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Evaluation of Seismic Response of Pile-Supported Structures with 3-D Nonlinear Approach

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SYNOPSIS: The seismic response of pile-supported structures is evaluated using a three-dimensional finite element subsystem methodology with an advanced plasticity based constitutive model for soils. The motion of the pile foundation is amplified due to the soil-pile-structure interaction. The dynamic internal forces of the structures obtained by the 3-D nonlinear approach deviate significantly from those obtained by the rigid ground motion model. The structures are generally subjected to three-dimensional forces and couples, despite the type of bedrock seismic excitation and the configuration of structures. Some components of the dynamic internal forces may be overlooked if the simplified symmetric models are used for the earthquake analysis. A comprehensive examination of the results from the rigid ground motion model and the 3-D interactive model may provide some evaluation bound of the seismic response of pile-supported structures.

1. INTRODUCTION

In order to evaluate the seismic response of pile-supported structures in a more realistic manner, a three-dimensional nonlinear finite element subsystem methodology has been developed. The structure subsystem is represented by spatial frame elements while the foundation subsystem, which consists of piles and the surrounding soil, is idealized as an assemblage of solid elements. To take account of the plastic nature of soil, the δ^*-version of the Hierarchical Single Surface (HiSS) modelling approach for cyclic behavior of soft clays is used to formulate tangential matrices of the soil properties for individual stress-strain regimes such as virgin loading, unloading, and reloading. A modified elastic-predictor-plastic-corrector method is used with the constitutive law to trace the trajectory of the variable yield surface of the soil. A successive-coupling incremental solution scheme in the time domain is constructed to deal with inertial and kinematic soil-pile-structure interactions simultaneously.

A FORTRAN code has been created to implement the proposed method. The seismic inputs can be any combination of three dimensional motions. Structures can be solved for uneven support excitations, different from conventionally used uniform free-field motions, which arise due to the soil-pile-structure interaction. As a preliminary example, a two-story spatial frame structure with an end-bearing pile foundation has been used with the proposed method to study the seismic response of pile-supported structures.

The results of the preliminary study show that, with the plasticity based soil model, the motion of the pile heads (column bases) differs greatly from the bedrock motion. The magnitude of the pile head motion is amplified due to the interactive mechanism of the soil-pile-structure system. Even though the bedrock input is horizontal, there are still some vertical acceleration acting on the column bases of the structure, which may not be overlooked in evaluating the seismic kinematic response of pile-supported structures. The three-dimensional approach also reveals that the structure is generally subjected to three-dimensional internal forces and couples even if the structure and the bedrock motion are symmetric. Some components of the seismic response such as transverse bending and torsional couples may be ignored if the simplified symmetric approaches are used to model the structure. The seismic responses of the structure obtained by the proposed interactive model deviate significantly from those obtained by the rigid ground motion model. A comprehensive examination of the results from both of the two models may be essential to evaluate the seismic responses of pile-supported structures.

2. THE 3-D NONLINEAR APPROACH

2.1 General

The analysis model used in the study is a three-dimensional finite element interactive subsystem model which consists of two subsystems: one is the structure subsystem and the other is the foundation subsystem. The two subsystems are connected at the joints between the pile heads of the foundation and the column bases of the structure. The interaction of the two subsystems is transferred through the motions and dynamic forces of the pile heads and the column bases. The structure subsystem is idealized as spatial frame elements which are able to describe most of pile-supported structures. Considering the geometry of the foundation and the constitutive model of soils, isoparametric hexahedral elements are used to represent both piles and surrounding soils [Figure 1].

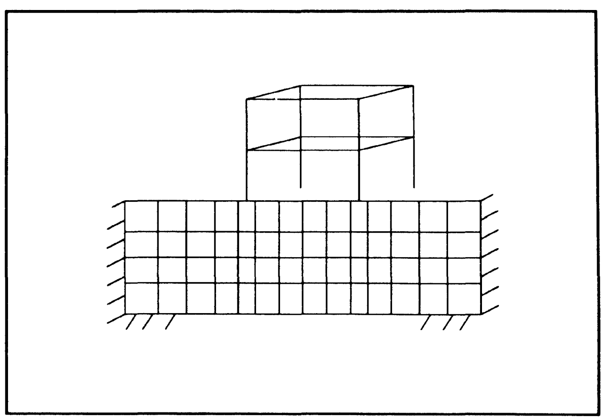

Fig. 1. 3-D FE Mesh of Soil-Pile-Structure System

To solve for the seismic response of the subsystem model, a successive-coupling (S-C) incremental solution scheme in the time domain has been developed to take account of both inertial and kinematic interaction of the two subsystems simultaneously. The whole time history of the seismic response is divided into n time steps. At each time step, the pile head motion is first obtained by solving the foundation subsystem for the bedrock seismic input and the dynamic pile head forces, then the seismic response of the structure is obtained by solving the structure subsystem for the corresponding pile head (column base) motion. Such a successive-coupling procedure can be repeated until the whole response history is determined. When the time step Δt is small enough, the continuous response history may be well approximated by the discrete step approach.

2.2 The structure Subsystem

The unique feature of the structure subsystem model is that the structure can be solved for non-uniform support (column base) motions and the coupling between support motion and the response of active degrees of freedom (DOF) needs to be considered (Clough and Penzien, 1975). The total response, U^t, of a structure with n active DOFs and m support DOFs can be expressed as

$$U^t = U + U^s = U + R\,U_g \qquad (1)$$

where, U is an n x 1 vector of dynamic response of the structure; U^s is an n x 1 vector of pseudostatic response of the subsystem; R is an n x m matrix of pseudostatic response influence-coefficients, which represents the active nodal displacements of the structure resulting from unit movements of support DOFs; U_g is an m x 1 vector of the support DOFs' motions.

By using the Newmark time integration rule (Bathe, 1982), the incremental equations of dynamic equilibrium of the structure at time $t+\Delta t$ can be derived as

$$(4M/\Delta t^2 + 2C/\Delta t + K)\Delta U = -MR\ddot{U}_g - K\,{}^tU + M(4\,{}^t\dot{U}/\Delta t + {}^t\ddot{U}) + C\,{}^t\dot{U} \qquad (2)$$

where Δt is the time step; superscript t indicates the time t; ΔU are increments of the dynamic response vector U, so that ${}^{t+\Delta t}U = {}^tU + \Delta U$; M, C, and K are the mass, damping, and stiffness matrices of the structure, respectively.

The support reactions of the structure will depend on the total displacements of the active DOFs as well as the relative displacements of the support DOFs. Therefore, the support forces for non-uniform support motion cases are different from those for rigid ground motion cases and should be calculated as follows.

$$F_g = K_{gu} U^t + K_{gg} U_g = K_{gu}(U + R\,U_g) + K_{gg} U_g \qquad (3)$$

where, F_g is an m x 1 support force vector; K_{gu} is an m x n matrix which represents the coupling of the support forces and the motions of the active DOFs; K_{gg} is an m x m matrix which represents the coupling of the support forces and the motions of the support DOFs.

2.3 The Foundation Subsystem

To model the constitutive law of soils more precisely, a recently developed plasticity based model, δ^*-version of the Hierarchical Single Surface (HiSS) modelling approach for cyclic behavior of soft clays such as Sabine Clay of Texas (Wathugala and Desai, 1993; Desai and Wathugala, 1993), has been used in the study.

For the Sabine Clay, the yield function of δ^*-version of HiSS approach is described as

$$F = (J_{2D} / P_a^2) + \alpha_{ps} (J_1/P_a)^n - \gamma(J_1/P_a)^2 = 0 \qquad (4)$$

where, J_1 is the first invariant of the stress tensor σ_{ij}; J_{2D} is the second invariant of the deviatoric stress tensor S_{ij}; P_a is the atmospheric pressure; n, γ are material parameters which can be obtained from laboratory tests on soils; α_{ps} is the hardening function which is dependent on the trajectory of volumetric plastic strains and material properties of soils. The variable yield surface of the soil stress is determined by a elastic-predictor-plastic-corrector method with the constitutive law.

The incremental stress-strain relationship for soils is defined as

$$d\sigma_{ij} = C^*_{ijkl}\, d\epsilon_{kl} \qquad (5)$$

where, the superscript* denotes that the marked terms correspond to different stress-strain regimes such as virgin loading, unloading, and reloading; C^*_{ijkl} is a constitutive stiffness tensor which can be expressed as

$$C^*_{ijkl} = C^e_{ijkl} - \frac{C^e_{ijnm} n^*_{nm} n^*_{op} C^e_{opkl}}{H^* + n^*_{rs} C^e_{rstu} n^*_{tu}} \qquad (6)$$

where, C^e_{ijkl} is a elastic stiffness tensor; H is the plastic modulus; the tensor n_{ij} represents the unit normals to the yield surface F for the virgin loading case or to the reference surface R for the reloading case. The reference surface R, which is used to describe the stress situation of a point inside the yield surface, can be written as

$$R = (J_{2D} / P_a^2) + \alpha_r (J_1/P_a)^n - \gamma(J_1/P_a)^2 \qquad (7)$$

where, α_r is the hardening coefficient for the corresponding reference surface.

For virgin loading, $H^* = H^{VL}$; for unloading, $H^* = \infty$ (infinite); for reloading, $H^* = H^{RL}$. At the beginning of each time step, the plastic modulus H^* is determined for each Gauss point of the soil elements based on the stress condition of the soil at the point. More details of the plastic moduli H^{VL} and H^{RL} as well as other formulations of the 3-D nonlinear subsystem model can be found in reference (Cai, Gould, and Desai, 1994).

3. EVALUATION OF THE SEISMIC RESPONSE

3.1 General

A two-story reinforced concrete spatial frame, similar to that shown in Figure 1, with an end-bearing pile foundation has been used to study the seismic response of pile-supported structures. The frame is nine meters high, ten meters long, and eight meters wide. The embedded length of the piles is eighteen meters. The floor mass is distributed to surrounding frame girders using the two-way slab principle of design. The dimension, stiffness, and mass of the frame are all symmetric about the longitudinal and transverse axes of the frame. As a preliminary study, the bedrock input is assumed to be horizontal motion along the longitudinal axis of the frame. The digitized ground motion data obtained from the 1989 Loma Prieta earthquake have been used for the study. The soil used in the study is assumed to be the type of Sabine Clay of Texas, which is similar to the so-called San Francisco "Bay Mud".

The time history of the seismic response of the frame is simulated by a comprehensive computer program created based on the 3-D nonlinear interactive methodology. The preliminary results show that the interactive foundation motion, the column base motion, deviates significantly from the bedrock motion [Figure 2]. The magnitude of the column base motion has been amplified due to the plastic nature of the soft clay. The output of the column base motion also reveals a interesting phenomenon that although the bedrock input is horizontal, yet there are some vertical accelerations on the column bases. For whole frame, the upward and downward accelerations balance each other. But for each column, vertical vibration will occur. These results indicate that the structure may respond both horizontally and vertically even if the bedrock input is only horizontal. The deviation of column base motion from the bedrock motion may need to be considered carefully in the seismic analysis of pile-supported structures.

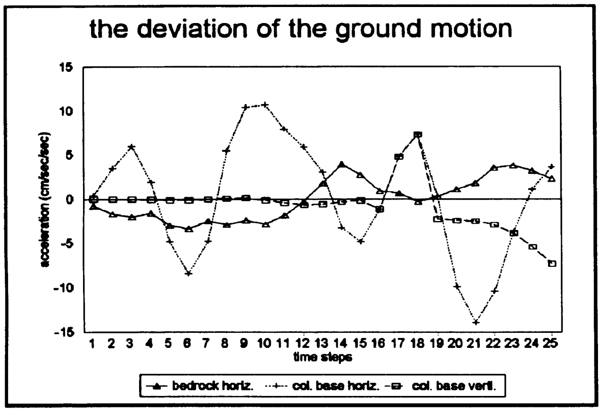

Fig. 2. Deviation of Ground Motions

The frame structure is in general subjected to three-dimensional forces and couples [Figure 3 and 4]. Even though the structure and bedrock motion are symmetric, there are still some torsional moments acting on each column base despite that the resultant of the torsional moments of all column bases is zero. It is believe that these torsional moments are due to the spatial distribution of the masses of the structure and may change with the variation of the mass distribution. For the structure studied, the absolute value of the torsional moments is smaller than those of the longitudinal bending moments. However, considering that the torsional capacity of a column is usually far smaller than its bending capacity, these torsional effects may not be neglected in the seismic design of the structure.

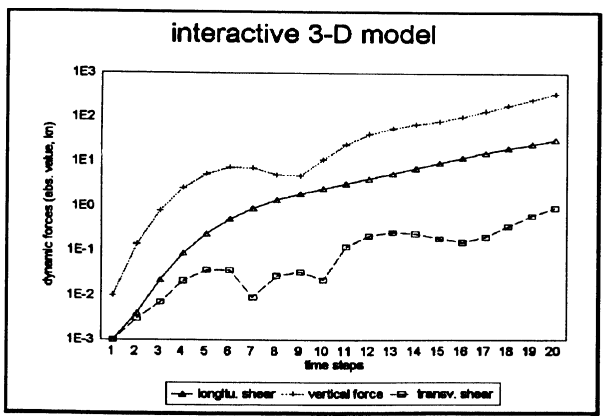

Fig. 3. Dynamic Forces of Interactive 3-D Model

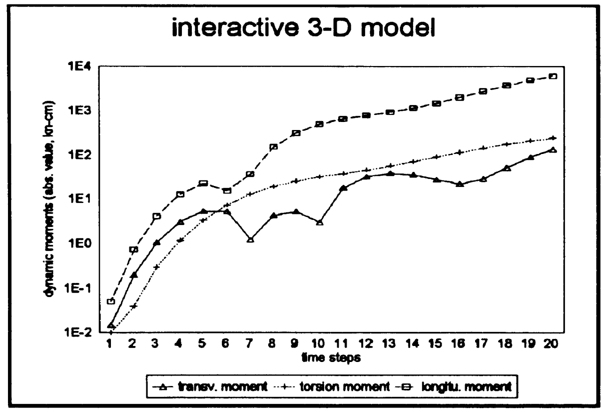

Fig. 4. Dynamic Moments of Interactive 3-D Model

The dynamic vertical (axial) forces at the column bases obtained from the 3-D interactive model are far greater than the longitudinal shear forces. The large dynamic vertical force may be due to the vertical vibration of the structure. To evaluate properly the seismic response of pile-supported structures, the potentiality of vertical vibration may not be ignored even the seismic excitation is assumed to be horizontal.

3.2 3-D Model vs. 2-D Model

To investigate the spatial effect of pile-supported structures, a two-dimensional planar frame derived from the spatial frame studied has been analyzed with the interactive approach for the same bedrock input. The floor mass is distributed uniformly to the longitudinal girders, and the pile foundation conditions are same as those for the spatial frame.

The results show that the longitudinal shear and bending, as well as vertical forces of the planar frame, are very close to those of the spatial frame. But the transverse shear, transverse bending, and torsional moments are very small and almost negligible compared with those of the spatial frame [Figure 5 and 6]. This investigation indicates that even for the symmetric structure subjected to symmetric excitation, the simplified symmetric model may not be able to include all aspects of the seismic response of pile-supported structures.

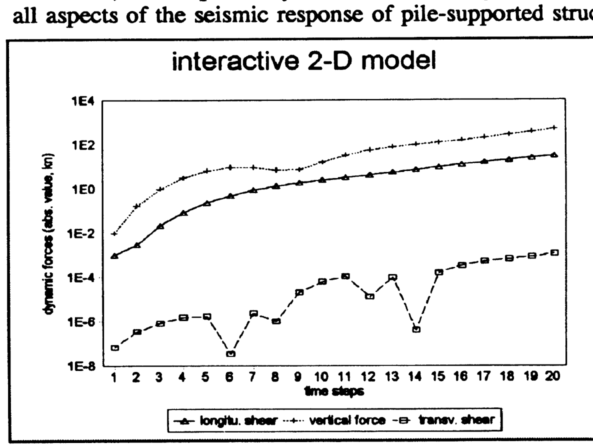

Fig. 5. Dynamic Forces of Interactive 2-D Model

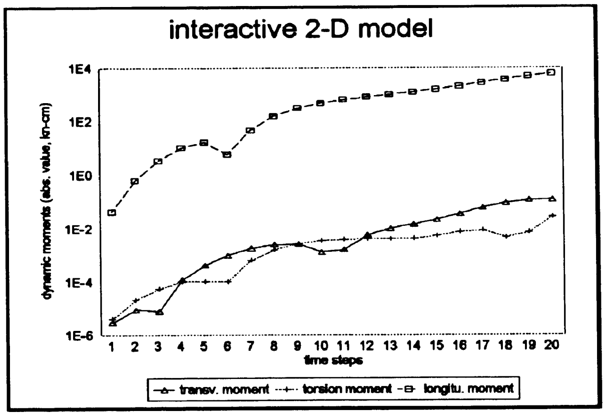

Fig. 6. Dynamic Moments of Interactive 2-D Model

3.3 Interactive Model vs. Rigid Ground Model

To observe the difference between the 3-D nonlinear interactive model and the conventionally used rigid ground motion model, the spatial frame is also analyzed with the assumption that the column base motion is uniform. The bedrock motion used for the interactive model is now used as the column base motion for the rigid ground motion model.

The preliminary simulations with a short duration of the seismic motion reveal that the longitudinal shear and bending moment of the column bases, which are the main force components considered in most simplified symmetric models, obtained from the interactive model are smaller than those from the rigid ground model. However, the transverse shear, transverse bending moment, vertical force, and torsional moment of the column bases gained from the interactive model are greater than those from the rigid ground model. The results of the rigid ground model are shown in Figure 7 and 8.

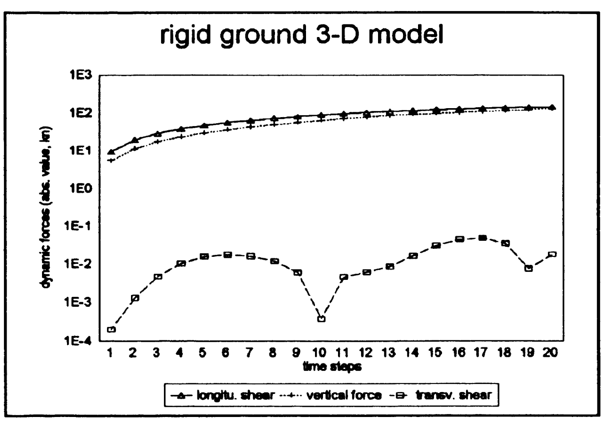

Fig. 7. Dynamic Forces of Rigid Ground 3-D Model

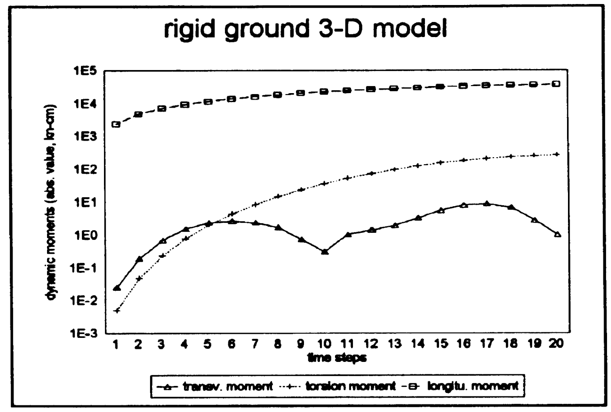

Fig. 8. Dynamic Moments of Rigid Ground 3-D Model

Comparing the results from the two models, one can find that the development of internal forces in the interactive model is more gradual than that in the rigid ground model. Therefore, the interactive model may have more time to re-distribute the internal stress within the structure before the seismic response reaches its peak value.

A seismic response envelope derived from a comprehensive examination of the results of both models may be valuable for evaluating the seismic capacity of pile-supported structures.

4. CONCLUSIONS

A three-dimensional finite element subsystem method with an advanced plasticity based constitutive model for soils has been used to investigate the seismic response of pile-supported structures. The preliminary simulation with a two-story spatial frame shows that the deviation of the interactive foundation motion from the conventionally used free-field motion should be taken into account for the proper design of pile-supported structures. The internal forces obtained from simplified symmetric design models may need to be checked against those from three-dimensional models so that certain components of internal forces (including couples) are not overlooked. The evaluation bound of the seismic response of pile-supported structures may be derived based on the comprehensive examination of the results from the 3-D nonlinear interactive model and the 3-D rigid ground model.

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