Influence of ground water on soil-structure interaction

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1 INTRODUCTION

The study of structural response to seismic inputs has been extensively studied and, particularly with the advent of the growth of digital computer capability, has lead to the development of numerical methods of analysis which are used as standard tools for the design of structures. One aspect of the soil-structure interaction (SSI) process which has not been developed to the same degree of sophistication is the impact of ground water (or pore water) on the response of the soil-structure system. There are very good reasons for this state of affairs, however, not the least of which is the difficulty of incorporating the true constitutive behavior of saturated soils into the analysis. At the large strain end of the spectrum, the engineer is concerned with the potential development of failure conditions under the structure, and is typically interested in the onset of liquefaction conditions. The current state of the art in this area is to a great extent based on empirical methods of analysis which were developed from investigations of limited failure data from specific sites around the world.

At the small strain end of the spectrum, the available analytic approaches that can be used to study the impact of pore water are more tenable. To be sure, difficulties still exist in this area, and these again are primarily associated with constitutive properties of real soils. However, with the availability of computer power, realistic problems can now be investigated to at least allow engineers to assess the potential impact of pore water on seismic response. The key to the adequacy of the seismic analysis performed, however, is the adequacy of the developed interaction coefficients used to represent the influence of the soil foundation. For single-phase, linear elastic materials, various procedures, both analytic and numerical, are available with which to generate such coefficients. However, for the case of saturated soils, no such comparable capability is generally available to perform the SSI analysis. It was the goal of this study to generate estimates of the impact of ground water on the SSI process, using finite element calculations.

The basic problem under consideration consists of a linear flexible structure situated at or near the surface of a soil half-space. In keeping with typical small strain seismic analyses, the soil skeleton is represented as a linear medium in which all potential nonlinearities are at most lumped together into an equivalent hysteretic damping modulus. In addition, the ground water level is located at some depth relatively close to the structure, and in a position to impact on the seismic response of the facility. In order to estimate the response of this soil-water system, the two-phased medium formulation of Biot (1941 to 1962) was used to treat the response of the solids and water as two separate linear media, coupled together through soil permeability and volume effects.

Since it is known that analytic solutions are available for only the simplest of configurations, a numerical finite element solution process was developed. Again, in keeping with typical SSI analyses, in order to make the finite element approach yield reasonable results, a comparable transmitting boundary formulation was included in the development. The purpose of the transmitting boundary is, of course, to allow for the treatment of extended soil/water half-space problems. For the calculations presented herein, a simple one dimensional transmitting boundary model was developed and utilized. The details of this formulation are provided by Lung (1980).

2 GOVERNING SYSTEM EQUATIONS

Assuming the soil skeleton to possess isotropic elastic properties, the standard stress-strain and strain-displacement relations can be written relating the intergranular stresses ($\sigma_{xx}, \ldots\ldots, \sigma_{yz}$), strains ($\varepsilon_{xx}, \ldots\ldots, \varepsilon_{yz}$) and displacements of the solid fraction (u_x, u_y, u_z). When the effects of pore pressure are included, the bulk (or total) stresses must also be considered. The components of the total stress tensor are denoted as τ_{ij}, where $i,j = x,y$ or z. Considering a unit volume of bulk material (solid plus fluid), we denote the components of the fluid displacement vector as (U_x, U_y, U_z). These components are defined such that the volume of fluid displaced through unit areas in the x, y and z directions are fU_x, fU_y, and fU_z respectively, where f denotes the porosity of the solid skeleton. The flow of the fluid relative to the solid skeleton, but measured in terms of the volume per unit area of the bulk medium is then

(1) $$w_x = f\,(U_x - u_x), \quad w_y = \ldots\ldots\ldots, \quad w_z = \ldots\ldots\ldots$$

Biot has shown that the pore pressure can be written in terms of the volume change of the solid fraction as well as the compressibility of both the fluid and solid fractions by

(2) $$p_f = -\alpha M(e_{xx} + e_{yy} + e_{zz}) + M\Psi$$

where Ψ is the volumetric fluid strain, α is the compressibility of the solid fraction and M is the compressibility of the fluid fraction. The bulk (or total) stress tensor is then given by

(3) $$\tau_{xx} = \sigma_{xx} - \alpha p_f, \qquad \tau_{xy} = \sigma_{xy}, \qquad \text{etc.}$$

Applying Lagrange's equations to this system, and considering (u_x, u_y, u_z) and (w_x, w_y, w_z) as the generalized coordinates, the equations of motions can be written in each direction as

(4) $$\partial\tau_{xx}/\partial x + \partial\tau_{xy}/\partial y + \partial\tau_{xz}/\partial z = \rho \ddot{u}_x + \rho_f \ddot{w}_x, \qquad \text{etc.}$$

(5) $$-\partial p_f/\partial x = \rho_f \ddot{w}_x/f + \eta \dot{w}_x/k, \qquad \text{etc.}$$

where ρ is the total mass density of the bulk material, ρ_f is the mass density of the fluid, η is the fluid viscosity, k is the soil permeability and f is the porosity of the soil.

3. NUMERICAL RESULTS

Based upon Biot's formulation briefly described above, a finite element compputer program was generated and exercised to compute interaction coefficients which account for the influence of pore water. The problem considered is shown in Figure 1 in which a uniform elastic porous halfspace is loaded by a

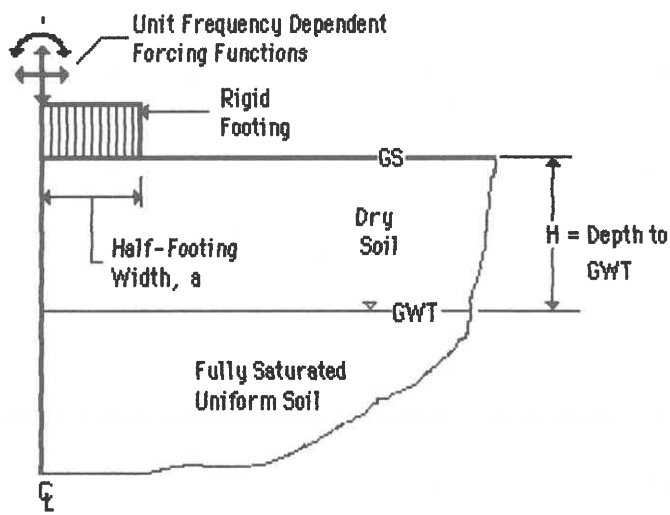

Figure 1. Plane Strain Halfspace of Uniform Elastic Soil Loaded by Rigid Strip Footing.

rigid strip footing of halfwidth a located at the ground surface. The ground water table is located at an arbitrary depth H below the ground surface. The properties of the soil used for these calculations are a shear wave speed of about 448 fps, Poisson's ratio of 0.25, dry density of 107.5 pcf and permeability of 0.1 cm/sec. The footing is then forced into unit steady state motions in the horizontal, vertical and rocking modes of vibration at various frequencies. The total forces and moments generated on the footing then represent the interaction coefficients (real and imaginary components). A typical finite element mesh used in the calculations of these coefficients is shown in Figure 2. A tran-

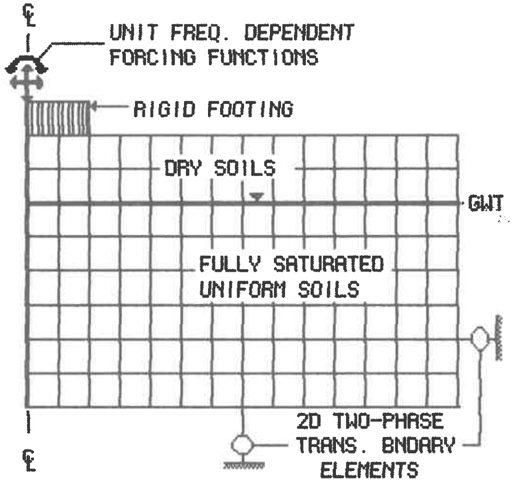

Figure 2. Finite Element Mesh Used to Generate Interaction Coefficients

smitting boundary is used on the right and bottom sides of the mesh, while standard roller conditions are used on the left, or centerline boundary. An extensive number of calculations were performed (Costantino - 1986, 1987) in an attempt to assess the impact of ground water on the SSI process, as well as mesh size and properties. Some typical data shown below are plotted in dimensionless form, where the dimensionless parameters are defined by

	Frequency:	$\lambda = a\,\Omega / V_s$
(6)	Rocking Interaction:	$(K_{tt}, C_{tt}) = (k_{tt}, c_{tt})/(\pi G a^2)$
	Trans. Interaction:	$(K_{ij}, C_{ij}) = (k_{ij}, c_{ij})/(\pi G)$

where 'a' is the halfwidth of the footing, Ω is the forcing frequency in radians, V_s is the shear wave velocity and G is the shear modulus. The lower case k and c represent the dimensioned interaction parameters.

Figure 3 presents typical results for the rocking interaction parameters for a variety of ground water depth ratios, H/a. If the GWT is at the depth of the foundation, the rocking stiffness is almost double that for the dry case. The presence of the pore water prevents large volume change of the soils directly under the foundation. The corresponding damping data shows that the saturated case has twice as much damping as the dry case. Both results indicate that the rocking mode for a typical structure on a saturated site would have a higher interaction frequency and lower magnitude of motion than the corresponding response on a dry soil. As the GWT is moved away from the foundation, the impact of the pore water decreases. The effective rocking stiffness approaches that for the dry case at a "cutoff depth" (depth/halfwidth ratio H/a) of about 1.5. The "cutoff depth" is rather crudely defined as that depth ratio below which the location of the GWT is relatively unimportant over the frequency range of interest. The damping value approaches the dry data at a "cutoff depth" of about 0.5, as can be seen from Figure 3.

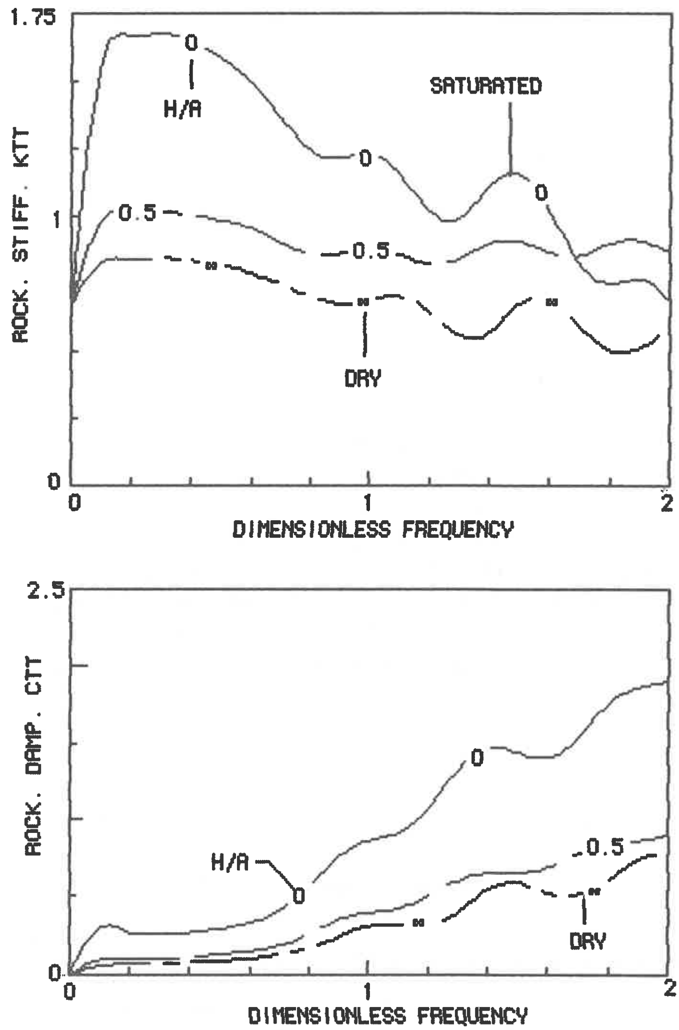

Figure 3. Dimensionless Rocking Coefficients for Various Depths to the GWT.

Similar data is shown for the vertical interaction coefficient in Figure 4. For the saturated case, the stiffness coefficient becomes negative above a dimensionless frequency of about 0.85. In addition, no simple "cutoff depth" can be chosen as for the rocking case. Rather, the effect of the GWT is found to be highly frequency dependent for both the stiffness and damping parameters. At shallow depths to the GWT, the stiffness and damping parameters are higher than those for the dry case.

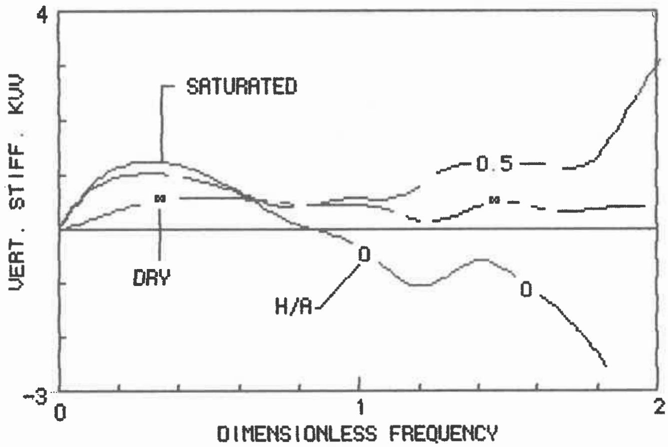

Figure 4. Dimensionless Vertical Stiffness Coefficient for Strip Footing.

4 SUMMARY AND CONCLUSIONS

The results of these calculations indicate that pore water effects can play a significant role in the SSI process. Some rather general conclusions are as follows. If the GWT is at the depth of the foundation, the horizontal interaction coefficients (stiffness and damping) increase by about 50% over the dry case. As the GWT moves to a depth ratio of 1.0, the damping coefficient approaches the values for the dry case, while the stiffness coefficient approaches the dry case at a depth ratio of about 2.0. The rocking mode, however, approaches the dry case results more rapidly, as stated above. No such simple interpretation can be reached for the case of the vertical mode of motion.

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