Analytical Approaches for Soil Structure Interaction

Ghalimath A.G[1], More Sheetal.A [2], Hatti Mantesh.A[3], Jamadar Chaitrali.A[4]

[1] *Assistant professor, civil department, A.G.P.I.T Solapur, Maharashtra, India*
[2 3 4] *Civil department, A.G.P.I.T Solapur, Maharashtra, India*

***

Abstract - ***Earthquake in populated areas throughhout the word causes entensive damage to the various structures that result in catastropic loss of human life and enormous economic losses. However, the damage can be attributed to the inadequate design of the structures. This paper deals with seismic soil structure interaction analysis. It has conventionally been considered that soil-structure interaction has a benificial effect on the seismic response of structure. Considering soil-structure interaction makes a structure more flexible and thus, increasing the natural period of the structure compared to the corresponding rigidly supported structure. The seismic waves circularise through soil during an earthquake, a discontiniuty in the metier of wave propagation is clashed at the interface of soil and structural foundations. A structure subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus changes the motion of the ground. The change in the material properties leads to scattering, diffraction, reflaction, and refraction of the seismic waves at this soil-foundation interface thereby changing the nature of ground motion at that point from what would have otherwise been observed in the absence of structure and foundation.***

Key Words: *soil structure interaction, kinematic interaction, inertial interaction, dynamic analysis approaches,*

1. Definition of soil structure interaction

The process in which the response of the soil influences the motion of the structure and motion structure influvences the response of the soil is termed as soil structure interaction.

There are two primary issues involved in the phenomenon of soil-structure interaction.

1.1 Kinematic interaction

First, as the seismic waves propoagate through soil during an earthquake, a discontinuity in the medium of wave propagation is encountered at the interface of soil and structual foundations. The change in the material properties leads to scattering, diffraction, reflaction, and refraction of the seismic waves at this soil-foundation interface thereby changing the nature of ground motion at that point from what would have otherwise been observed in the absence of structure and foundation. Further, the seismic wave propagation takes place by deformations in the medium. Since the foundation can be cosidered to be very rigid in comparison to the soil deposits, the deformations of the soil at the soil-foundation interface are constrained as the foundation cannot deform by the same amount as the soil. This further leads to slippage across the soil-foundation interface-a nonlinear phenomenon- which is very difficult to account for in the mathematical models for practical vibration analysis. Moreover, the rigid foundation acts like a low-pass filter by averaging out the high frequency components in seismic motions due to the kinematic constraint imposed by the rigid foundation. It should be noted that the above-mentioned effects are only due to the wave propagation in elastic medium. The dynamic behaviour of the structure has no role to play in this aspect. Therefore, these effects arising out of the wave propagation considerations are known as kinematic interaction effects.

1.2 Inertial interaction

The actual seismic input motion to the structural foundation is the result of kinematics interaction analysis considering only the geometry and stiffness properties of the structural foundation and soil.the second aspect of the soil- structure interaction analyasis involves the deforamations and stresses in supporting soil, induced due to the base shears and moments generated in the vibrating structure. The soil deformations further lead to a modification of the dynamic response of structural system and thereby creating a dynamically interacting system. This second aspect of soil-structure interaction problem which results from the dynamic response of structural system is known as the inertial interaction.

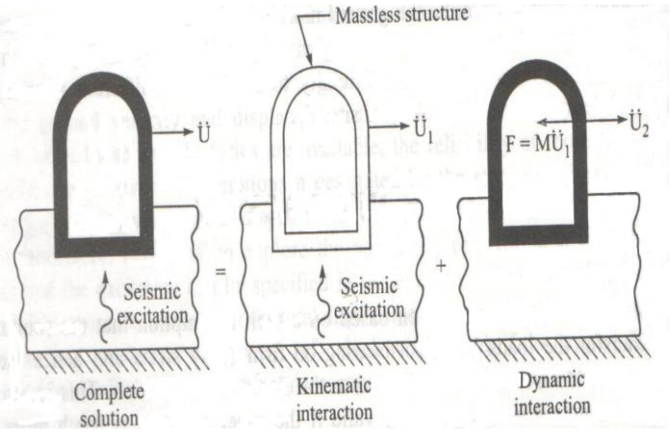


Fig -1: Soil-structure interaction analysis.

2. Dynamic analysis including SSI effects

Two different approaches have been adopted in the past to investigate the problem of soil-structure interaction and incorporate the effect of soil compliance in the dynamic analysis:

1. **The Direct approach**
2. **The Substructure approaches.**

2.1 The Direct approach

It is based on including the soil medium in the mathematical model developed for dynamic analysis. This is typically done by using finite element discretisation of the domin with appropriate absorbing/transmitting boundaries. Thes special boundary elements are necessary to simulate the effects of unbounded soil medium which requires that the seismic energy should radiate away from the vibration source. The use of absorbing/transmitting boundaries prevent the seismic energy being reflected back into the problem domain.The essential features of this approach can be understood from figure 11.9.although the method is quite simole in concept, its implimentation for anslysis of practical problems presents a formidable computational task. The requirement of including the soil strata in the mathematical model for dynamic analysis leads to a very large system of equations to be solved. Further, the development of absorbing/transmitting boundaries is based on the assumption of the presence of soil layer that is bounded by rocky strata at the base. The computed results could be erroneous if the site has deep soil deposoits and the bottom boundry of the finite element model is placed at a shallow depth instead of the bedrock level. Further,the lower modes with the superstructure riding on top of soil mass as a rigid body owing to the more flexible nature of soil in comparison with the structural system since the deformations and stresses in structural system are of primary interest for the purpose of design, huge computational effort and storage is required to compute and store the eigen-pairs required for inclusion of all modes, ensuring more that the cumulative effective modal mass is more than 90% of the total vibrating mass. A common numerical trick to force the lower modes of the combined soil-structure system to correspond to the deformations in structural system is to consider the soil medium to be massless. This forces the modes for soil deformation to move to the higher end of the Eigen spectrum, thereby providing structural modes at the lower end of the Eigen spectrum.

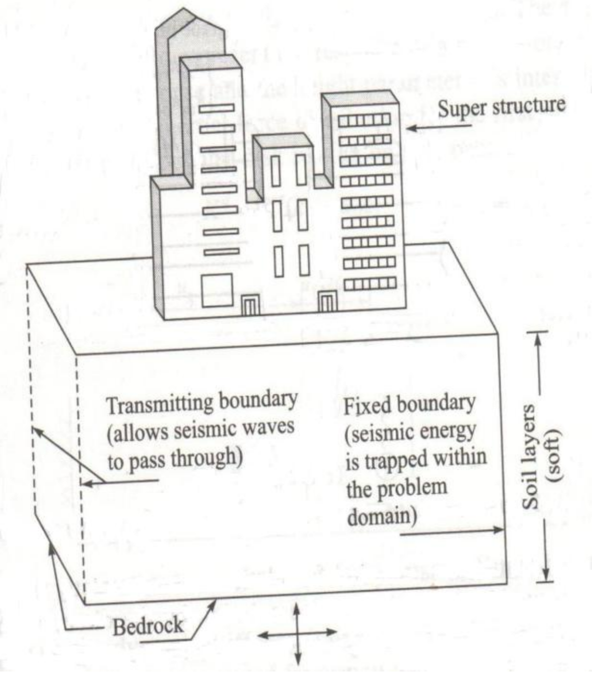


Fig -2: Seismic input is applied at the bedrock level and the complete system of soil and structure is analysed. The interaction effects are naturally taken care of.

2.2 The substructure approach

In the substructure approach the SSI problem is divided into three distinct parts which also demonstrates the basic concept of substructure method of soil-structure interaction analysis. The three-step solution for SSI problems consists of:

i) Determination of foundation input motion by solving the kinematic interaction problem,

ii) Determination of the frequency dependent impedence founctions describing the stiffness and damping characterstics of the soil-foundation interacting system. This step should account for the geometric and material properties of foundation and soil deposits and is generally computed using equivalent linear elastic properties for soil appropriate for the in-situ dynamic shear strains. This step yields the so-called soil springs.

iii) Computation of response of the real structure supported on frequency dependent soil springs and subjected at the base of thes springs to the foundation input motion computed.

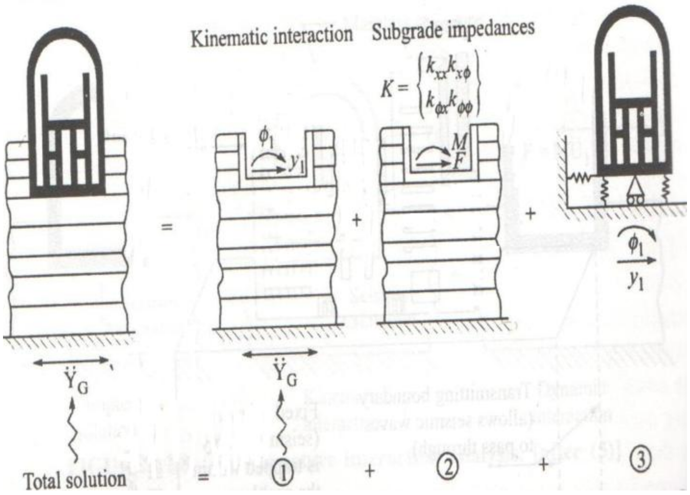
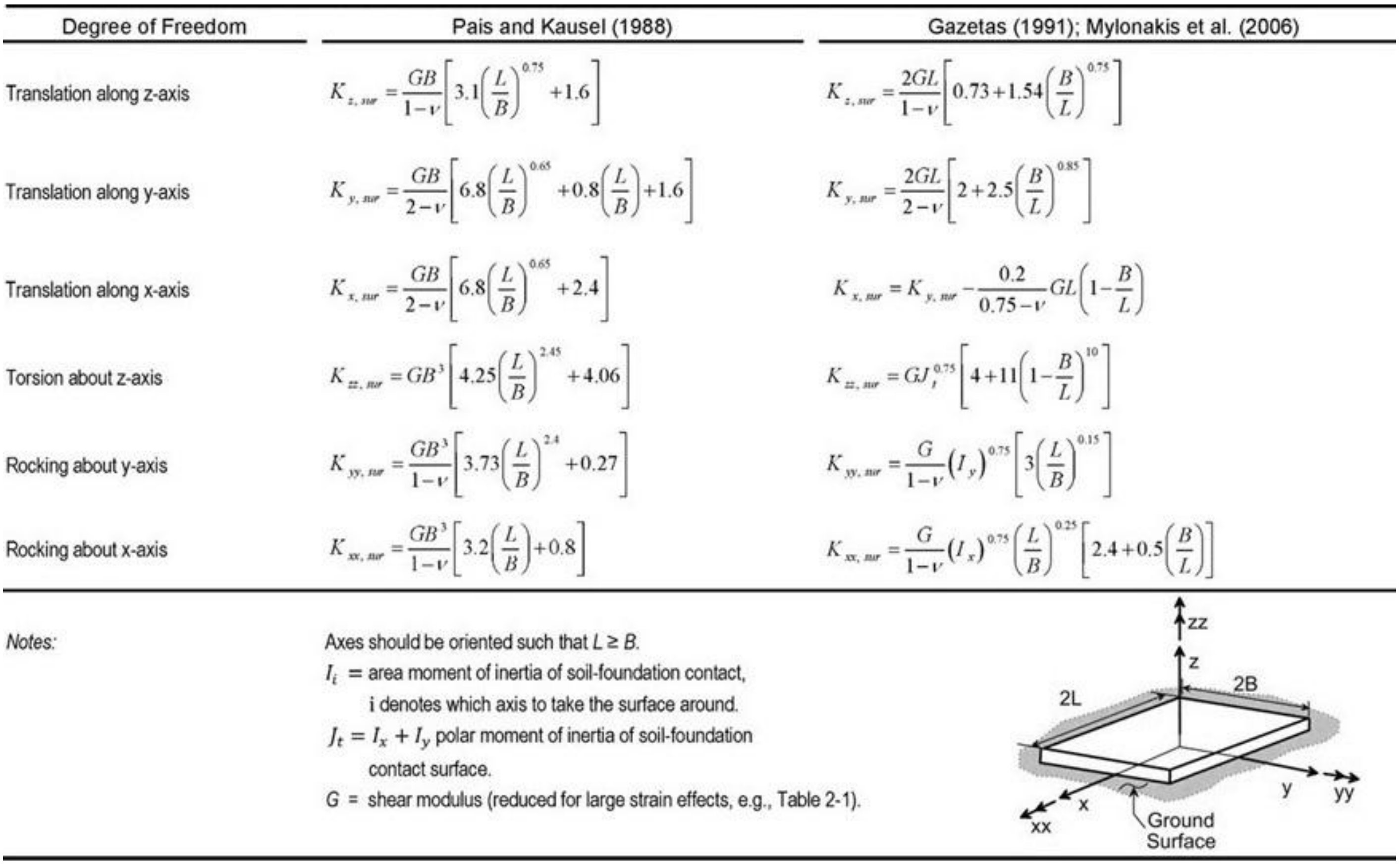


Fig -3: Soil-structure interaction analysis by substructure method.

It should be noted that if the structural foundations were perfectly rigid, the solution by substructure approach would be identical to the solution by the direct method. Further, the superposition principle is valid for linear systems only. Since the shear modulus and damping properties of soil are strain dependent, the use of the principle of superposition can be questioned. However, it has been observed that most of the nonlinearity in soil-structure interaction itself. Therefore, the soil properties estimated for the same strain levels as expected during a postulated design earthquake may be used in the steps (i) and (ii) without any further modification. Resonable approximations can be obtained on the basis of one-dimentional wavepropogation theory for the solution of step (i), and by using some correction factors for modifying the springs for a surface footing on a layered soil deposits to account for the embedment of foundation as a solution to step (ii) of the problem. Several investigators have provided expressions/curves/charts for the impendance founctions for different parameters of the soil-foundation system. A concise summary of available impedence functions and approximate analytical expressions has been presented by pais and kausel.

The formulaes for soil-structure interaction analysis is given by pais and kausel are given below which are modified by Gazetas.

Table -1: Elastic solutions for static stiffness of rigid footings at the ground surface

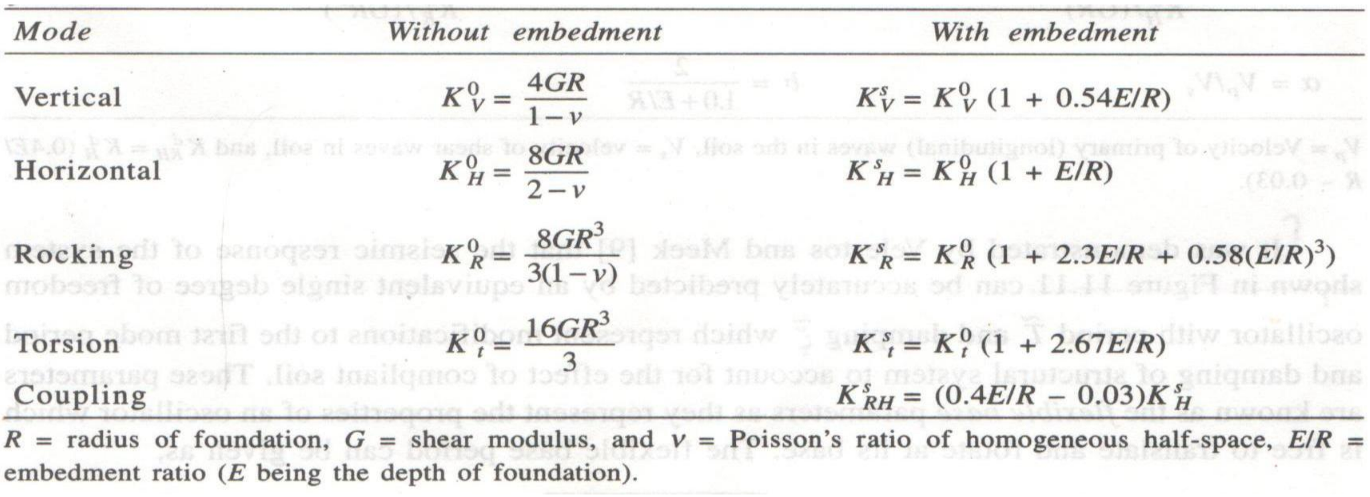


Degree of Freedom	Pais and Kausel (1988)	Gazetas (1991); Mylonakis et al. (2006)
Translation along z-axis	$K_{z,\,sur} = \frac{GB}{1-\nu}\left[3.1\left(\frac{L}{B}\right)^{0.75} + 1.6\right]$	$K_{z,\,sur} = \frac{2GL}{1-\nu}\left[0.73 + 1.54\left(\frac{B}{L}\right)^{0.75}\right]$
Translation along y-axis	$K_{y,\,sur} = \frac{GB}{2-\nu}\left[6.8\left(\frac{L}{B}\right)^{0.65} + 0.8\left(\frac{L}{B}\right) + 1.6\right]$	$K_{y,\,sur} = \frac{2GL}{2-\nu}\left[2 + 2.5\left(\frac{B}{L}\right)^{0.85}\right]$
Translation along x-axis	$K_{x,\,sur} = \frac{GB}{2-\nu}\left[6.8\left(\frac{L}{B}\right)^{0.65} + 2.4\right]$	$K_{x,\,sur} = K_{y,\,sur} - \frac{0.2}{0.75-\nu}GL\left(1-\frac{B}{L}\right)$
Torsion about z-axis	$K_{zz,\,sur} = GB^3\left[4.25\left(\frac{L}{B}\right)^{2.45} + 4.06\right]$	$K_{zz,\,sur} = GJ_t^{0.75}\left[4 + 11\left(1-\frac{B}{L}\right)^{10}\right]$
Rocking about y-axis	$K_{yy,\,sur} = \frac{GB^3}{1-\nu}\left[3.73\left(\frac{L}{B}\right)^{2.4} + 0.27\right]$	$K_{yy,\,sur} = \frac{G}{1-\nu}(I_y)^{0.75}\left[3\left(\frac{L}{B}\right)^{0.15}\right]$
Rocking about x-axis	$K_{xx,\,sur} = \frac{GB^3}{1-\nu}\left[3.2\left(\frac{L}{B}\right) + 0.8\right]$	$K_{xx,\,sur} = \frac{G}{1-\nu}(I_x)^{0.75}\left(\frac{L}{B}\right)^{0.25}\left[2.4 + 0.5\left(\frac{B}{L}\right)\right]$

Notes:

Axes should be oriented such that $L \geq B$.
I_i = area moment of inertia of soil-foundation contact, i denotes which axis to take the surface around.
$J_t = I_x + I_y$ polar moment of inertia of soil-foundation contact surface.
G = shear modulus (reduced for large strain effects, e.g., Table 2-1).

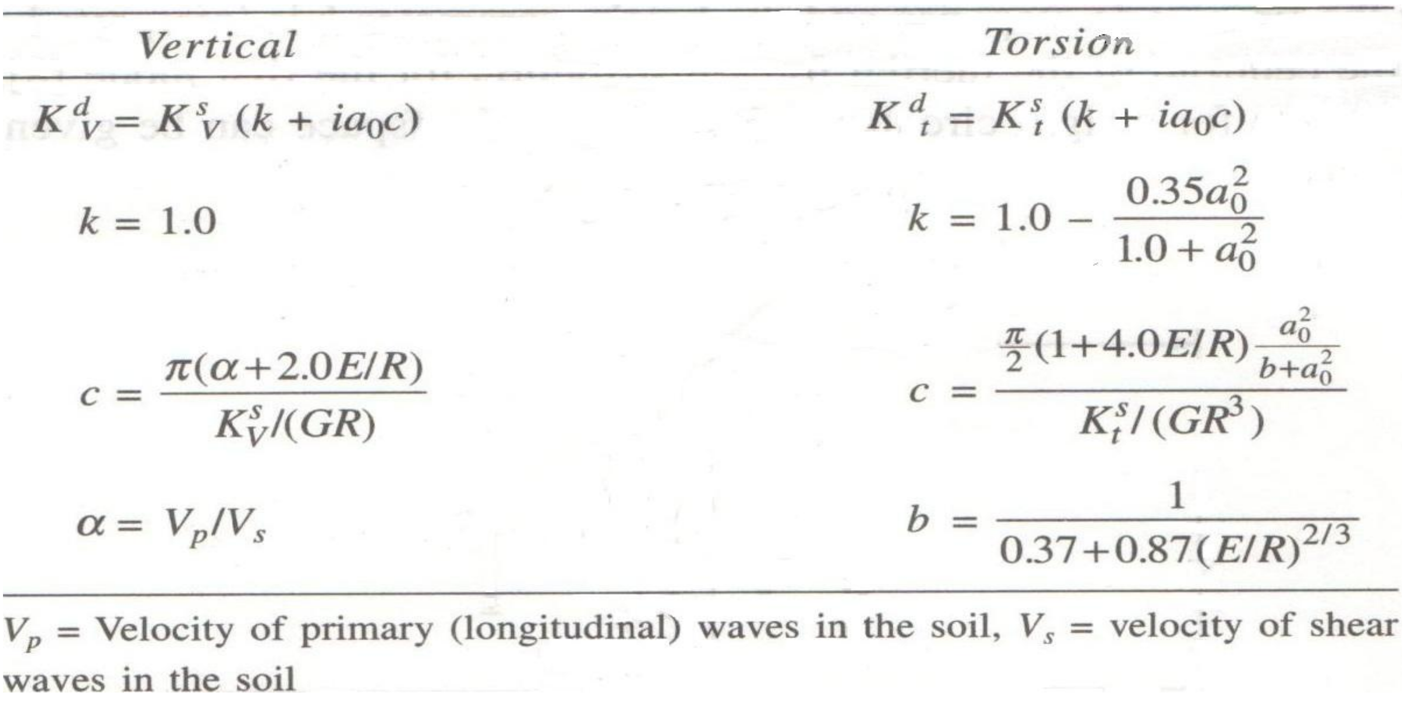
Table -2: Static stiffness coefficients for rigid, circular cylindrical foundation



Mode	*Without embedment*	*With embedment*
Vertical	$K_V^0 = \frac{4GR}{1-\nu}$	$K_V^s = K_V^0\ (1 + 0.54E/R)$
Horizontal	$K_H^0 = \frac{8GR}{2-\nu}$	$K_H^s = K_H^0\ (1 + E/R)$
Rocking	$K_R^0 = \frac{8GR^3}{3(1-\nu)}$	$K_R^s = K_R^0\ (1 + 2.3E/R + 0.58(E/R)^3)$
Torsion	$K_t^0 = \frac{16GR^3}{3}$	$K_t^s = K_t^0\ (1 + 2.67E/R)$
Coupling		$K_{RH}^s = (0.4E/R - 0.03)K_H^s$

R = radius of foundation, G = shear modulus, and ν = Poisson's ratio of homogeneous half-space, E/R = embedment ratio (E being the depth of foundation).

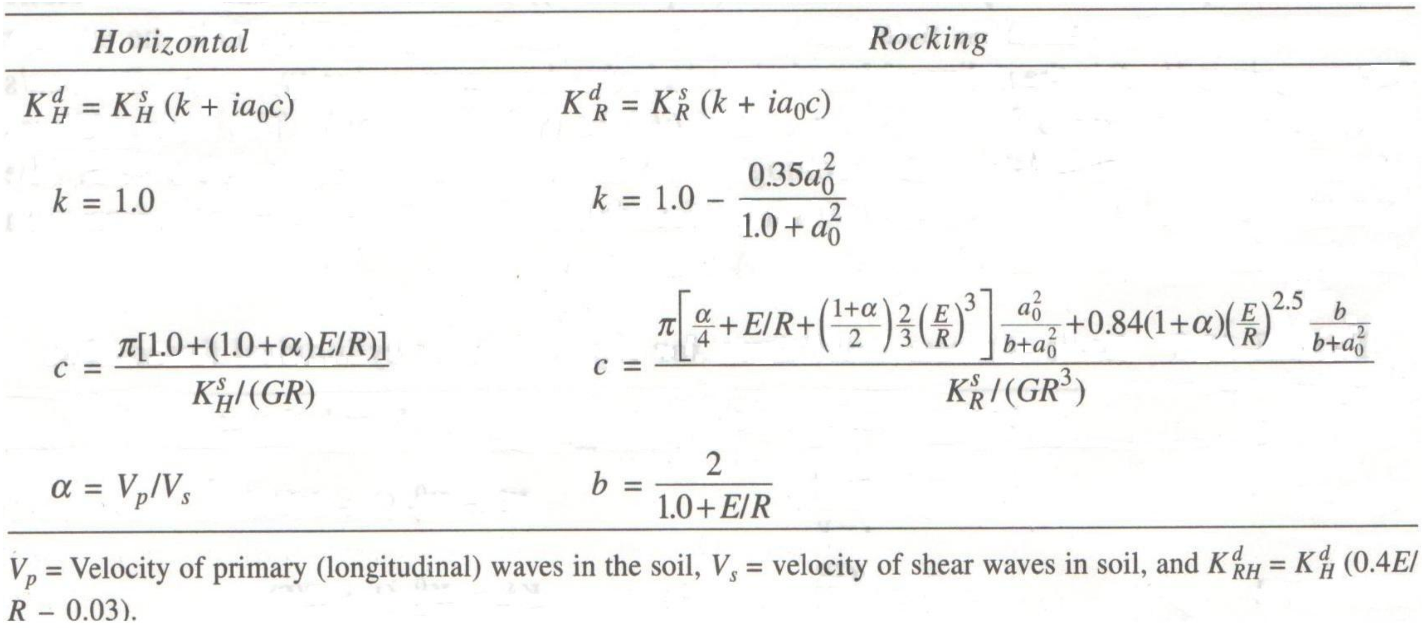
Table -3: Dynamic stiffness for rigid, circular cylindrical foundation: vertical and torsion



Vertical	Torsion
$K^d_V = K^s_V (k + ia_0 c)$	$K^d_t = K^s_t (k + ia_0 c)$
$k = 1.0$	$k = 1.0 - \dfrac{0.35a_0^2}{1.0 + a_0^2}$
$c = \dfrac{\pi(\alpha + 2.0E/R)}{K^s_V/(GR)}$	$c = \dfrac{\frac{\pi}{2}(1+4.0E/R)\frac{a_0^2}{b+a_0^2}}{K^s_t/(GR^3)}$
$\alpha = V_p/V_s$	$b = \dfrac{1}{0.37+0.87(E/R)^{2/3}}$

V_p = Velocity of primary (longitudinal) waves in the soil, V_s = velocity of shear waves in the soil

Table -4: Static stiffness coefficients for rigid, circular cylindrical foundation



Horizontal	Rocking
$K^d_H = K^s_H (k + ia_0 c)$	$K^d_R = K^s_R (k + ia_0 c)$
$k = 1.0$	$k = 1.0 - \dfrac{0.35a_0^2}{1.0 + a_0^2}$
$c = \dfrac{\pi[1.0+(1.0+\alpha)E/R)]}{K^s_H/(GR)}$	$c = \dfrac{\pi\left[\frac{\alpha}{4}+E/R+\left(\frac{1+\alpha}{2}\right)\frac{2}{3}\left(\frac{E}{R}\right)^3\right]\frac{a_0^2}{b+a_0^2}+0.84(1+\alpha)\left(\frac{E}{R}\right)^{2.5}\frac{b}{b+a_0^2}}{K^s_R/(GR^3)}$
$\alpha = V_p/V_s$	$b = \dfrac{2}{1.0+E/R}$

V_p = Velocity of primary (longitudinal) waves in the soil, V_s = velocity of shear waves in soil, and $K^d_{RH} = K^d_H (0.4E/R - 0.03)$.

It was demonstrated by velestos and meek that the seismic response of the system can be accurately predicted by an equivalent single degree of freeedom oscillator with period $\tilde{T}$ and damping $\tilde{\zeta}$ which represent modifications to the first mode period and damping of structural system to account for the effect of compliant soil. These parameters are known as the flexible base parameters as the represent the properties of and oscillator which is free to translate and rotate at its base. The flexible base period can be given as,

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k_1}{K_H^d} + \frac{k_1 h^2}{K_R^d}} \qquad \text{………… (1)}$$

Where T is the period of the (fixed base) structure in its first mode and k_1 represents the model stiffness for first mode of (fixed-base) structure. the equivalent viscous damping ratio can be defined in terms of the viscous damping of the structure and radiation and hysteretic damping of the soil-foundation system. The flexible base damping can be given as,

$$\tilde{\zeta} = \tilde{\zeta}_0 + \frac{\zeta}{(\tilde{T}/T)^3} \qquad \text{……….. (2)}$$

Where $\tilde{\zeta}_0$ represents the damping contributions (radiation and hysteretic) from the soil-foundation system. A closed form expression for $\tilde{\zeta}_0$ can be found in the article by velestos and nair. It can be inferred from equations (1) and (2) that the primary effect of inertial interaction is the lengthening of natural period and increase in the damping ratio of the dynamical system.

3. CONCLUSIONS

There are two primary issues involved in the phenomenon of soil-structure interaction.1.Kinematic interaction 2.Inertial interaction

This paper has presented a proposed methodology for modelling the effects of interaction between soil and building structure. The admissible ways of modeling of soil where analysed for chosen structure. There are two approches for modelling of soil–structure interaction (i) direct approach and (ii) substructure approach. In this paper stiffnesses for both static analysis and dynamic analysis were introduced.

REFERENCES

[1] Sesmic behaviour of geotechnial structures,annals of geophysics, vol.45,n.6, december 2002

[2] SSI analysis of a massive concrete structure based on a novel convolution/deconvolution technique, *S¯adhan¯a* Vol. 32, Part 3, June 2007,

[3] Studies on Soil Structure Interaction of Multi Storeyed Buildings with Rigid and Flexible Foundation, Volume 2, Issue 12, December 2012.

[4] Dynamic Soil Structure Interaction Study, Volume 6, No.2,2012

[5] Effect of Soil Structure Interaction in Seismic Loads of Framed Structures, Volume 4, Issue 5, May-2013.

[6] Soil structure interaction analysis methods State of artReview , Volume 2, No 1, 2010

[7] Soil-structure interaction analysis of RC frame shear wall buildings over raft foundations under seismic loading, Volume 4, Issue 5, May-2013.

[8] Different models of soil-structure interaction and consequent reliability of foundation structure.

BIOGRAPHIES

Ms. Sheetal.A. More
Department of civil engineering,
A.G.PATIL INSTITUTE OF
TECHNOLOGY SOLAPUR

Mr. Mantesh.A.Hatti
Department of civil engineering,
A.G.PATIL INSTITUTE OF
TECHNOLOGY SOLAPUR.

Ms.Chaitrali.A.Jamadar
Department of civil engineering,
A.G.PATIL INSTITUTE OF
TECHNOLOGY SOLAPUR.