SOIL-PILE-STRUCTURE-FLUID INTERACTION UNDER SEISMIC LOADS

H. Kamil[I], G. Kost[II], and A. Gantayat[III]

SYNOPSIS

The major problems associated with dynamics of soil-pile-structure-fluid interaction are discussed. State-of-the-art procedures for seismic analysis of structural systems involving soil-pile-structure interaction and fluid-structure interaction are reviewed. The applications of these techniques to large scale problems in light of recent experience by the authors are discussed, with emphasis on the use of soil finite elements and fluid finite elements. The use of probabilistic methods in explicitly treating the uncertainties in soil properties and structural response characteristics are also briefly reviewed.

INTRODUCTION

Soil-pile-structure-fluid interaction under seismic loads has become an increasingly important problem recently due to the growing construction of offshore drilling platforms, underground storage facilities for hazardous materials, and possible future construction of underground nuclear power plants. The overall problem of soil-pile-structure-fluid interaction is so complex that it is not practically possible to touch every facet of the problem and present instant solutions in this short space. The purpose of this paper is to, first, review the state-of-the-art procedures, with emphasis on the merits and demerits of individual techniques. The procedures recently employed by the authors are then discussed, and the effectiveness of the application of soil finite elements and fluid finite elements of the in-house computer system EDAC/ISAS (Integrated Structural Analysis System) to soil-pile-structure-fluid interaction problems is examined. The use of probabilistic methods in quantifying the uncertainties and variabilities in the soil properties and the different possible methods of determining the resulting response variabilities are also discussed.

SOIL-PILE-STRUCTURE INTERACTION

Extensive research efforts have been expended in the general area of soil-structure interaction during recent years. However, only a limited amount of work has been done on the topic of soil-pile-structure interaction.

[I] Dr. Hasan Kamil, Manager-Technical Development, Engineering Decision Analysis Company, Inc., 480 California Avenue, Suite 301, Palo Alto, California 94306

[II] Dr. Garrison Kost, Vice President, Engineering Decision Analysis Company, Inc., 480 California Avenue, Suite 301, Palo Alto, California 94306

[III] Dr. Akhil Gantayat, Manager-Computer Development, Engineering Decision Analysis Company, Inc., 480 California Avenue, Suite 301, Palo Alto, California 94306

Even in the general area of soil-structure interaction, in spite of considerable efforts, the basic issues underlying the problem are still not completely resolved. Confusion and controversy still prevail regarding the appropriateness and effectiveness of the different analytical techniques currently in use. The variabilities and uncertainties in the soil properties have not been explicitly considered, and their dominating influence on the response of structures and equipment has not been rationally taken into account. The basic phenomenological aspects such as wave propagation effects, including effects of surface waves, attenuation effects due to distance from source to site, effects of size of structures in relation to wave characteristics passing across the site, and the actual variation of ground motion accelerations with depth, etc, have not been considered. Also, the nonlinear behavior of soils is included in a very approximate manner in most of the current analytical procedures, if it is at all considered.

The above general considerations are also applicable to the problem of soil-pile-structure interaction. The limited amount of available literature (Ref. 1 through 7) deals mainly with the static aspects of the problem, and explores the dynamics of the interaction only to a limited extent with no attempts to investigate the overall general considerations described above. References 4, 5, 6, and 7 suggest some practical approaches viz-a-viz dynamic modeling of the soil-pile-structure interaction problem. However, there is still considerable confusion regarding the effectiveness of the different approaches with the result that there are no definite ready-to-use procedures available for obtaining reliable results for the response of soil-pile-structure systems to dynamic loads.

Most of the present techniques employ a beam-on-elastic-foundation type approach with an assumed variation of static soil modulus with depth. This approach, based on an assumed deflected shape, is not directly applicable to dynamic problems. The inertial effects corresponding to the mass of piles and the surrounding soil medium are not generally included. The damping effects, especially those corresponding to geometric damping, are not considered. Also, the nonlinear behavior of soils including degradation effects, the P-Δ effects, and the loss of bond between piles and the surrounding soils are completely ignored.

Some investigators have attempted to model the dynamic soil-pile-structure interaction using lumped-mass cantilever type systems with modified spring-dashpot (e.g., with friction-blocks) rheological models with some success (Ref. 6 and 7). Different approaches to model the soil-pile-structure interaction problem were also recently explored by the authors. One of the approaches involves the use of soil elements, developed in-house and incorporated in the general purpose computer system EDAC/ISAS (Integrated Structural Analysis System). Spring type linear elements as well as plane-strain and axisymmetric elements are currently available. An iterative quasi-nonlinear approach is used. A series of analyses are performed for an appropriate consideration of the variation of modal damping, soil-degradation effects, P-Δ effects, and soil-pile bond degression effects. The properties under consideration are modified at each iterative step based on the results of the previous analysis. The procedure is still in the process of application to different problems and definitive conclusions may be reached in the near future.

An attempt is also being made by the authors to explicitly consider the variabilities of important soil parameters and the structural response characteristics by the use of probabilistic techniques, mainly because these variabilities may actually dominate the entire solution. Well-developed techniques exist for considering the variability of a function of random variables, although no attempts have yet been made, to the best of authors' knowledge, to apply these technqiues to soil-pile-structure interaction problem. The probabilistic techniques under study by the authors include the possible use of Jacobians, Monte Carlo techniques, the relationship between the normal and the lognormal probability distribution, and the Taylor Series expansion for the determination of expected value and the variance of response quantities. A desired ultimate objective in using these approaches is to develop combined deterministic-cum-probabilistic procedures, along the general lines of Reference 8.

FLUID-STRUCTURE INTERACTION

The motion of a structure vibrating in fluid results in resisting fluid forces on the structure. These forces are directly related to the inertia of the displaced fluid, the formation of waves, and the propagation of these waves into the surrounding medium. For steady-state harmonic oscillations of the structures, these hydrodynamic resisting forces can be approximated by two parameters, viz, the added mass and the damping. Added mass is obtained by means of inertia mechanisms of the displaced water and the formation of waves. Damping is obtained by means of the mechanism of propagated waves. Both of these parameters are frequency-dependent and have different values corresponding to each degree of freedom of the structural system.

For obtaining a reliable estimate of the response of complex structural systems under seismic loads including their interaction with the surrounding (or contained) fluid, however, more sophisticated techniques are generally necessary. Several investigators have made concerted efforts in applying techniques with different levels of sophistication to the fluid-structure interaction problem (Ref. 9 through 13). Most of these approaches have treated the fluid as a continuum and attempted to explicitly solve the governing wave equations. An alternate approach is to treat the fluid as an assemblage of finite-elements. An advantage of such an approach is its effectiveness in idealizing complex structural systems of arbitrary shapes with unusual boundary conditions. Different types of formulations have been suggested for fluid elements by different authors (Ref. 10, 11, 12). For example, Reference 10 treats fluid as a special case of isotropic elastic solid and employs two-dimensional quadrilateral elements with displacements as the basic unknowns. A different formulation is presented in Reference 11, where pressures are considered as the basic unknowns for the fluid, and displacements for the structure. Reference 12 uses a sub-structure approach along the lines of Reference 11.

The authors have recently employed fluid finite elements, developed in-house and incorporated in the general purpose computer system EDAC/ISAS (Integrated Structural Analysis System), for modeling the fluid-structure interaction for different types of problems, including pressure pulse transmission problems. In the formulation of these fluid elements, it is assumed that fluid is compressible with no shearing deformations. It can resist only volumetric changes with the Bulk Modulus as its only elastic property. A displacement field within the elements is assumed and expressed in terms of nodal displacements. Standard displacement formulation is then used for generating the system stiffness matrix. The elements yields reasonably good comparison against exact solutions, as demonstrated by an example in Figures 1 and 2.

CONCLUSIONS

State-of-the-art techniques were reviewed for the soil-pile-structure and fluid-structure interaction problems. Procedures currently being used by the authors were then briefly presented. The use of soil elements and fluid elements for the solution of problems involving soil-pile-structure-fluid interaction was discussed. A probabilistic technique can be simultaneously used to quantify the uncertainties in the soil properties. A realistic estimate of the response of the system can thus be obtained.

BIBLIOGRAPHY

1. Matlock, H., and L. C. Reese, "Generalized Solutions for Laterally loaded Piles", Transactions, American Society of Civil Engineers, Volume 127, 1962.
2. Brandes, G., "Über das Verhalten von Pfahlgründungen bei Schwingungserregung", Bautechnik-Archiv, H-9:20-44, Wilhelm Ernst and Sohns, Berlin, West Germany.
3. Madhav M. R., N. S. V. Kameswara Rao, and K. Madhovan, "Laterally Loaded Pile in Elastoplastic Soil", Soils and Foundation, 11(2): 1-15, Tokyo.
4. Alpan, I., "The Dynamic Response of Pile Foundation to Lateral Forces", Proceedings, Fifth World Conference on Earthquake Engineering, Rome, Italy, 1972.
5. Novak, M., "Dynamic Stiffness and Damping of Piles", Canadian Geotechnical Journal, Volume 11, 1974.
6. Penzien, J., C. F. Scheffey, and R. A. Parmelee, "Seismic Analysis of Bridges on Long Piles", Journal of the Engineering Mechanics Division, American Society of Civil Engineers, Volume 90, No. EM3, June 1964.
7. Stockard, D. M., "Effects of Pile-Soil-Water Interaction on the Dynamic Response of a Seismically Excited Offshore Structure", Paper No. OTC 2762, Proceedings, Offshore Technology Conference, Houston, Texas, 1976.
8. Kamil, H., "Computer-aided Deterministic-cum-Probabilistic Approach to the Design of Structures Under Extreme Loading Conditions", Second National Symposium on Computerized Structural Analysis and Design, George Washington University, Washington, D. C., March, 1976.

9. Ursell, F., "On the Heaving Motions of a Circular Cylinder on the Surface of a Fluid", Quarterly Journal of Mechanics and Applied Mechanics Volume II, 1969.

10. Chopra, A. K., E. L. Wilson, and I. Farhoomand, "Earthquake Analysis of Reservoir-Dam Systems," Proceedings, Fourth World Conference on Earthquake Engineering, Santiago, Chile, 1969.

11. Zienkiewicz, O. C., and R. E. Newton, "Coupled Vibrations of a Structure Submerged in a Compressible Fluid", International Symposium on Finite Element Techniques, Stuttgart, May 1969.

12. Liaw, C. Y., and A. K. Chopra, "Earthquake Response of Axisymmetric Tower Structures Surrounded by Water", Earthquake Engineering Research Center, Report No. 73-25, College of Engineering, University of California, Berkeley, California.

13. Garrison, C. J., "Hydrodynamics of Large Objects in the Sea, Part I - Hydrodynamic Analysis", Journal of Hydronautics, Volume 8, January 1974.

14. Benjamin, Jack R., and C. Allin Cornell, *Probability, Statistics, and Decision for Civil Engineers,* McGraw-Hill Book Company, 1970.

15. Benjamin, J. R., and G. Kost, "Balanced Design Criteria for Multiple Hazards," Proceedings, ASCE Conference, Structural Design for Nuclear Power Plants, New Orleans, 1975.

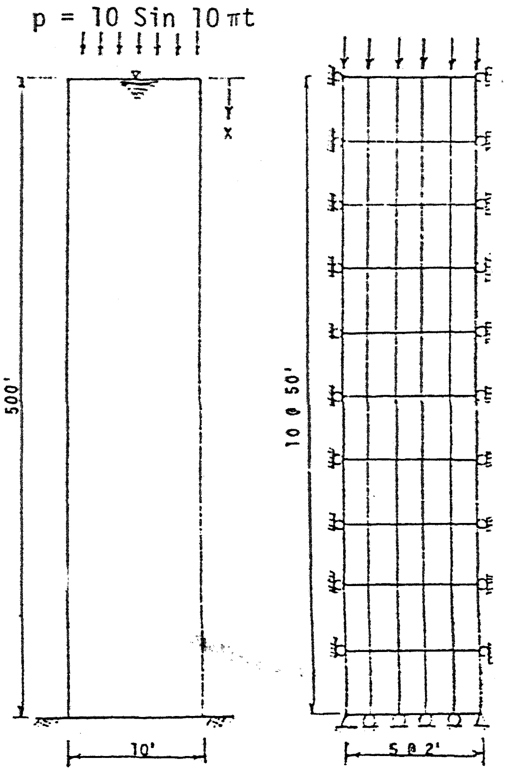

FIGURE 1 FINITE ELEMENT IDEALIZATION OF SEMI-INFINITE WATER-TANK SYSTEM

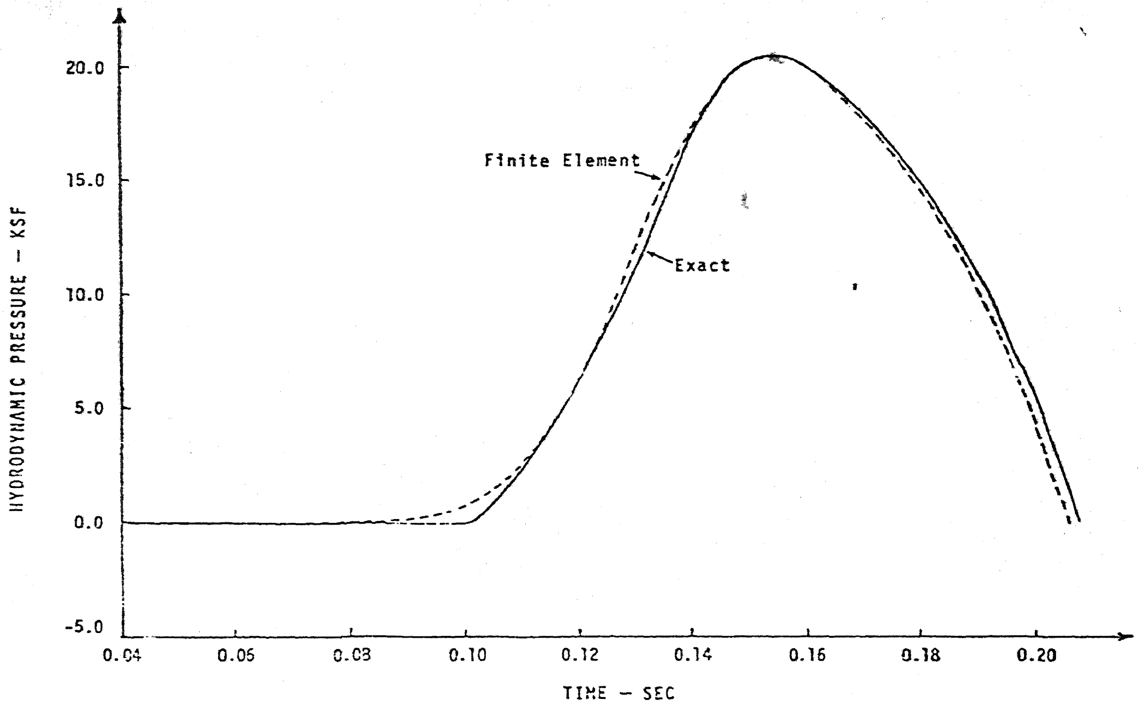

FIGURE 2 PRESSURE RESPONSE OF WATER-TANK SYSTEM OF FIGURE 1