SOIL-STRUCTURE INTERACTION USING A SIMPLIFIED MODEL:
PARAMETRIC STUDY

Ganesh M. Pai, M.Tech. Student, Dept. of Earthquake Engg., IIT Roorkee, ganeshpai87@gmail.com
B. K. Maheshwari, Associate Professor, Dept. of Earthquake Engg., IIT Roorkee, bkmahfeq@iitr.ernet.in

ABSTRACT: It is well appreciated fact, from the past, that consideration of soil flexibility is an important issue that should be included in dynamic analysis of structures. The present study focuses on inclusion of soil flexibility in dynamic analysis using a simplified model. An attempt has been made in this paper to study and understand effects of some of the parameters i.e. frequency dependent characteristics, embedment of foundation, stratum depth and material properties of soil for better understanding the behaviour of the simplified model. The study shows that kinematic interaction and dynamic stiffness highly demonstrates the dependency on frequency contents. It is also seen that effects of kinematic interaction is negligible for surface foundation. There is significant effect of depth of embedment and stratum depth on kinematic interaction and impedance function.

INTRODUCTION
As an alternate to rigorous methods (i.e. finite element method, boundary element method and finite differences method), for dynamic soil-structure interaction analysis, another approach for the analysis known as simplified method exists. In this method, the soil-structure interaction problem is broken into a series of simpler problems, which are solved independently using simplified models, and the results are then superimposed to yield required solutions. This approach is simple and sufficiently accurate. The major advantage for using simple models for analysis is that they are simple and economical to perform. Another advantage of this approach is that, once the kinematic interaction and impedance problems are solved, this does not need to be repeated if the properties of the structure are changed in the design process. Simplified models with one-dimensional free-field analysis allow surface and embedded foundations to be analysed leading to results, which provide remarkable agreement with rigorous methods.

Several simplified methods were proposed for estimating kinematic interaction. The mathematical transformation from the free field motion \((u_f)\) to the foundation input motion \((u_0)\) by use of frequency dependent transfer function is one of the most widely used technique for calculating foundation input motion. Morray [1] suggested simple rules for estimating transfer function relating base-slab translational and rotational motions to free-field translations for an incident wave field consisting of vertically propagating, coherent SH waves. Veletsos et al. [2], developed several transfer functions which were calibrated later by Kim [3] against observed foundation and free field behaviour.

A number of methods have been developed for estimating dynamic stiffness for soil foundation system. Gazetas [4], presented simple formulas and charts for impedance functions of both surface and embedded foundations. Wolf and Meek [5] developed model to analyse the vibrations of a foundation on the surface or embedded in a layered half-space or full-space. To estimate foundation input motion and dynamic stiffness matrix, an approach using conical bars and beams, called cones, were used.

MODELLING AND FORMULATION
In the present study, circular foundations resting on soil over bedrock or homogeneous half-space are considered for demonstrating the effect of different parameters on kinematic interaction and dynamic stiffness using cone model shown in Figs. 1a, b, respectively.

![Fig. 1 Soil-foundation profiles considered for the study](image-url)
\[ S(a_0) = K_s [k(a_0) + ia_0 c(a_0)] \]  

(1)

Where, \( K_s \) is a constant representing the static component of resistance called static-stiffness coefficient. \( k(a_0) \) and \( c(a_0) \) are the frequency-dependent stiffness and damping coefficients, respectively, accounting for the dynamic components of soil resistance and \( a_0 \) represents dimensionless frequency equal to \( \omega r_0/V_s \), where \( \omega \) is the angular frequency, \( r_0 \) is the radius of foundation and \( V_s \) is the shear wave velocity of the soil.

For all calculation the Poisson’s ratio is taken as 0.33; shear wave velocity of soil is taken as 200 m/s and density of soil is considered to be 1800 kg/m³.

**FREE-FIELD ANALYSIS**

Free-field motion refers to the ground motion that is not influenced by the presence of the structure. One-dimensional ground response analyses have shown to predict ground response that is in reasonable agreement with measured response in many cases. This technique for ground motion analysis is based on the use of frequency dependent amplification factor (A.F.). Amplification factor can be used to express various response parameters such as displacement, velocity, acceleration, shear stress and shear strain [7]. Amplification factor is defined as the ratio of displacement at free surface \( (u_f) \) to the displacement at the bed rock \( (u_b) \).

\[ A.F. = \frac{u_f(\omega)}{u_b(\omega)} \]  

(2)

A typical amplification curve for 5% damping ratio of soil, over rigid base (Fig. 1a) is shown in Fig. 2.

\[ T.F. = \frac{u_f(\omega)}{u_f(\omega)} \]  

(3)

For the present study foundation resting on soil over bedrock is considered, as shown in Fig 1a.

**Effect of Embedment**

The depth of embedment is varied, i.e. embedment ratio \( (e/r_0) \), varies. Embedment ratios considered are 0, 0.5, 1 and 2. The damping ratio of the soil is 5%. It can be observed from Fig. 3 that the T.F. amplitude for \( e/r_0 = 0 \) is unity thought the frequency range. The curve for \( e/r_0 = 0.5 \) decreases gradually, whereas for \( e/r_0 = 2 \), the decrease is sudden. By this, it can be inferred that the translational foundation response of massless foundation decreases with increase in foundation embedment.

**Effects of Stratum Depth**

To study this effect, 3 cases of different \( H/r_0 \) are considered with \( r_0 = 5 \) m. The height of the stratum is varied with values 5m, 10m, and 15m, keeping all other parameters constant. The \( e/r_0 \) is 0.5 and \( \xi \) is 5%. The results are shown in Fig. 4. It is observed that for greater stratum depth, the T.F. curve is relatively smoother with gradual decrease, while for smaller depth, drop in the curve is sudden. There is a slight decrease in T.F. amplitude with increase in \( H/r_0 \).

Fig. 3 Transfer function for translational motion for different \( e/r_0 (H/r_0 = 4, \xi = 5\%) \)

Fig. 4 Transfer function for translational motion for different \( H/r_0 \) for \( e/r_0 = 0.5, \xi = 5\% \)
Effects of Damping of Soil
To study the effect of damping ratio, the values of damping ratio of the soil are varied with values 0, 5%, 10% and 20%
keeping all other parameters constant. The e/r₀ = 1 and H/r₀ = 4. From Fig. 5, there is an increase in amplitudes of T.F. with increase in damping ratio. Also number of troughs decreases with increase in damping.

DYNAMIC STIFFNESS
Parametric study on spring coefficient [k(a₀)] and damping coefficient [c(a₀)] for horizontal motion are presented in this section. Variation of these coefficients with dimensionless frequency is plotted. The parameters considered are boundary conditions, embedment ratio (e/r₀), stratum ratio (H/r₀) and damping ratio (ζ).

Effects of Boundary Conditions
Two cases were considered. First, foundation resting on soil over bedrock (Case 1 – Fig. 1 a) and second, foundation resting over homogeneous half-space (Case 2 – Fig. 1 b). The damping ratio, ζ = 5%, e/r₀ = 1 and H/r₀ = 4. From Figs. 6 a, b, the spring coefficients for case 1 show oscillating behaviour. The damping coefficient is smaller for the case 1 than that of case 2.

Effect of Embedment
The embedment ratios considered are 0, 0.5, 1 and 2. The hysteretic damping of the soil is 5% and H/r₀= 4. Figure 7 a shows relatively smooth curve for surface foundation than that for embedded foundations. k₁(a₀) decreases with increase in embedment depth. While Fig. 7 b shows increase in c₁(a₀) with increase in embedment depth.

Effects of Stratum Depth
The height of the stratum is varied with values 5m, 10m, and 15m, keeping all other parameters constant. e/r₀ is 0.5 and ζ is 5% for all the cases. From Fig. 8 a, as the stratum ratio is increased, the k₁(a₀) curve increases and oscillation is more. Fig. 8 b shows that c₁(a₀) increases with increase in stratum ratio. It can be inferred that greater the depth of stratum, radiation damping is more.

Effects of Damping of Soil
Keeping all the values constant, only the values of damping ratio of soil is varied. The values are 0, 5%, 10% and 20%. The geometric and soil properties are the kept constant with e/r₀ = 1 and H/r₀ = 2. It can be observed from Fig. 9 a, spring coefficient decreases with increase in damping. The damping coefficients, Fig. 9 b, shows sharp peak at very low frequency (a₀ ~ 0.02) and then retain a constant value. It can also be observed that for undamped case the initially damping coefficient is zero (up to, a₀ = 0.046) and later has a constant value.

CONCLUSIONS
The study indicates frequency dependent characteristics for both foundation input motion and dynamic stiffness. Based on the work carried out, it is observed that there is no effect of kinematic interaction for surface foundation. The damping coefficient of the soil increases while stiffness coefficient decreases with increase in embedment depth. The damping coefficient increases with increase in stratum depth. This shows the radiation damping is more for greater stratum depth. Damping coefficient represents the damping characteristics of soil. At lower frequency level, the material damping has dominant effect on damping coefficient. At higher frequencies radiation damping comes into picture. With increase in material damping of soil, the amplitude of transfer function increases.
The boundary condition is an important factor which affects the dynamic stiffness. Radiation damping is more in case of homogenous half-space compared to that of soil over rigid bedrock. Though study is based on simplified model but the outcome has very much practical significance.

REFERENCES

Fig. 6 Effect of boundary conditions for horizontal motion (a) spring coefficient; (b) damping coefficient

Fig. 7 Effect of embedment on horizontal motion (a) spring coefficient; (b) damping coefficient

Fig. 8 Effect of stratum height ($e/r_0 = 0.5$) on horizontal motion (a) spring coefficient; (b) damping coefficient

Fig. 9 Effect of damping ratio ($e/r_0 = 1$ & $H/r_0 = 2$) on horizontal motion (a) spring coefficient; (b) damping coefficient