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Dynamic response
and wave propagation
in soils

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Dynamic behavior of embedded foundations

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With the advent of fast digital computers, and particularly following the development of finite element techniques, many difficult problems involving the dynamic response of structures to a seismic excitation, accounting for foundation interaction effects, became amenable to calculation. In earlier times, it was only possible to analyze idealized cases of structures resting on circular or rectangular rigid plate foundations underlain by elastic, homogeneous, isotropic half spaces. More recently, however, analytical or closed-form solutions have also been developed for (geometrically) more complicated plates welded to viscoelastic, layered half spaces. Nevertheless most, if not all, of these newer solution disregard embedment, and are thus strictly applicable to surface foundations only. This embedment has in many cases considerable effect on the dynamic response of the structure, both in terms of relative frequency contents and amplitude of the resulting motions. While rigorous analytical solutions for embedded foundations are nonexistent at present, it is possible to use approximations and corrections to the available results for surface foundations, to account for the increase in stiffness (Elsabee 1975, Kausel et al, 1977, Novak 1973) and the scattering of the incident seismic waves by the embedded walls (Kausel et al. 1977, Morray 1975). These approximate solutions are particularly useful in cases where direct analyses with finite elements are not practical or feasible, either when the ultimate use of the analysis does not warrant the added cost or refinement, or when the geometry —fully three dimensional— cannot adequately be modeled with available programs based on plane-strain axisymmetric formulations.

KINEMATIC INTERACTION
Soil structure interaction effects arise on the one hand by relative motions of the foundation with respect to the surrounding soil —the free field— as a result of inertial forces in the structure being transmitted to the compliant soil. This effect can be defined as Inertial Interaction (Ad hoc group ASCE). On the other hand, interaction effects in the absence of inertial forces can also arise because the stiffer structural foundation cannot conform to the distortions of the soil generated by the traveling waves. For ideally rigid, massless foundations, this effect depends only on the geometry of the foundation, the soil configuration, and the travel path of the seismic excitation across the soil-structure interface. It is generally referred to as Wave Passage Effects, Scattering of the Seismic Waves by a Rigid Foundation or Kinematic
Interaction (Ad hoc group ASCE). For embedded foundations, this effect is always present, irrespective of the seismic environment prescribed, and is one of the chief sources of discrepancy between traditional lumped spring interaction analyses and more involved procedures using finite elements.

It can be shown that in order to obtain consistent results using both approaches, it would be necessary to prescribe at the base of the soil "springs and dashpots" a support motion consisting of translations and rotations (Kausel, Roësset, 1974). The components of this support motion vector $U_b$ are related to the displacements $U$ and internal forces $P$ along the soil-structure interface in the free field (i.e., before any structure has been built), and to the subgrade impedance matrix $X$ for the foundation under consideration. This matrix represents the forces acting on the soil along the soil-structure interface, necessary to produce unit harmonic displacements of these same points when there is no seismic excitation and the soil has been excavated. For a structure embedded in a viscoelastic, horizontally layered half space or stratum, the solution to the free field problem $U, P$ can be obtained analytically or numerically for any train of waves, and in particular, for any combination of plane body and surface waves. However, obtaining the subgrade impedance matrix $X$ is not an easy task for the stated conditions except for the case of zero embedment (Gazetas, Roësset 1976).

In most cases, only the global subgrade stiffness matrix $K_o = T^T X T$ (where $T$ is a rectangular rigid body transformation matrix) containing the frequency dependent soil "springs" is available, either from an analysis with finite elements or from published approximate solutions. This matrix $K_o$ is not sufficient to solve the free field problem, that is, to determine the support motion vector (Novak 1973)

$$U_b = K_o^{-1} T^T (P + XU)$$

because the inverse transformation, from stiffness matrix to impedance matrix, is not defined. Note, however, that the subgrade impedance matrix $X$ and the subgrade stiffness matrix $K_o$ are independent of the seismic environment, except for possible nonlinear effects which are not being considered here. Therefore, parametric studies can easily be conducted once any of these matrices is available.

Most of the research efforts for embedded foundations have in the past been directed towards determining approximate solutions of the stiffness matrix $K_o$ (Elsabee 1975, Novak 1913 etc.). More recently, the problem of kinematic interaction, expressed formally by equation 1 above, has also received some attention (Kausel et al. 1977, Morray 1975) although much remains to be studied. It is true that some earlier papers have investigated the problem of wave passage on soil-structure interaction, but their models were generally simple (Winkler or Boussinesq foundation impedances; sinusoidal wave train etc.) and did not account for embedment. While these solutions have a theoretical interest, they are inadequate in a practical situation involving deep embedment.
A point of concern is the simulation of material nonlinear effects in the soil when the impedance (spring or lumped parameter) method is used, since the method is based on the principle of superposition. In particular, the components of the subgrade stiffness matrix $K_o$ and support motion vector $U_b$ are sensitive to a detachment of the lateral walls with the surrounding backfill. Admittedly, this situation is rarely given attention in direct finite element analysis as well, although it can have an effect as important as that of the embedment itself. Some debate has also centered on the use of one single wave pattern to define the free field motion (vertically propagating shear waves; Raleigh waves; Love waves, etc.) which could result in unrealistic spatial variations of the seismic motions with depth. The resulting deamplification (or lack of it) would lead to unconservative estimates for the motions of the structure, or greatly exaggerate wave passage effects at selected frequencies. Under such conditions, it might be better to regard the design motion as an average motion in the vicinity of the structure and use it directly at the support of the springs, without correction for kinematic interaction. It is hoped that more work will be done to provide relatively simple "engineering" solutions to the problems posed by embedded foundations so that a greater confidence can be placed in the resulting dynamic analyses, and realize savings in design through smaller factors of safety.

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