Influence of Foundation Layering on Soil-Structure System Motion

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Abstract

This paper is concerned with effects on structural motion due to layering of the foundation. Impedance functions for foundations which consist of a layer resting on a viscoelastic half-space are used on a simple 3-dof SSI system and transfer functions are generated. It is shown that the layering of the foundation effects the motion of the SSI system. These effects are more pronounced for shallow layers with large difference in shear wave velocity from the underlying half-space.

1. Introduction

Soil-structure interaction effects during earthquakes in nuclear power plants are often assessed with the lumped spring-mass method. This method is computationally more efficient than the direct method and is less sophisticated than the general substructure method. The computational requirements using spring-mass models are further reduced by using frequency-independent impedances. Tsai (1) has shown that for nuclear plant sites having sufficiently deep and uniform overburdens the foundation impedances can be adequately represented by constant parameters. Certain sites, however, such as those exhibiting strong layering, cannot be represented by the half-space constant parameters. It is known that layering introduces a marked frequency dependence of the stiffness and radiation damping. The objective of this paper is to present layering effects in soil-structure interaction using the lumped spring-mass
method. Investigation of layering via the finite element method is not presented here. Some results are given from Phase I of an investigation of layering effects on the structural response. In this phase, these effects are treated with simple soil-structure models. The later allow for a wide variation of parameters needed for a good understanding of the physical problem. Detailed models are employed in Phase II of the program.

2. Foundation impedance functions

The layered foundation was first treated in its simplest form i.e., a soil layer over a rigid medium. In early studies, Bycroft (1) presented solutions of the associated wave equations for the case of an elastic stratum. Warburton (2) treated the vibration of a foundation on an elastic stratum making an a priori assumption for the contact pressure. Kobori, Minai and Suzuki (3) presented solutions for the viscoelastic stratum on a rigid base. Kobori and Suzuki (4) considered the vibration associated with a viscoelastic multi-layered medium.

In a recent study (5), Luco extended his results for the half-space problem (6) to the case of a layer resting on an elastic half-space. The procedure used in these treatments is based on a reduction of the associated mixed boundary value problem to a set of Fredholm integral equations. Relaxed condition is assumed at the foundation-layer interface. In a subsequent study (7) Luco considered the case of a rigid disk resting on a multi-layered viscoelastic medium using a similar approach. Most recently, Apsei (8) considered the general problem of multi-layered medium and presented solutions for the Green's functions. In this paper, impedances are generated using the general approach proposed by Wong and Luco (9) which is implemented in the CLASSI (10) code.

3. System description

A 3-DOF soil-structure system is considered in the Phase I of the program. It represents a structure resting on a foundation which
consists of a viscoelastic layer over a viscoelastic half-space. The inertia of the structure and the base are \( m, l \) and \( m_b, l_b \) respectively. The impedances are \( k_t, c_t \) and \( k_r, c_r \) in translation and rocking respectively. The structure is represented by a fixed-base frequency \( \Omega_s \) and damping \( \beta_s \).

Transfer functions between the free-field and the structural parameters:

\[
\begin{align*}
T_y(\Omega) &= D_1(\Omega) \\
T_a(\Omega) &= -\left(1/\Omega^2 \Delta(\Omega)\right) D_2(\Omega) \\
T_{hb}(\Omega) &= D_3(\Omega)
\end{align*}
\]

(2)

where \( T_y, T_a, T_{hb} \) denote the transfer functions between the free-field and the relative displacement, sliding and rocking of the foundation respectively. The complex functions \( D_1, D_2, D_3 \) and \( \Delta \) are:

\[
\begin{align*}
\text{Re}(D_1) &= A(1-B)\Omega^2 + B\Omega_R^2 - 4AB B_H \Omega_R^2 \\
\text{Re}(D_2) &= (1-AB)\Omega^2 + (1-A)B\Omega_R^2 + B\Omega_R^2 - 4AB \beta_H \Omega_R \Omega_H \\
\text{Re}(D_3) &= A \Omega^2 - 4AB \beta_H \Omega_R^2 \\
\text{Im}(D_1) &= 2AB \Omega R \Omega_H \Omega_R \\
\text{Im}(D_2) &= 2AB \Omega_R \Omega_H (\beta_H \Omega_R^2) + 2 \beta_H \Omega_H (1-AB) + 2 \beta_R \Omega_R \Omega (1-A) \\
\text{Im}(D_3) &= 2A \Omega_H (\beta_H \Omega_H^2) \\
-\text{Re}(\Delta(\Omega)) &= (\Omega^2 - 1) + A(\Omega^2_0 - 1) + B(\Omega_R^2 - 1) - AB(\Omega^2_1 - 1)(\Omega^2_2 - 1) \\
&+ 4AB(\Omega^2_1 - 1) \beta_H \Omega_R \Omega_H (\Omega^2_0 - 1) \beta_H \Omega_R \Omega_H \\
&+ (\Omega^2_R - 1) \beta_H \Omega_R \Omega_H \\
\text{Im}(\Delta(\Omega)) &= -2(\beta_H \Omega_H^2 + 4AB \beta_H \Omega_R \Omega_H + 4AB \beta_H \Omega_R \Omega_H) \\
&+ 2AB(\beta_H \Omega_R (\Omega^2_0 - 1)(\Omega^2_2 - 1) + \beta_H \Omega_H (\Omega^2_1 - 1)(\Omega^2_R - 1)) \\
&+ \beta_R \Omega_R (\Omega^2_1 - 1)(\Omega^2_R - 1)
\end{align*}
\]
4. Some numerical results

The parameters varied are mainly the ratio of the layer thickness to the foundation radius (H/R), the ratio of the shear wave speed between the layer and the half space (Vs1/Vs2) and the fixed-base structural frequency. Hysteretic type of damping was assumed for the soil (5%). Similarly the structural damping was kept at 5%. Results from six cases have been obtained thus far. These cases correspond to: Vs1/Vs2= 0.6 and 0.3 and H/R= 0.5,1.0 and 3.0. Foundation impedances are shown in Fig. 1 for Vs1/Vs2=0.3. Transfer functions are shown in Figs. 2a,2b. For comparison purposes the corresponding half-space transfer functions are also plotted in the same figures by a solid line. By inspection it may be seen that layering influences the SSI system. Amplitudes become higher and frequencies are shifted to higher values. This is more pronounced for the smaller value of wave speed ratio i.e., 0.3 as well as for small values of H/R ratios. For H/R greater than 3.0 these differences practically do not exist. Further studies are underway in order to see how other parameters such as the structural mass and height effect these results.

Conclusion

Some results from a study of the layering effects was presented. Based on these it may be concluded that layering can result in both higher amplitudes as well as higher natural frequencies. Such effects were found more important in foundations with shallow layers and small shear wave velocity ratios.

References
Fig. 1 Impedance functions $V_{s1}/V_{s2}=0.3$ $H/R=0.5, 1.0, 3.0$

Fig. 2 Transfer functions (a) $V_{s1}/V_{s2}=0.6$ (b) $V_{s1}/V_{s2}=0.3$