this program is considerably faster than the original LUSN program it has been called FLUSH (for Fast LUSN). The increase in speed can be judged from the approximate relative computer times for different analytical approaches now available listed in Table 1. Furthermore for particularly deep soil profiles, a transmitting boundary may be incorporated along
the base, if required, to provide radiation damping effects equivalent to a half-space. Experience shows that this is rarely necessary due to the material damping characteristics in the soil layers themselves.

**Table 1**

<table>
<thead>
<tr>
<th>Type of Analysis</th>
<th>Computer Program</th>
<th>Relative Computer Time</th>
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<tbody>
<tr>
<td>Axi-symmetric analysis with extensive mesh (deterministic)</td>
<td>ALUSH</td>
<td>1.00</td>
</tr>
<tr>
<td>Axi-symmetric analysis with transmitting boundaries (deterministic)</td>
<td>(after Kaufel)</td>
<td>0.50</td>
</tr>
<tr>
<td>Plane strain analysis with extensive mesh (deterministic)</td>
<td>LJUSH</td>
<td>0.35</td>
</tr>
<tr>
<td>Plane strain analysis with transmitting boundaries (deterministic)</td>
<td>FLUSH</td>
<td>0.19</td>
</tr>
<tr>
<td>Three-dimensional analysis with viscous and transmitting boundaries (deterministic)</td>
<td>FLUSH</td>
<td>0.20</td>
</tr>
<tr>
<td>Three-dimensional analysis with viscous and transmitting boundaries and deconvolution through finite element mesh (deterministic)</td>
<td>FLUSH</td>
<td>0.10</td>
</tr>
<tr>
<td>Probabilistic three-dimensional analysis with viscous and transmitting boundaries</td>
<td>FLUSH</td>
<td>0.03</td>
</tr>
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</table>

**Probabilistic Analysis for Single Control Motion Specification**

In the design of nuclear power plants, the control motion for the seismic soil-structure interaction analysis, often termed the Design Basis Earthquake, is defined in the form of a response spectrum of specified shape. The designer can then develop, for analysis purposes, any reasonable time-history of motions which has a spectrum falling above that specified for the control motion. Analyses performed using such a time-history are deterministic in nature, although parametric studies, particularly involving variations in soil properties, are customarily required for the determination of design motions in the plant itself.

In fact, there are theoretically an infinite number of time-histories of motion whose spectra would have the form prescribed by the control motion and the use of different time histories will lead to some degree of variation in the computed response. To determine the magnitude of these possible effects, a new probabilistic analysis procedure has recently been developed, based on the finite element analysis approach used in the program FLUSH, but incorporating in a probabilistic way, all possible time-histories of motion having a response spectrum corresponding to that of the design basis earthquake (Romo-Organista et al, 1977). The computer program for accomplishing this has been named PLUSH (Probabilistic LUSH).

The procedure eliminates the need for generation of any time history of motion, it presents response data in probabilistic form in terms of confidence limits, and it permits the analysis to be made still more efficiently than following a deterministic procedure (see Table 1). It is believed that the capability to present potential variations in structural response in this way aids considerably in selecting criteria for structural design.

**Non-vertical Wave Effects**

In recent years there has been much discussion concerning the possible need to consider motions other than vertically-incident shear and compression waves in the evaluation of soil-
structure interaction effects. Methods of considering non-vertically incident waves for evaluating ground response (Joyner et al, 1976), horizontally propagating motions in soil deposits (Iseberg, 1970; Chen, 1976), horizontally propagating motions at the base of soil deposits (Udaka, 1975) and non-vertically incident shear waves (Luco, 1976) on soil-structure interaction have all been developed and are available to the designer.

It is the general conclusion of these studies that for design purposes, vertically propagating waves provide an adequate evaluation of response for engineering design purposes. For example, Joyner et al (1976) found that the angle of incidence of wave motions to the rock boundary at the base of a soil deposit had virtually no effect on the response of the deposit; Udaka (1975) found only slight differences in horizontal motions in a reactor containment structure whether the analysis was made for travelling base motions or rigid base motions; and Luco (1976) found that vertically propagating waves (for translational and rocking motions) provided a somewhat more conservative evaluation of structural response than non-vertical wave motions.

Thus although finite element analysis techniques are available for investigating these types of motion, the problem seems to be of little practical importance except in so far as it might influence the torsional motions developed on a structure. There does not appear to be any totally rational procedure for evaluating torsional effects at the present time since they are determined by the spatial variations of motions in a soil deposit, and virtually no factual information in the form of recorded data is available on this subject. Thus it is necessary to use simplistic models of torsional interaction effects supplemented by considerable judgment to determine appropriate design criteria for such motions at the present time.

Conclusion

In the preceding pages the authors have attempted to summarize the current capability for evaluating soil-structure interaction effects during earthquakes using finite element procedures. A concise summary of methods available, together with their capabilities and relative costs is presented in Table 1. It is believed that these procedures provide a powerful tool for use in the design of nuclear plants. However like all such procedures they must be used with an intimate knowledge of the technical details which are built into the various computer programs and which are necessary for adequate modelling of soil-structure systems. Used in this way, in conjunction with good engineering judgment, and with full recognition of their limitations (Christian, 1975), they provide evaluations of response with a level of accuracy entirely adequate for engineering design as evidenced by the recently completed study of the motions developed in the Humboldt Bay Power Plant (Valera et al, 1977). This is not meant to imply that other procedures, not involving finite element techniques, cannot provide equally good evaluations of response in many cases. However any method used for evaluating the response of embedded structures should provide the same level of capability; without this, computed responses may need more careful modification on the basis of the judgment of the engineer in order to provide a valid basis for the design of critical structures.
References


Fig. 1 COMPLETE AND IDEALIZED COMPLETE ANALYSES OF SOIL-STRUCTURE INTERACTION.

Fig. 2 SCHEMATIC VIEW OF AN AXISYMMETRIC MODEL.
Fig. 3 SCHEMATIC VIEW OF A SIMPLIFIED 3-DIMENSIONAL MODEL.

Fig. 4 SCHEMATIC VIEW OF A SIMPLIFIED 3-DIMENSIONAL MODEL WITH MULTIPLE STRUCTURES