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SYNOPSIS: An extended summary is presented of a state-of-the-art report on the subject matter. The report parallels one presented at the Fourth U. S. National Conference on Earthquake Engineering, in May 1990.

EXTENDED SUMMARY

It is generally recognized that the motion experienced by the foundation of a structure during an earthquake may be substantially different from the free-field ground motion, which is the motion that the ground would experience at its interface with the foundation in the absence of the structure. Two factors are responsible for this difference: First, the inability of a rigid foundation to conform to the generally non-uniform, spatially varying, free-field ground motion; and second, the interaction or coupling between the vibrating structure, its foundation, and supporting soils.

Several factors contribute to the spatial variation of the free-field ground motion. The seismic waves may emanate from different points of an extended source and may impinge the foundation at different instants or with different angles of incidence, or they may propagate through paths of different physical properties and may be affected differently in both amplitude and phase by the characteristics of the travel paths and by reflections from, and diffractions around, the foundation. Even when the seismic wave front is plane, it may impinge the foundation-soil interface obliquely, leading to ground motions that differ in phase from point to point. The spatial variation of the ground motion due to the propagation of a plane wave is known as the wave passage effect, whereas that due to the other, generally random, factors is known as the ground motion incoherence effect.

The seismic response of a structure is frequently evaluated considering the motion of its base to be equal to the stipulated free-field ground motion at a convenient reference or control point of the ground surface. No provision is made in this approach either for the spatial variation of the free-field ground motion or for the properties of the supporting medium. The exact analysis requires that the structure be considered to be part of a larger system which includes the foundation and the supporting medium, and that due cognizance be taken of the spatial variation of the ground motion and of the properties of the soils involved.

Such an analysis is implemented in two steps: First, the motion of the foundation is evaluated considering both the foundation and the superimposed structure to be massless. Referred to as the foundation input motion, the resulting motion generally includes torsional and rocking components in addition to translational components. Next, the response of the actual foundation-structure system with mass to the foundation input motion is evaluated using the actual properties of the supporting medium and providing for the dynamic interaction between its elements. The flexibility of the supporting medium has a two-fold effect: (1) It increases the number of degrees of freedom of the system and lowers its effective stiffness; and (2) it makes it possible for part of the vibrational energy of the structure to be dissipated in the supporting medium by radiation of waves and by hysteretic action in the soil itself. These forms of energy dissipation have no counterpart in a rigidly supported structure.

The difference in the responses of the superstructure computed for the foundation input motion and the free-field control-point motion represents the kinematic interaction effect, whereas the difference in the responses computed with and without regard for the flexibility of the supporting medium is known as the inertial interaction effect.

The objectives of this presentation are: to highlight the nature and relative importance of the kinematic and inertial interaction effects; to present information and concepts with which these effects may be provided for readily in design; and to identify some areas of needed research. The presentation is based mainly on material contained in the references listed at the end.

The concepts involved are identified by reference to single-degree-of-freedom systems supported through rigid circular foundations at the surface of a homogeneous, elastic or viscoelastic halfspace. The foundation mat is presumed to be bonded to the halfspace so that no uplifting or sliding can occur. The structure may be viewed either as the direct model of a single-story building frame or, more generally, as the model of a multi-story, multi-mode structure that responds as a system with one lateral and one torsional degrees of freedom in its fixed-base condition. The free-field control-point motion is defined at the center of the foundation-soil interface, and it is considered to be a uni-directional, horizontal excitation. Both wave-passage and ground-motion incoherence effects are examined. The principal conclusions may be summarized as follows:

1. Whether due to wave passage or ground-motion incoherence, kinematic interaction reduces the horizontal component of the foundation input motion and induces a rotational or torsional component of motion, the magnitude of which depends on the dominant frequency of the excitation. These changes are typically large for acceleration, moderate for velocity, and almost negligible for displacement. Inasmuch as the foundation filters the high-frequency wave components more effectively than the low-frequency components, the acceleration trace of the ground motion, which is richer in high-frequency content than the velocity and displacement traces, is affected more by kinematic interaction than are the other two traces.

2. Reliable estimates of the effects of kinematic interaction on the peak values of structural response may be obtained from knowledge of the corresponding values of the acceleration, velocity and displacement traces of the foundation input motion. The latter values may be computed from analyses of the response of the massless foundation to the free-field ground motion.

3. Because high-frequency systems are acceleration-sensitive whereas low-frequency and medium-frequency systems are displacement- and velocity-sensitive, respectively, the effects of kinematic interaction on the lateral component of response are greatest for high-frequency systems, inconsequential for low-frequency systems, and intermediate in magnitude for systems of medium frequency.

4. Insofar as the maximum values of the responses are concerned, the kinematic interaction effects due to ground motion incoherence are similar to those due to wave passage, and the two effects may be interrelated.

5. The effects of inertial interaction are generally more important than those of kinematic interaction.

6. The inertial interaction effects may be approximated with good accuracy by a previously recommended simple procedure, in which the dynamic properties of the structure are modified, and the response of the modified structure to the foundation input motion is computed considering the structure to be rigidly supported at the base. The interaction effects in this approach are expressed approximately by a decrease in the fixed-base natural frequency of the structure for the mode of vibration considered, and by a change (generally an increase) in the associated damping. The reduction in frequency results from the flexibility of the supporting medium, whereas the increase in damping results from the capacity of the medium to dissipate energy by radiation of waves and hysteretic action.

7. Inertial interaction may increase, decrease, or have no effect on the maximum response of a system. The outcome depends on the characteristics of the relevant response spectrum and on the regions of the spectrum in which the fundamental natural frequencies of the fixed-base and interacting systems fall. In particular,

a. If both frequencies fall in the extremely high-frequency spectral region, soil-structure interaction will have no effect on the maximum response, as the pseudo-acceleration value in this case is unaffected by changes in either frequency or damping.

b. If the fixed-base natural frequency falls either in the amplified, nearly constant pseudo-acceleration region of the response spectrum or to the left of this region, inertial interaction will reduce the maximum response. An increase in damping under these conditions decreases the pseudo-acceleration, whereas a reduction in natural frequency either does not change it or decreases it further.

c. If the fixed-base natural frequency of the system falls in the intermediate spectral frequency region, inertial interaction may increase or decrease the response. A reduction in frequency in this case increases the response, whereas an increase in damping has the opposite effect.

8. The interaction effects of low-frequency, highly compliant structures are negligible because such systems "see" the supporting half-space as a very stiff, effectively rigid medium.

Topics requiring further study include: the behavior of structures with embedded foundations, for which the kinematic effects are more important than for surface-supported structures; the behavior of pile-supported structures; and the interaction effects for structures that respond in the inelastic range of deformation.

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