Dynamics of Soil Structure Interactions

Dr. Bharat Bhushan Prasad [1] and **Monika Tewari**[2]
Department of Civil Engineering, Ajay Kumar Garg Engineering College,
27 Kmstone, NH-24, Ghaziabad 201009 UP India
bhushanbharat1947@gmail.com, monikatewari15@gmail.com

Abstract-**There is a general belief that soil structure interaction (SSI) always plays a favorable role in decreasing the inertia force. It has conventionally been considered that SSI has beneficial effect on the seismic response of a structure. Many design codes have suggested that the effect of SSI can reasonably be neglected for the seismic analysis of structures. This myth about SSI apparently stems from the false perception that SSI reduces the overall seismic response of a structure, and hence, leads to improved safety margins. Most of the design codes use oversimplified design spectra, which attain constant acceleration up to a certain period, and thereafter decrease monotonically with period. 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. Moreover, considering the SSI effect increases the effective damping ratio of the system. The smooth idealization of design spectrum suggests smaller seismic response with the increased natural periods and effective damping ratio due to SSI.**

Keywords: Free Field Kinematic Interaction, Inertial Interaction, Special Dynamic Loading, Soil Structure Interaction (SSI)

I. INTRODUCTION

THE process in which response of the soil influences motion of the structure and motion of the structure influences response of the soil is termed as soil-structure interaction. Earthquake ground motion causes soil deformation known as free-field motion. Such ground motions that are not influenced by the presence of structures are called free-field motions. When they interact owing to very presence of structure, soil structure vibration as a process becomes very important. These interactions have little effects on some systems and larger influences on the response of other system.

Stiff or heavy structures resting on relatively soft soil are more prone to such influence. On the other side, for flexible or light structures on stiff soils soils-structure interaction effects are generally smaller. Under the influence of such interactions the natural frequency of a soil-structure system shall be lower than the natural frequency of the structure itself.

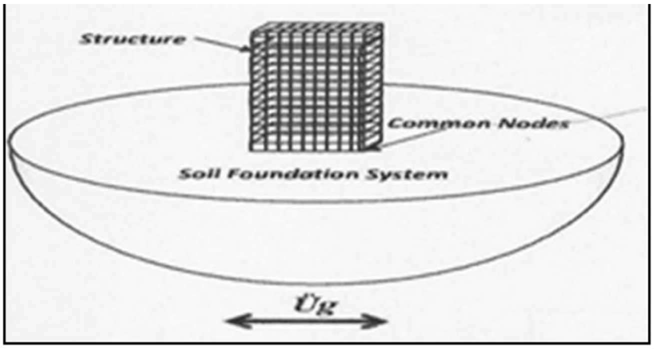


Figure 1. Soil structure system.

Structural dynamics faclitates to evaluate the stresses and deformations of a structure subjected to dynamic loads. The finite dimensions of structure dictate the dynamic model with a finite number of degree of freedom. However, in case the structure does interact with the surrounding soil, it is not sufficient to analyze only the structure. In many types of dynamic loading specially earthquake excitation, the loading is first applied to the soil region around the structure, this means that the former has to be modeled anyway. The soil is a semi-infinite medium, an unbounded domain. However for static loading, a fictitious boundary at a sufficient distance from the structure resting on soft soil where the response is expected to die out from a practical standpoint is generally introduced and takes care of everything.

In brief, it can be candidly stated that a structure by a dynamic load interacts with the surrounding soil in contrast to the structure, the soil is an unbounded domain whose radiation condition has to be taken into account in the dynamic model.

Structural engineering and Geotechnical engineering are closely connected subjects in analysis of civil engineering structures, often analysis in neither of the two subjects can be performed independently with accurate results. To get the superstructure's real behaviour, the sub grade must be modeled sufficiently well. On the other hand, an advanced model of the superstructure is needed to get the correct response in the subgrade. To capture the right behaviours of both superstructure and subgrade in one model, it must include a good soil-structure interaction.

Structural engineers in practice often use software where the structure is modelled in detail, but the subgrade is represented with simple structural element models which sometimes poorly describe the behavior of the soil. Geotechnical engineers instead use software with advanced soil model, but with a simple model of the structure. However, merging today's most advanced commercial design software for the two disciplines, would result in demand for unrealistic large computation time. The user would in such a model also need great knowledge in both of the subjects. Therefore, there is a need for simplified methods in practice to model SSI. Consequently, it is of great interest how the simplifications influence the results.

In engineering practice, there are different opinions how to model SSI. In design of the superstructure, some consider that it's enough with structural element model of the subgrade. Others claim that the soil should be modelled more physically correct with a continuum model, to achieve a good enough SSI-analysis.

II. FREE FIELD MOTION

When earthquake waves hit areas which are not supporting structures rather open lands, then motion produced in the ground are known as free-field motions. In other words ground motions that are not influenced by the presence of the structures are referred to as free-field motion. Consider a hypothetical case wherein earthquakes hit the site having

- Open lands –no foundation or structures
- Only foundation and structure is yet to be constructed
- Ground supporting structures on foundations.

The general response will be very different in all three cases in their own way. In the first case, it will be free-field motion as shown in Figure 2. In second case foundation deformation will be along with free-field motion. There may be a situation wherein, the inability of the foundation to conform to the deformation of free-field motion. Even without the structure as shown in Figure 2, the motion of the foundation will be different from the free-field motion because of the difference in rigidity between the soil on the one hand and the foundations on the other hand.

In the third case as shown in Figure 2, the dynamic response of the structure itself would induce the deformation of the supporting soil. Thus, it is candidly shown that the kinematic interaction is produced by the inability of the foundation to match the free-field deformation, where as inertial interaction is produced by the effect of the dynamic response of the structure foundation on the movement of the supporting soil. However evaluation of free-field motion is itself very complex and difficult for accurate determination.

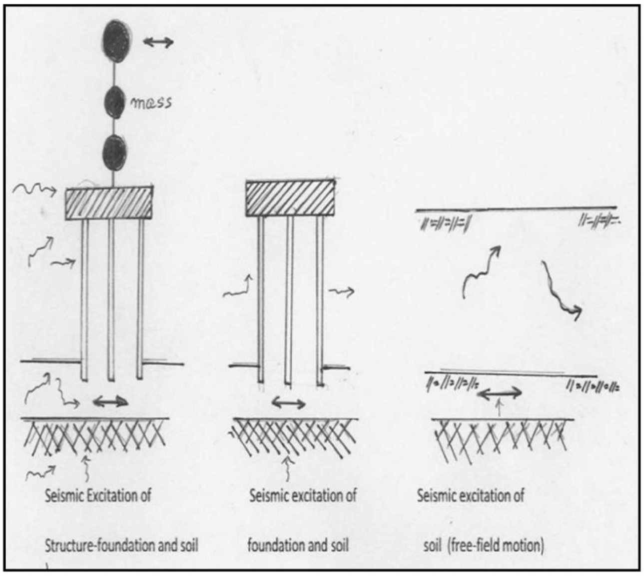


Figure 2. Earthquake excitation and receiving site.

Thus the ground motions that are not influenced by the presence of structures are called free-field motions. When they interact owing to very presence of structure, soil structure interactions as a process becomes very important. These interactions have little effects on some systems and larger influence on the response of source other system, depending upon stiffness or flexibility of the system. Stiff or heavy structures resting on relatively soft soil are more prone to such influence. On the other side, for flexible or light structures on stiff soils soils-structure interaction effects are generally small. Under the influence of such interactions, the natural frequency of a soil-structure system shall be lower than the natural frequency of the structure itself.

The radiation damping will also cause the total damping of a soil-structure system to be greater than them that of the structure itself. Naturally then these interactions affect to reduce the demands on structure but because the foundation can translate and rotate can increase the overall displacement.

Unlike static loading, for dynamic loading the procedure cannot be used as finite domain for the soil and then total discredited system consisting of the structure and the soil cannot be analyzed effectively. The fictitious boundary would reflect waves originating from the vibrating structure back to the discretized soil instead of allowing them to pass through and propagate towards infinity. This need to model the unbounded foundation medium properly distinguishes soil dynamics from structural dynamics. In general soil-structure interaction boils down to two phenomenons namely:

- Kinematic interaction
- Inertial interaction.

III. KINEMATIC INTERACTION

Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes motions at the foundation to deviate from free-field motions. One cause of these deviations is base-slab averaging, in which spatially variable ground motions within the building envelope are averaged within the foundation footprint due to the stiffness and strength of the foundation system. Another cause of deviation is embedment effects, in which foundation-level motions are reduced as a result of ground motion reduction with depth below the free surface. If the foundation is pile-supported, the piles interact with wave propagation below the base slab, which can further modify foundation-level motions at the base of a structure. This section describes the phenomena of base-slab averaging, embedment effects, and kinematic pile response, and presents available models for analysis of SSI.

The kinematic interaction is produced by the inability of the foundation to match the free-field deformation, whereas inertial interaction is produced by the effect of the dynamic response of the structure foundation on the movement of the supporting soil. Kinematic interaction can induce torsion and rocking motion that are not present in a free-field motion. The inertial interaction occurs when the forces transmitted to the soil by the dynamic response of the structure produce foundation movements that would not occur in a fixed base structure. The effects of inertial interaction are usually more pronounced than the effects of kinematic interaction.

When the earthquake ground motion in the free-field is varying over the area corresponding to that of the rigid foundation, then it can be constrained and modified by the rigid foundation.

This deviation from free field motion is called kinematic interaction. In other words, this inability of the foundation to match the free-field motion causes kinematic interactions, as shown in Figure 2.

Moreover, stiffness of the foundation can cause variation of ground motion with depth and scattering of waves at the corners of the foundation. If the foundation dimensions are small compared to the wave length of interested frequency range, kinematic interaction has negligible effects on the response [4]. But if the foundation dimensions are in the same order of the wave length, then interaction has pronounced effects on the response.

The output from an analysis accounting for the kinematic interaction is an effective input motion, which is denoted as foundation input motion. The mathematical transformation from the free-field motion to the foundation input motion could be performed by a frequency dependent transfer function which is a site-specific curve.

At low level of ground shaking, kinematic effect is more dominant causing lengthening of period and increase in radiation damping. In other words, when the earthquake ground motion in the free-field is varying over the area corresponding to that of the rigid foundation, then it can be constrained and modified by the rigid foundation.

The kinematic approach based on the yield design theory applied to foundation behaviour mechanism of the type as shown in Figure 3, permits the determination of seismic demand. In terms of vertical force, horizontal force and overturning moment are applied to the foundation with respect to the sets of allowable loads.

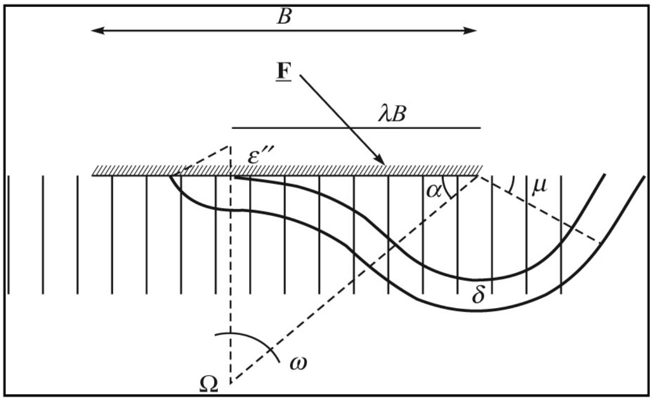


Figure 3. Kinematic mechanism.

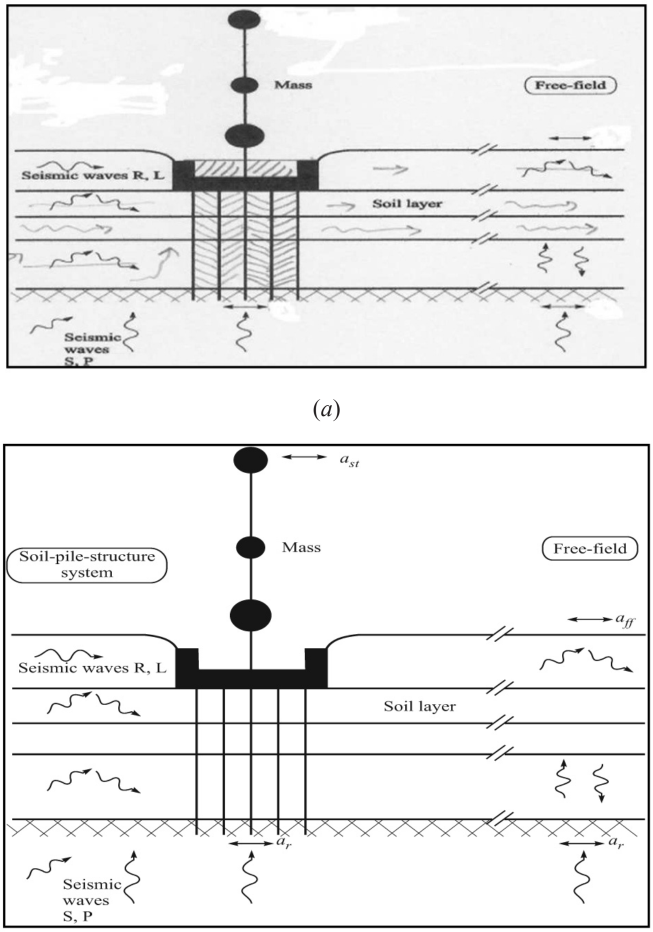
IV. INERTIAL INTERACTION

Mass of the structure transmits inertial force to soil causing further deformation in it, which is popularly known as inertial interaction. Inertial forces induced by foundation motion during the earthquake can cause the compliant soil to deform which in turn affects the super-structure inertial forces. This deformation propagates away from the structure in six degrees of freedom of the foundation motion. In other words, the dynamic response of the superstructure decreases. This removal of energy from the system is referred to as radiation damping in literature [1]. He used a viscous damper to take into account the radiation damping.

The coefficient of the viscous damper is proportional to the wave velocity in the soil and the foundation area. This increase in effective damping is significant for a soil site. This increase in effective damping is significant for a soil site approaching a homogeneous elastic half space [1]. This deformation propagates away from the structure in six degrees of freedom.

V. COMBINATION OF KINETIC AND INERTIAL INTERACTION

The soil-structure interaction studies may be considered as kinematic interactions or inertial interactions or combination of kinematic and inertial interactions. As such the foundation, in a broad sense is checked for the combined inertial and kinematic loading.



(*a*)

(*b*)

Figure 4. Models for soil-structure interaction Problem.

VI. FIXED BASE AND FLEXIBLE BASE

When analyzing the seismic response of structures, it is common practice to assume the base of the structure to be fixed, which is a gross assumption since in most situations, the foundation soil is flexible. This assumption is realistic only when the structure is founded on solid rock or when the relative stiffness of the foundation soil compared to the superstructure is high. In all other cases, compliance of the soil can induce two distinct effects on the response of the structure:

- modification of the free-field motion at the base of the Structure (kinematic interaction)
- introduction of deformation from dynamic response of the structure into the supporting soil (inertial interaction).

The former is referred to as kinematic interaction, while the latter is known as inertial interaction and the whole process is commonly referred to as soil-structure interaction. The main concept of site response analysis is that the free-field motion is dependent on the properties of the soil profile including stiffness of soil layers. The stiffness of the deposit can change the frequency content and amplitude of the ground motion. Likewise, on the path to the structure, wave properties might be changed due to the stiffness of the foundation.

The term dynamic is defined simply as time varying and as such, a dynamic load is any load whose magnitude, orientation and direction vary with time. In other words, the dynamic forces are those that are time-dependant and act for small or bigger interval of time or quickly change in magnitude or direction.

The response to dynamic loading may be evaluated in a deterministic way or non-deterministic way depending upon whether the variation of loading is totally known or partially known. Further the deterministic loadings are of two types, namely, periodic and non-periodic.

Non-periodic loading is either a short-duration impulse loading or a long-duration general type of dynamic loading. An impact owing to explosion (Bomb blast on building) is typical source of impulsive loading.

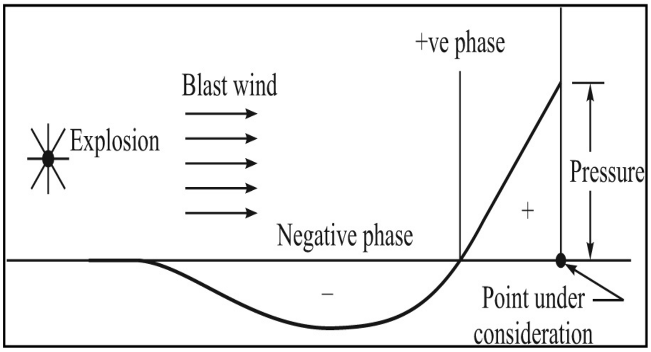


Figure 5. Bomb Blast Shock.

Figure 6. Blast loads on a building.

Explosion loads act directly on the exterior envelope whereas earthquakes load buildings at the base of the building. Consequently the focuses are out of plane response for explosions and in plane response for seismic loads.

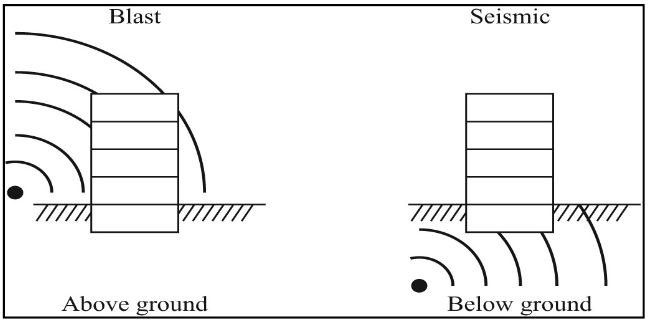


Figure 7. Blast load and seismic load on structure.

Explosion loads are characterized by a single high pressure impulsive pulse acting over milliseconds rather than the vibration loading of earthquakes which is acting over seconds as shown in figure 7.

Explosion loads generally cause localized damage. Mass helps resist explosion loads whereas mass worsens earthquake response.

VII. STRESS CONDITIONS OF SOIL UNDER STATIC AND DYNAMIC LOADING

There are two types of forces/loads that may act on soil mass or sub-structure or earth retaining structures namely static and dynamic forces.

Static forces are those that are gradually applied and remain in place for longer duration of time. These forces are either not dependant on time or have less dependence on time. For this reason live load acting on them is considered as a static load because it usually varies gradually in magnitude. There are many factors which are equally important under static loading and dynamic loading namely

- Void ratio
- Confining stress
- Water content
- Stress history
- Level of strain.

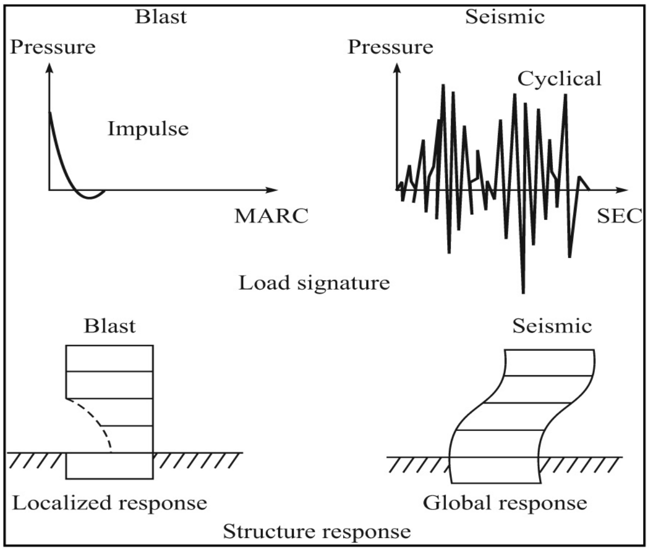


Figure 8. Seismic loads and Bomb blast load.

The duration of time or time of loading is crucial in deciding static response or dynamic behavior of soil. The rapidity of load application is definitely a feature characterizing the load phenomenon. Several events are generally classified on time of loading namely as shown in Figure 8, Bomb blasting, Earthquake, Pile Driving, Traffic loads/movements, Machine Vibrations/Machine foundations, Wave induced loads, Static loads.

In soil dynamics, the load on soil is repetitively applied many times. Thus repetitiveness in loading is main criteria to classify dynamic problems.

The problem with rapid application of one single impulse is represented by shock such as that generated by dropping of mobs or blasting of explosives. The duration of loading is as short as 10^3 to 10^2 seconds. Such dynamic loads are generally called as an Impulse or shock load as shown in Figure 9.

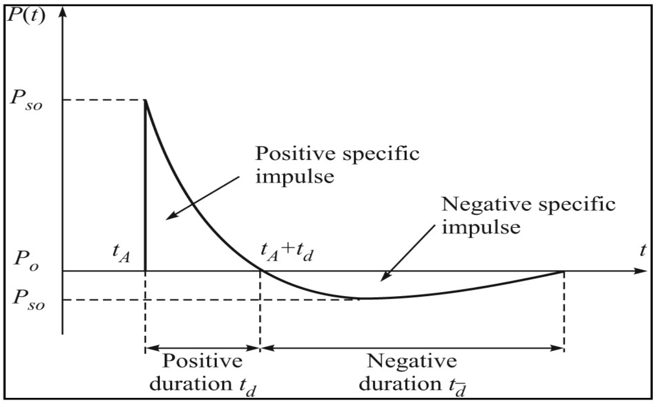


Figure 9. Blast wave pressure-time history.

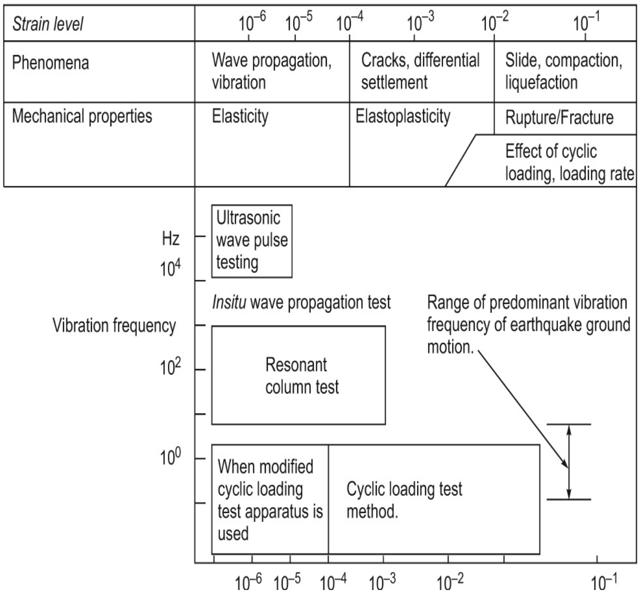
VIII. DYNAMIC LOADING-STRAIN LEVEL DEPENDENCE

Stress conditions, shear deformations and strength characteristics of soil subjected to static loads depend on soil characteristics such as initial void ratio, relative density, initial static stress level and above all stress history. The stress deformations and strength characteristics of soils subjected to dynamic loads also depend upon initial static stress field, initial void ratio, pulsating stress level and the frequency of the loading. In this context, various problems in geotechnical engineering require determination of the dynamic soil properties. In case of dynamic loading, such problems are either of small strain amplitude response type or of large strain amplitude response type. Machine foundations subjected to dynamic loads can sustain small levels of strains while structural elements subjected to seismic forces or bomb blast loading must sustain large strain levels. Ishihara [6] suggested the values of strain levels from various field and laboratory tests and the corresponding state of soil. The dynamic soil properties are strain level dependent as shown in Table 1.

The IS 5249 recommended various field and laboratory tests for evaluating dynamic soil properties. As the dynamic properties of soils are strain level dependent, various laboratory and field tests have been developed to include a wide range of strain amplitudes. The large strain amplitude responses are of the order of 0.01% to 0.1%, whereas small strain amplitude responses are of the order of 0.0001% to 0.001%.

Force is replaced by pseudo equivalent static force and then for convenience a simple solution is obtained. In important cases this sometimes may lead to dangerous results. Here, in such cases, the dynamic analysis is at times essential and dynamic characteristics should be evaluated for the natural frequency wherein it should be assumed that the resonance will not occur.

TABLE 1 -STRAIN LEVEL DEPENDENCE OF SOIL BEHAVIOUR



As all structures on earth are supposed by ground realities the problem of dynamic loading of soils and foundations has existed ever since the art came into existence. Earthquakes producing damage, deformation and rupture of earth mass and so tackling them in seismic and technical way, the soil dynamics and earthquake engineering are under use simultaneously. The concepts of random process, probability theory, reliability analysis providing positive definite confidence level in analysis and design are need of the present time to insure earthquake resistant design and construction not from forces acting on a super structure but from the supporting soil. Consequently, they are transmitted to the structure which reacts in accordance with its own characteristics and that of the soil as well. Often motion of the soil is caused by the earthquakes. Either the ground motions are taken care of in deterministic way or else they are postulated by probability methods or random process or through shock spectra.

The dynamic analysis of bases and foundations subjected to dynamic loads is expected to provide a time wise history of displacement, stress, strain and similar quantities. It is also expected to provide certain dynamic characteristics of the soil and foundations such as natural frequencies. From the design point of view, it is sufficient to know the maxim of the responses. In such a case special and often simpler methods of analysis are involved without the need of detailed time history response. However in many stability problems, the dynamic response to base and foundations of dynamic loads may be evaluated by the deterministic and non-deterministic approach. The response to prescribed dynamic loading is obtained by a deterministic analysis whereas in non-deterministic analysis, the analysis to a random dynamic loading is expressed basically in terms of displacements. Thus, a deterministic analysis leads to a displacement time history corresponding to the presented loading history, whereas other parameters such as stress, and strains are usually obtained as secondary phase of analysis. On the other hand, a non-deterministic analysis provides statistical information about the displacement, which results from a statistically defined loading.

The design process is necessarily a synthesis of the methods of analysis and expected experimental data. Prof. Lamb has candidly expressed that the optimum accuracy in analysis and design can be achieved only by proper match of experimental analysis and methods of analysis. Dispersion of ground properties also affects the design and evaluation results. It should, therefore, be properly estimated considering the reasons for fluctuation, its extent, testing methods, precision of design method and so forth, and the same then gets reflected in the design. Detailed studies are necessary when the safety margin is very tight. For correct estimation of dispersed properties the results obtained from a survey or tests are processed statistically to arrive at the dispersion index and distribution function.

Design methods, which consider dispersal of ground properties, include:

- Deterministic method
- Probabilistic method.

In the deterministic method, representative ground properties (values) are used for design, which are decreased or increased considering the fluctuation. In the probabilistic method, ground property values are considered as stochastic variables and are used in the design equation in the form of distribution function. The obtained results are also stochastic variables. The probabilistic design method in combination with economic considerations can lead to rational design and is, therefore, desirable; but, since the calculations become complex, the deterministic method is widely used these days.

For dynamic analysis, it is necessary to determine the details of the following four items:

(*a*) Dynamic input–dynamic force
(*b*) Material properties
(*c*) Method of analysis
(*d*) Safety valuation on the basis of analytical results.

IX. MODEL FOR SSI STUDIES

The structure is modeled by a mass, a spring and a dashpot placed at elevation *h* above the foundation as show in Figure 10. The connection between the structure and the foundation is ensured by rigid beam. The foundation rests on the soil deposit and its interaction with the soil is modeled by the following supporting strata.

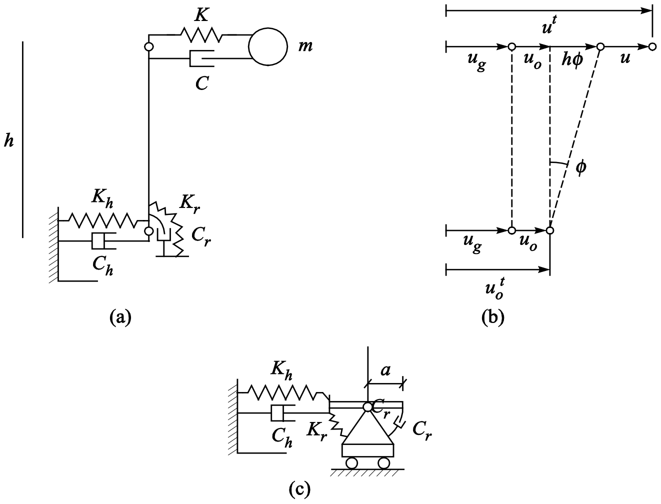


Figure 10. Idealized model for SSI illustration.

X. ILLUSTRATION OF INTERACTION EFFECTS

The most important effects of soil-structure interaction may be illustrated by a simple analysis. Following the approach of Wolf [1], considering the case of the simple SDF system mounted on a rigid, mass less, L-shaped foundation supported on an elastic soil deposit as shown in Figure 10, wherein the structure is characterized by its mass, *m*, stiffness, *k*, and damping coefficient, *c*. If the material supporting the foundation is rigid, the natural frequency of the resulting fixed-base system would depend only on the mass and stiffness of the structure, that is,

$$\omega_0 = \sqrt{\left(\frac{k}{m}\right)} \tag{1}$$

and the hysteretic damping ratio may be expressed as

$$\xi = c\,\omega_0/2k \tag{2}$$

The foundation can translate and rotate provided the supporting material is compliant. The stiffness and damping characteristics of the compliant soil-foundation system can be represented by the transnational and rotational springs and dashpots shown in Figure10. The foundation dashpots represent two sources of damping: material damping caused by

- inelastic behaviour of the soil supporting the foundation,
- rotation damping that occurs as dynamic forces in the structure cause the foundation to deform the soil, producing stress waves that travel away form the foundation.

The amount of material damping will depend on the level of strain induced in the soil; if the strains are high, material damping can be substantial, but if they are low, the material damping may be negligible. In contrast, radiation damping is a purely geometric effect that exists at low as well as high strain amplitudes.

For typical foundations, radiation damping is often much greater than material damping. It is mathematically convenient and advantageous to split total displacements of the mass and the base of the structure into their individual components (Figure 10).

$$(-m\omega^2 + i\omega c_e + k_e)\, u = m\omega^2\, U_{gE} \tag{3}$$

where ^{U}gE is the equivalent seismic input motion. Note that the mass is the same for the equivalent and actual models. For the equivalent system

$$k_e = m\omega_e^2 \tag{4}$$

$$\xi_e = \frac{c_e\, w}{2k_e} \tag{5}$$

The natural frequency of the equivalent model, ω_e, is the frequency at which the response of the equivalent system goes to infinity for $\xi_e = 0$. This occurs when

$$\frac{1}{w_e^2} = \frac{1}{w_0^2} + \frac{1}{w_h^2} + \frac{1}{w_r^2} \tag{6}$$

Equation (6) indicates that the natural frequency of the equivalent system is always lower than that of the fixed-base structure. In other words, an important effect of soil-structure interaction is to reduce the natural frequency of the soil-structure system to a value lower than that of the structure under fixed-base conditions.

XI. FOUNDATION STIFFNESS AND DAMPING.

Inertia developed in a vibrating structure gives rise to base shear, moment, and torsion. These forces generate displacements and rotations at the soil-foundation interface. These displacements and rotations are only possible because of flexibility in the soil-foundation system, which significantly contributes to overall structural flexibility. Moreover, these displacements give rise to energy dissipation via radiation damping and hysteretic soil damping, which can significantly affect overall system damping. Since these effects are rooted in structural inertia, they are referred to as inertial interaction effects. The values of the stiffnesses of the springs are dependent on the mechanical characteristics of the soil material, the dimensions of the foundation, and its embedment depth. The mechanical characteristics of the foundation soil medium are represented by the effective shear modulus G, the mass density ρ, and

Poisson's ratio V. At low strain, the maximum shear modulus G is related to the shear wave velocity and the shear wave velocity is expressed as

$$V_5^2 = [G/\rho] \qquad (7)$$

When comparing a structure embedded in soil with same structure resting in rock, the motion at the base of structure is affected in three ways namely,

- Free-field response is modified (usually amplified)
- Kinematic interaction- excavation of the soil and insertion of the base of the mass less structure into it resulting in relation and additional rotation
- Inertial interaction- the inertial load from seismic excitation will alter the motion along the base.

It has been shown that the SSI effect is higher for tall buildings than for low-rise buildings. If the shear wave velocity of the soil is in range of $180 < V_5 < 360$ m/sec, then it can be assumed of resulting in worst scenario of flexible base.

In other words, an important effect of soil-structure interaction is to reduce the natural frequency of the soil-structure system to a value lower than that of the structure under fixed-base conditions.

XII. MYTH ABOUT SSI EFFECTS

With this assumption, it was traditionally been considered that SSI can conveniently be neglected for conservative design. In addition, neglecting SSI tremendously reduces the complication in the analysis of the structures which has tempted designers to neglect the effect of SSI in the analysis.

This conservative simplification is valid for certain class of structures and soil conditions, such as light structures in relatively stiff soil. Unfortunately, the assumption does not always hold true. In fact, the SSI can have a detrimental effect on the structural response, and neglecting SSI in the analysis may lead to unsafe design for both the superstructure and the foundation.

Using rigorous numerical analyses, Mylonakis and Gazetas [5] have shown that increase in natural period of structure due to SSI is not always beneficial as suggested by the simplified design spectrums. Soft soil sediments can significantly elongate the period of seismic waves and the increase in natural period of structure may lead to the resonance with the long period ground vibration. Additionally, the study showed that ductility demand can significantly increase with the increase in the natural period of the structure due to SSI effect. The permanent deformation and failure of soil further aggravate the seismic response of the structure.

XIII. SOIL STRUCRURE INTERACTION IN CODES

Similar to all other modern seismic codes in the world, Eurocode 8, in all its Parts, considers the structure separately from the soil and from the foundation; soil-structure interaction is taken into account to a limited extent and only in special cases. Eurocode 8 addresses the design and verification of the structure, its foundations and the soil as a system and not as isolated parts. This consists of the following:

(*i*) Assessment of the effects on the superstructure of (important) phenomena in the soil (large soil deformations), or at its interface with the structure (*e.g.* sliding and/or uplift/rocking).
(*ii*) Evaluate the implications of considering the structure, its foundations and the soil as a system, leading to alternative cost-effective seismic design concepts that will allow—under certain conditions—concentration of non-linearity and energy dissipation in the soil or in the foundation, as well as a change in the ductility demand in the superstructure, leading to a modification of the recommended values of the behaviour factor.
(*iii*) Extend the research work to structures developing large interaction with the surrounding ground, like underground facilities (including tunnels, buried storage systems, oil wells, etc.).

The development of concepts and procedures for the seismic design and verification of the structure, its foundations and the soil as a system, is a new idea and a longer-term objective, not expected realistically to be covered for the second generation of national codes even if intensive R&D work were to start tomorrow.

Many buildings around the globe in various countries house valuable contents or equipment that may suffer heavy damage, or even total loss, under earthquakes that the structure of the building is designed to safely sustain. Other than the concern for elements that pose a risk to life, to the structure itself or to the functioning of critical facilities, seismic codes do not have specific provisions for the protection of building contents that are sensitive to accelerations, regardless of their value or importance.

Euro Code EN 1998-1 provides a single approach to seismic isolation of buildings: full isolation of the entire building, by providing an isolation system between the foundation and the superstructure. According to EN 1998-1:2004, the superstructure of the so-isolated building should be designed to remain elastic under the "design seismic action". In fact, it needs to enlarge the scope of Section 10 of EN 1998-1 to include "partial isolation" of buildings.

Nonetheless, providing through isolation enhanced protection only to the part of the building that supports sensitive and valuable equipment or artifacts (*e.g.* works of art) may be a much more effective approach than full isolation at the base of the entire building. Moreover, such an approach may not only achieve isolation of the sensitive and valuable equipment or artefact against the horizontal components of the seismic action and of the structural response to it: it may also provide the means of protecting it from the vertical component (or other vertical vibration that causes fatigue, e.g. due to traffic) and from overturning due to any rotational component (about a horizontal axis) of the seismic action, or of the response at the point where the equipment or artifact is supported. The provisions of EN 1998-1 should, therefore, be supplemented with:

(*i*) The rules for the development of horizontal and vertical "floor spectra" at various levels of the building, as input for the full seismic design of equipment and artifacts supported on the structure (with or without isolation of the equipment and the artifact); floor spectra should take into account the non-linearity of the response of the supporting structure;

(*ii*) The design rules for the protection of sensitive and valuable equipment and artifacts through horizontal and vertical isolation of the very part of the structure supporting this equipment and artifacts (including prevention of overturning);

(*iii*) The design concepts and guidance for enhanced seismic protection of sensitive and valuable equipment and artifacts supported by building structures.

Beneficial effect of soil structure interaction and its complicated process of analysis is the main cause to ignore their existence in seismic codes. Eurocode 8 is probably the only exception in which SSI effect is respected. The important cases in which SSI has a pronounced effect need to be considered according to part five of Eurocode 8. These cases are as follows:

- Structure where P-Δ effects play a significant role.
- Structures with massive or deep-seated foundations, such as bridge piers, offshore caissons, and silos;
- Slender tall structures, such as towers and chimneys.
- Structures supported on very soft soils, with average shear wave velocity less than 100m/s, such as subsoil class S1.

XIV. REFERENCES

[1]. John P Wolf, *Dynamic Soil-Structure Interactions,* Prentice Hall Inc, Englewood, New Jersey, 1985

[2]. Bharat Bhushan Prasad, *Fundamentals of Soil Dynamics and Earthquake Engineering*, PHI Learning, New Delhi, 2013

[3]. Bharat Bhushan Prasad, *Advanced Soil Dynamics and Earthquake Engineering*, PHI Learning, New Delhi, 2013

[4]. M. A. Chen and J. Penzien. Nonlinear soil–structure interaction of skew highway bridge. Report UCB/EERC-77/24, Earthquake Engineering Research Center, 1977.

[5]. G. Gazetas and G. Mylonakis, "Seismic Soil–Structure Interaction New Evidence and Emerging Issues", *J. ASCE-Geotechnical Earthquake Engineering and Soil Dynamics*, Volume II, pp. 1119–1174.

[6]. K. Ishihara, "Factors Affecting Dynamic Properties of soil", IVth Asian Regional Conference in Soil Mechanics and Foundation Engineering, Bangkok, Volume 2, 1971.

[7]. N. Makris, D. Badoni, E. Delis and G. Gazetas. "Prediction of observed bridge response with soil-pile-structure interaction", *ASCE J. of Structural Engineering,* Volume 120, Number 10, 1995, pp. 2992–3011.

[8]. H. B. Seed, R. T. Wong, I. M. Idriss and K. Tokimatsu. Moduli and damping factros for dynamic analysis of cohesionless soils. Earthquake Engineering Research Center Report UCB/EERC 84/14, University of California Berkeley, 1984.

[9]. A. Pecker, *Advanced Earthquake Engineering Analysis*, Springer Publication, Amsterdam, 2012.

Dr. Bharat Bhushan Prasad is working as professor and Head of department of Civil Engineering at AKGEC, Ghaziabad. He graduated in Civil Engineering, winning Gold Medal at B.Tech level. He secured his M.Tech. degree in Civil Engineering with specialization in Soil Dynamics from IIT Kanpur in 1975 and Ph.D in 1987. Apart from teaching and research for several years, he worked as a renowned consultant in the field of geotechnical engineering.

He was awarded Gold Medal by Indian Geotechnical Society, New Delhi for best research paper on Soil dynamics.

Published two books on Soil dynamics and Earthquake Engineering (PHI New Delhi). Guided several M.Tech and Ph.D research scholars. Published large number of technical papers in International journals.

Monika Tewari obtained B.Tech degree from U.P Technical University and M.Tech in Structural Engineering from G. B. Pant University of Agri. & Technology, Pantnagar.

Her research areas are Concrete Technology, Seismic design of structures and Non-Linear analysis.

Published various technical papers in international journals and proceedings of national conferences. Currently, working as Assistant Professor in Department of Civil Engineering at AKGEC, Ghaziabad.