# Seismic Soil-Structure Interaction

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***Abstract* - It has been well known that earthquake ground motions results primarily from the three factors, namely, source characteristics, propagation path of waves, and local site conditions. Also, the Soil-Structure Interaction (SSI) problem has become an important feature of Structural Engineering with the advent of massive constructions on soft soils such as nuclear power plants, concrete and earth dams. Buildings, bridges, tunnels and underground structures may also require particular attention to be given to the problems of SSI. If a lightweight flexible structure is built on a very stiff rock foundation, a valid assumption is that the input motion at the base of the structure is the same as the free-field earthquake motion. If the structure is very massive and stiff, and the foundation is relatively soft, the motion at the base of the structure may be significantly different than the free-field surface motion. If the structure is supported on soft soil deposit, the inability of the foundation to conform to the deformations of the free field motion would cause the motion of the base of the structure to deviate from the free field motion. Also the dynamic response of the structure itself would induce deformation of the supporting soil. When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus changes the motion of the ground. Soil-structure interaction broadly can be divided into two phenomena: a) kinematic interaction and b) inertial interaction. Earthquake ground motion causes soil displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion. This inability of the foundation to match the free field motion causes the kinematic interaction. On the other hand, the mass of the superstructure transmits the inertial force to the soil, causing further deformation in the soil, which is termed as inertial interaction.**

***Keywords - Soil Structure Interaction; Resonance; Impedance Contrast; Basin edge effect; Damping in soil; Free Field Motion; Fixed Base structures.***

## INTRODUCTION

The scales of socio–economic damages caused by an earthquake depend to a great extent on the characteristics of the strong ground motion. It has been well known that earthquake ground motions results primarily from the three factors, namely, source characteristics, propagation path of waves, and local site conditions. Also, the Soil-Structure Interaction (SSI) problem has become an important feature of Structural Engineering with the advent of massive constructions on soft soils such as nuclear power plants, concrete and earth dams. Buildings, bridges, tunnels and underground structures may also require particular attention to be given to the problems of SSI. If a lightweight flexible structure is built on a very stiff rock foundation, a valid assumption is that the input motion at the base of the structure is the same as the free-field earthquake motion. If the structure is very massive and stiff, and the foundation is relatively soft, the motion at the base of the structure may be significantly different than the free-field surface motion. For code design buildings it is important to consider the effect of the SSI. The objective of this paper is to understand the basic concept of the Soil-Structure Interaction and some technical terms associated with it.

## FREE FIELD MOTION AND FIXED BASE STRUCTURES

Ground motions that are not influenced by the presence of structure are referred as free field motions.

Structures founded on rock are considered as fixed base structures. When a structure founded on solid rock is subjected to an earthquake, the extremely high stiffness of the rock constrains the rock motion to be very close to the free field motion.

Ductility demand in fixed-base structures is not necessarily a decreasing function of structural period, as suggested by traditional design procedures. Analysis of motions recorded on soft soils have shown increasing trends at periods higher than the predominant period of the motions.

Soil-structure interaction in inelastic bridge piers supported on deformable soil may cause significant increases in ductility demand in the piers depending on the characteristics of the motion and the structure. However. inappropriate generalization of ductility concepts and geometric considerations may lead to the wrong direction when assessing the seismic performance of such structures.

## SOIL-STRUCTURE INTERACTION

If the structure is supported on soft soil deposit, the inability of the foundation to conform to the deformations of the free field motion would cause the motion of the base of the structure to deviate from the free field motion. Also the dynamic response of the structure itself would induce deformation of the supporting soil. This process, in which the response of the soil influences the motion of the structure and the response of the structure influences the motion of the soil, is referred as SSI as shown in Figure.1.

These effects are more significant for stiff and/ or heavy structures supported on relatively soft soils. For soft and /or light structures founded on stiff soil these effects are generally small. It is also significant for closely spaced structure that may subject to pounding, when the relative displacement is large.

In order to understand the SSI problem properly, it is necessary to have some information of the earthquake wave propagation through the soil medium for two main reasons. Firstly, when the seismic waves propagates through the soil as an input ground motion, their dynamic characteristics depends on the modification of the bedrock motion. Secondly, the knowledge of the vibration characteristics of the soil medium is very helpful in determining the soil impedance functions and fixing the boundaries for a semi-infinite soil medium, when the wave propagation analysis is performed by using numerical techniques. To understand the influence of local soil conditions in modifying the nature of free field ground motion it is very essential to understand the terminology of local site effect. Therefore, in this chapter, the terminology of local site effect is discussed first and then, seismic SSI problems are presented.

The first significant structure where the dynamic effect of soil was considered in the analysis in industry in India was the 500MW turbine foundation for Singrauli (Chowdhary, 2009).

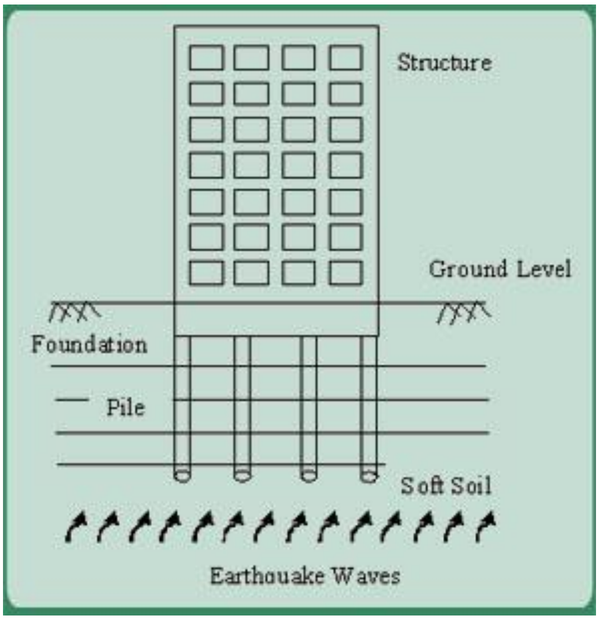


Fig 1: Seismic soil structure interaction

## EFFECT OF SSI AND SSI PROVISIONS OF SEISMIC DESIGN CODES ON STRUCTURAL RESPONSES

It is conventionally believed that SSI is a purely beneficial effect, and it can conveniently be neglected for conservative design. SSI provisions of seismic design codes are optional and allow designers to reduce the design base shear of buildings by considering soil-structure interaction (SSI) as a beneficial effect. The main idea behind the provisions is that the soil-structure system can be replaced with an equivalent fixed-base model with a longer period and usually a larger damping ratio. Most of the design codes use oversimplified design spectra, which attain constant acceleration up to a certain period, and thereafter decreases 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, which is the main justification of the seismic design codes to reduce the design base shear when the SSI effect is considered. The same idea also forms the basis of the current common seismic design codes such as ASCE 7-10 and ASCE 7-16. Although, the mentioned idea, i.e. reduction in the base shear, works well for linear soil-structure systems, it is shown that it cannot appropriately capture the effect of SSI on yielding systems .More recently, Khosravikia et al.evaluated the consequences of practicing the SSI provisions of ASCE 7-10 and those of 2015 National Earthquake Hazards Reduction Program (NEHRP), which form the basis of the 2016 edition of the seismic design standard provided by the ASCE. They showed that SSI provisions of both NEHRP and ASCE 7-10 result in unsafe designs for structures with surface foundation on moderately soft soils, but NEHRP slightly improves upon the current provisions for squat structures. For structures on very soft soils, both provisions yield conservative designs where NEHRP is even more conservative. Finally, both provisions yield near-optimal designs for other systems.

## DETRIMENTAL EFFECTS OF SSI

Using rigorous numerical analyses, Mylonakis and Gazetas 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 may further aggravate the seismic response of the structure.

When a structure is subjected to an earthquake excitation, it interacts with the foundation and the soil, and thus changes the motion of the ground. Soil-structure interaction broadly can be divided into two phenomena: a) kinematic interaction and b) inertial interaction. Earthquake ground motion causes soil displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion. This inability of the foundation to match the free field motion causes the kinematic interaction. On the other hand, the mass of the superstructure transmits the inertial force to the soil, causing further deformation in the soil, which is termed as inertial interaction.

At low level of ground shaking, kinematic effect is more dominant causing the lengthening of period and increase in radiation damping. However, with the onset of stronger shaking, near-field soil modulus degradation and soil-pile gapping limit radiation damping, and inertial interaction becomes predominant causing excessive displacements and bending strains concentrated near the ground surface resulting in pile damage near the ground level.

Observations from recent earthquakes have shown that the response of the foundation and soil can greatly influence the overall structural response. There are several cases of severe damages in structures due to SSI in the past earthquakes. Yashinsky cites damage in number of pile-supported bridge structures due to SSI effect in the Loma Prieta earthquake in San Francisco in 1989. Extensive numerical analysis carried out by Mylonakis and Gazetas have attributed SSI as one of the reasons behind the dramatic collapse of Hanshin Expressway in 1995 Kobe earthquake.

## TERMINOLOGY OF LOCAL SITE EFFECTS

## BASIN/SOIL EFFECT ON THE GROUND MOTION CHARACTERISTICS

### IMPEDANCE CONTRAST

Seismic waves travels faster in hard rocks in compare to softer rocks and sediments. As the waves passes from harder to softer rocks they become slow and must get bigger in amplitude to carry the same amount of energy. Thus, shaking tends to be stronger at sites with softer surface layers, where seismic waves move more slowly. Impedance contrast defined as the product of velocity and density of the material (Pisal, 2006).

### RESONANCE

When the signal frequency matches with the fundamental frequency or higher harmonics of the soil layer, we say that they are in resonance with one another. This results into tremendous increase in ground motion amplification. Various spectral peaks characterize resonance patterns. The frequencies of these peaks are related to the surface layer's thickness and velocities. Further, the amplitudes of spectral peaks are related mainly to

- The impedance contrast between the surficial layer and the underlying bedrock.
- To sediment damping.
- To a somewhat lesser extent, to the characteristics of the incident wave-field.

### DAMPING IN SOIL

Absorption of energy occurs due to imperfect elastic properties of medium in which the particle of a medium do not react perfectly elastically with their neighbor and a part of the energy in the waves is lost instead of being transferred through medium, after each cycle. This type of attenuation of the seismic wave is described by a parameter called as quality factor (Q). It is defined as the fractional loss of energy per cycle

$$\frac{\pi}{Q} = \frac{\Delta E}{E}$$

Where $\Delta E$ is the energy lost in one cycle and $E$ is the total elastic energy stored in the wave. If we consider the damping of a seismic wave as a function of the distance and the amplitude of seismic wave, we have

$$A = A_0 \exp\left(\frac{-\pi r}{Q \lambda}\right) = A_0 \exp(-\alpha r)$$

where $\alpha$ is called the absorption coefficient and is inversely proportional to quality factor (Q). Damping of soil mainly affects the amplitude of surface waves (Narayan, 2005).

### BASIN EDGE EFFECT

When the seismic waves incident near the basin edge, it enter the basin from its edge and travel in the direction in which the basin is thickening. Figure 6.2 shows that when the wave can become trapped within the basin, if post critical incident angles develop. Interference of trapped waves generates surface waves, which propagate across the basin. The generation of surface waves near the basin is known as basin-edge effect (Bard and Bouchon 1980 a & b, Bakir et al. 2002, Graves et al., 1998, Hatyama et al.1995, Pitarka et al., 1998, Narayan, 2005) . Waves that become trapped in deep sedimentary basins can produce stronger amplitudes at intermediate and low frequencies than those recorded on comparable surface material outside basins, and their durations can be twice as long. This basin edge effect can amplify long period components of ground motion and significantly increases the duration of strong shaking. Basin induced surface waves cause intense damage which is confined in a narrow strip parallel to the edge.

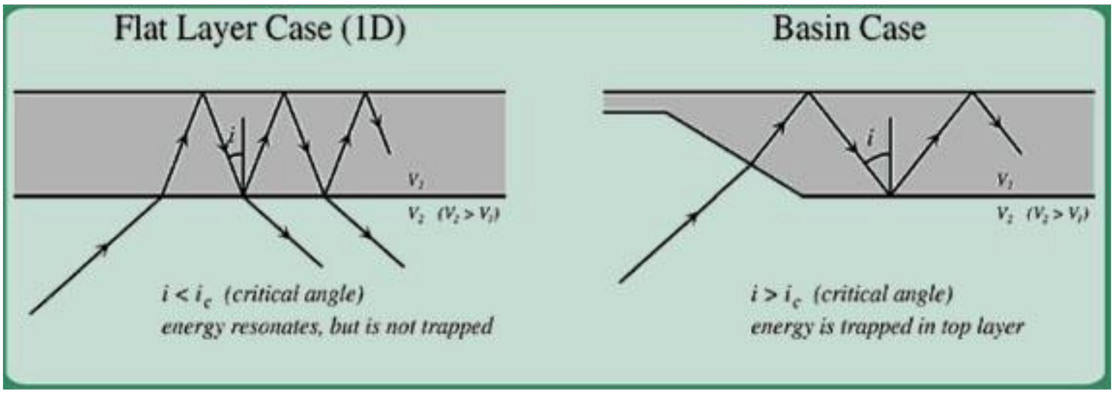


Figure 2: Schematic diagram showing that seismic waves entering a sedimentary layer from below will resonate within the layer but escape if the layer is flat (left) but become trapped in the layer if it has varying thickness and the wave enters the layer through its edge (right) (After Grave, 1998).

## EFFECT OF SOIL STRUCTURE INTERACTION ON SEISMIC ANALYSIS OF STRUCTURE

Common practice of analysis and design of buildings is to assume the base of building to be conventionally fixed, whereas in reality supporting soil influences the structural response by allowing movement due to its natural ability to deform. Failure of the structures in past earthquakes with neglecting the effect of soil showed the importance of considering soil-structure interaction in the seismic analysis of structures. The seismic response of structures due to the effect of soil flexibility depends on both the soil property and structural property. The overall stiffness of the structural system is decreased and hence, may increase the natural period of the system. The extent of fixity offered by soil at the base of the structure depends on the load transferred from the structure to the soil as the same decides the type and size of foundation to be provided. Such an interdependent behaviour between soil and structure regulating the overall response is referred to as soil structure interaction.

In reality the structure and the foundation have mass and when there is acceleration acting on mass inertial forces will be developed. This inertial force will try to move the soil underneath the structure and when the soil is compliant the forces transmitted to it by the foundation will produce foundation movement i.e. displacement and rotation at the soil foundation interface. Secondly, with the seismic wave propagation, scattering, diffraction, reflection and refraction of the seismic waves at the soil foundation interface takes place, changing the nature of ground motion at that point. These effects are known as kinematic interaction effects.

There are two methods of implementing soil structure interaction. First is the direct method in which the soil, structure and foundation is represented as a continuum and modelled together using finite element method. The ground motion is specified as free field motion and is applied at all boundaries. Second method is the substructure method in which soil material properties are used for incorporation of springs to represent the stiffness at the soil foundation interface. Sub-structure method is computationally more efficient than the direct method as most of the disadvantages of the direct method can be removed, if the substructure method is employed.

The supporting soil influences the behaviour of the structure due to its ability to deform. The fixed support neglects all these deformations.

The response of the structure obtained using both square and rectangular footing is same. A constant trend may be seen in percentage change of time period with increasing number of stories.

It may be seen that the time period and lateral deflection of buildings increased from fixed to both flexible support .

## EFFECTS OF SSI ON ELASTIC AND INELASTIC STRUCTURES

The role of SSI is always beneficial for the design seismic forces developing in a structure. It is shown that, in certain seismic and soil environments, an increase due to SSI in the fundamental period of a moderately flexible structure may have a detrimental effect on seismic demand, contrary to the conclusion drawn on the basis of idealized (“average”) code spectra. Using a simple 2-dof system and a number of actual ground motions as excitation, it may also be seen that indiscriminate use of presently popular “geometric” ductility relations may lead to erroneous conclusions in the prediction of seismic performance of flexibly-supported structures. Soil-structure interaction may have played a decisive even if subtle role in that failure.

## CONCLUSION

It has been observed in studies that the time period is changed for different soil conditions or foundation flexibility and base shear is decreased from fixed to flexible foundation. The axial force increases from fixed to flexible foundation and the column end moment is uncertain on increasing or decreasing nature. The response of the structure may vary from structure to structure.

By comparing conventional code design spectra to actual response spectra, it may seen that an increase in fundamental natural period of a structure due to SSI does not necessarily lead to smaller response. The prevailing in structural

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engineering view of an always beneficial role of SSI is an oversimplification which may lead to unsafe design.
Averaging response spectra of motions recorded on soft soil without proper normalization of periods may lead to errors.
Ductility demand in fixed-base structures is not necessarily a decreasing function of structural period, as suggested by traditional design procedures. Analysis of motions recorded on soft soils have shown increasing trends at periods higher than the predominant period of the motions.
Soil-structure interaction in inelastic bridge piers supported on deformable soil may cause significant increases in ductility demand in the piers depending on the characteristics of the motion and the structure. However. inappropriate generalization of ductility concepts and geometric considerations may lead to the wrong direction when assessing the seismic performance of such structures.

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