Soil-Structure Interaction for Building Structures: A Review

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Abstract: Experiences from past earthquake disasters clearly show that the ground motion was responsible for majority of property and life loss. Among the collapsed structures during the 1964 Niigata (Japan) earthquake, the 1995 Kobe (Japan) earthquake, the 1999 Kocaeli (Turkey) earthquake, the 2001 Bhuj (India) earthquake and the 2004 Sumatra (Indonesia) earthquake, excessive damage was occurred to pile supported bridges, towers, chimneys, high rise structures, etc. In view of the above, there is a need to study the complex behavior of soil-structure interaction for structures specially for building problems. Based on several literature, a systematic review of the history and status of the structure–soil–structure interaction problems which consider the adjacent structures is proposed as a reference to the readers/researchers.

Keywords: Disasters, Earthquake, Soil-Structure Interaction, Building.

Introduction

The response of a structure to earthquake shaking is affected by interactions between three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation. Soil-structure interaction analysis evaluates the collective response of these systems to a specified ground motion. The terms *Soil-Structure Interaction* (SSI) and *Soil-Foundation-Structure Interaction* (SFSI) are both used to represent the analysis of building structures. Problems associated with the practical applications of SSI for building structures are rooted in a poor understanding of fundamental SSI principles. Once the decision to implement SSI has been made, a basic level of understanding of the physical phenomenon and a practical analysis methodology for simulating its effects are needed.

A seismic soil-structure interaction analysis evaluates the collective response of the structure, the foundation, and the geologic media underlying and surrounding the foundation, to a specified free-field ground motion. The term *free-field* refers to motions that are not affected by structural vibrations or the scattering of waves at, and around, the foundation. SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. The effect of soil on the response of structures depends on the properties of soil, structure and the nature of excitation. The three main effects of SSI which need to be addressed in any SSI model are categorized as *inertial interaction effects, kinematic inertial effects* and *soil-foundation flexibility effects*. These effects can be related to structural analysis in terms of:

Foundation stiffness and damping: As compared to the normal assumption of rigid foundation, the inertial forces (base shear, moment and torsion) generate lateral displacement and rotation at the foundation level. These effects introduce flexibility in the structure and lead to period elongation. Since, these effects are rooted in structural inertia, they are referred to as *inertial interaction effects.*

Variation between foundation input motions and free filed ground motion: Kinematic effects of SSI represent the change in response of structure when response is obtained using free-field motions and when the presence of structure is considered. It doesn't depend on the mass of the structure and is affected by the geometry and configuration of the structure, the foundation embedment, the composition of incident free-field waves, and the angle of incidence of the waves. This effect is called *kinematic interaction* effect as it does not involve any inertial forces.

Foundation deformations: Flexural, axial and shear deformation of structural foundation elements occur as result of forces and displacements applied by the superstructure and the soil medium. These represent the seismic demand for which foundation component should be designed and they could be significant, especially for flexible foundations such as rafts and piles.

Literature Review

The problem of soil-structure interaction is quite complex. The dynamic forces make it further complicated. The effort on evaluating the effect of soil-structure interaction has been continuing for a few decades. In this study, a comprehensive review of the literature for the dynamic behavior of buildings considering the soil-structure interaction effect is presented.

Direct Approach

In 1936, Reissner treated the vertical oscillation of an elastic half-space subjected to sinusoidal forces acting on the limited circular portion on the surface (Minami et al., 1972). In 1953, Sung extended Reisnner's solution to consider the effects of changes in pressure distribution over the circular area of contact on the surface of the half-space. In 1964 and 1967, Kobori et al. studied the dynamic compliance of a rectangular footing resting on the elastic half-space in Cartesian co-ordinates. Assuming the linear variation of contact pressure, the solutions were developed for all the four nodes of oscillations i.e. horizontal and vertical translations, rocking and torsional vibrations. Liu et al. (1971) investigate the earthquake response including the interaction effects of a single-storey structure resting on an elastic half space by using Fast Fourier Transform (FFT) technique. The dynamic model used in the study was of a single storey, shear type structure-foundation. The transfer functions were solved through numerical procedure and subsequently used in conjunction with FFT subroutines to obtain the transient time history of the coupled motion of the system. Liu et al. (1973) extended their previous work (1971) to investigate the soil-structure interaction effect of multi-storey buildings during earthquake. Lee et al. (1968) concerning the influence of soil-coupling between adjacent structures on the seismic loading of nuclear reactors has been investigated considering soil-structure interaction. Three-dimensional flexible structures were bonded to an elastic half-space for investigation purpose. Seismic response of the structures was determined both with and without influence of the nearby structure.

Indirect Approach

Merit et al. (1954) investigated the interaction phenomenon by studying foundation of multi-storey buildings subjected to strong motion earthquakes. The foundation medium was assumed to be homogenous, isotropic and linearly elastic body. Fleming et al. (1965) reported the effects of foundation-super structure interaction on the dynamic response of multi-storey building. The structure is replaced by a lumped mass mathematical model which was attached to the rock layer below the foundation by a flexible member having the same force-displacement relationship as the foundation. Liu et al. (1973) used FFT technique while investigating earthquake soil-structure interaction effect on the response of a 20-story building founded on various soil media. The structure-foundation systems were treated as linear discrete systems or lumped-mass. Nandakumaran et al. (1977) investigated the foundation type and the effect of soil-structure interaction on the seismic response of the buildings. The model used in the study consisted of an equivalent lateral spring representing the stiffness of the soil-foundation system along with the usual lumped-mass model of the building. Gupta et al. (1978) investigated the seismic response of multistoried buildings including the effects of soil-structure interaction. Response spectrum superposition method was used for the dynamic analysis of multistoried building. Fourier transformation frequency domain was involved in generalization of response to earthquake excitation. Authors considered the lumped mass model of building subjected to horizontal component and rocking component of ground acceleration at its base.

Analytical and Numerical Approach

Khanna (1969) investigated the effects of soil-structure interaction of multi-storey buildings founded on shallow foundation and deep foundation idealizing the supporting soil by finite element method (FEM). Seed et al. (1973), analyzed soil-structure interaction effects for massive embedded structures during earthquakes and illustrated the possible difference in results by using the finite element method for the analysis to show the possible effects of soil characteristics, depth of embedment and proximity of rock surface on the response of a deeply embedded structure. Ciongradi et al. (1977) investigated the effects of interaction between structure, substructure and soil in particular reference by using finite element method. The foundation soil was assumed to be linear-deformable-homogenous-isotropic. Stewart et al. (1980) analyzed the procedures and system identification techniques for evaluating the inertial SSI effects on seismic structural response. The analysis procedures are similar to provisions in some building codes but incorporate more rationally the influence of site conditions and the foundation embedment, flexibility, and shape on foundation impedance. Numerical approach is considered for seismic structural response.

After 19th century most of the researchers used the numerical approach with the help of half-space theory in which software were used to analyze the soil-structure interaction effect. Now a day's Finite element method (FEM) has been extensively used by researchers. There are some more literature available after 19th century-

Mylonakis et al. (2001) reviewed the approach of seismic regulations for assessing SSI effects on elastic single-degree-of-freedom (SDF) oscillators. Inelastic continuum approach was considered to analyze the SSI effects. Yingcai (2002) studied a 20-storey building as a typical structure supported on a pile foundation for different conditions: (1) rigid base, i.e. no deformation in the foundation: (2) linear soil-pile system; and (3) nonlinear soil-pile system. The seismic behavior of tall buildings was greatly affected by non-linear soil-pile interaction during strong earthquakes. Zaicenco et al. (2007) highlighted the use of FEM and bidirectional lumped mass story stiffness numerical models for the study of the SSI effects on an instrumented building. Authors concluded that the SSI becomes more pronounced for higher level of ground shaking amplifying the natural period of the structure and slightly suppressing high frequencies on the foundation in comparison with the free field motion. Matinmanesh et al. (2011) presented an idealized two dimensional plane strain finite element seismic soil-structure interaction analysis. The analysis was performed by considering three actual ground motion recorded representing seismic motions with low, intermediate and high frequency content earthquakes. The results illustrated that both sandy soils amplify seismic waves on the soil-structure interface because of the soil-structure interaction effect. Priyanka et al. (2012) studied the effect of lateral forces on tall buildings with different type of irregularities. An attempt was made in the study to understand the behavior of tall buildings subjected to lateral forces for different soil conditions. Authors found that building with soft soil gives more deflection as compared to medium and hard soil for all types of building. Building with stiffness irregularity gives more deflection as compared to other type of buildings with different irregularity. Li et al. (2014) indicated that the SSI has a significant impact on the dynamic characteristics of supertall buildings, which may lead to unexpected structural seismic responses and/or failure. The SSI is a very complex nonlinear process and these nonlinearities may include: (1) Yielding of the lateral resistance system in the superstructure; (2) Yielding of the soil; (3) Gapping between the foundation and the soil (4) yielding of the foundation structural elements. Nonika et al. (2015) studied the effect of elevation irregularity and behaviour of 3-D R.C. building subjected to earthquake load. Irregular building was assumed to be located in all zones. Linear dynamic analysis using Response Spectrum method of the irregular building is carried out using the standard and convenient FE software package. Garag et al. (2016) determined the effects of soil structure interaction on dynamic properties of medium rised RC framed structure with various plan irregularities resting on different types of soil. In the study, two methods of soil-structure interaction were considered i.e. Winkler method and Elastic continuum method. Thusoo et al. (2016) studied the effect of Soil Structure Interaction (SSI) on multistory buildings with varying under-laying soil types after proper validation of the effect of SSI. Analysis for soft, stiff and very stiff base soils was carried out using finite element based software package ANSYS v14.5. Results lead to some very important conclusions regarding time period, deflection and acceleration responses. Suhas et al. (2017) presented the study on structure-soil-structure interaction effects of two similar adjacent reinforced concrete multi-storey buildings founded on sandy-silty clay soil beneath the foundation. Single building on similar soil was also analyzed for earthquake ground motion apart from fixed base model. Responses such as maximum displacement, base shear and modal time period were studied. FEM or Elastic Continuum method was used to model the soil continuum. The multistoried building was analyzed for fixed base condition.

Soil-structure interaction (SSI) analysis is a special field of earthquake engineering. Every seismic structural response is caused by soil-structure interaction forces impacting structure (by the definition of seismic excitation). However, engineering community used to talk about soil-structure interaction only when these interaction forces are able to change the basement motion as compared to the free-field ground motion.

Now a day's FEM is most prevalent method to perform the soil-structure interaction analysis. The main beauty of finite element analysis is that the non-linear soil properties and others types of material behavior can be included in the analysis.

Approaches for Soil-Structure Interaction Analysis

There are several methods for solving soil-structure interaction problems-

1. Methods based on the half-space theory
    a. Direct approach
    b. Indirect approach

2. Analytical methods
    a. Winkler approach
    b. P-y method
    c. Elastic continuum approach

3. Numerical Methods
    a. Finite element method
    b. Finite difference method
    c. Boundary element method

Direct approach – Direct approach is one in which the soil and structure are modelled together in a single step accounting for both inertial and kinematic interaction. Inertial interaction develops in structure due to own vibrations giving rise to base shear and base moment, which in turn cause displacements of the foundation relative to free field. While kinematic interaction develops due to presence of stiff foundation elements on or in soil causing foundation motion to deviate from free-field motions.

In the direct approach of the half-space theory, the structures treated as an oscillator resting on a homogenous, isotropic and semi-infinite body. The solution is obtained by the finding out the vertical, horizontal and rocking displacements. This method is developed from the tests on a rigid circular plate resting on an elastic half-space for vertical, horizontal and rocking vibrations produced by a steady-state harmonic force and moment.

Indirect approach – In the indirect approach of the method which is based on the half-space theory. The half-space space is replaced by a system of equivalent lumped mass, spring and dashpots. This approach is more convenient for dynamic soil-structure interaction systems, especially for complex ones.
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:

a. Determination of foundation input motion by solving the kinematic interaction problem.
b. Determination of the frequency dependent impedance functions describing the stiffness and damping characteristics of the soil-foundation interacting system.
c. Computation of response of the real structure supported on frequency dependent soil springs and subjected at the base of the springs to the foundation input motion computed.

Winkler Approach- Winkler's idealization represents the soil medium as a system of identical but mutually independent, closely spaced, discrete and linearly elastic springs. According to this idealization, deformations of foundation due to applied load are confined to loaded regions only. The fundamental problem with the use of this model is to determine the stiffness of elastic springs used to replace the soil below foundation.

P-y Method- The P-y analysis is numerical model that simulates the soil resistance as predefined nonlinear springs, where P is the soil pressure per unit length and y is the pile deflection. The soil is represented by a series of nonlinear P-y curves that vary with depth and soil type. The P-y curve for a particular point on a foundation depends on many factors, such as-

- Soil type
- Type of loading
- Foundation diameter and cross-sectional shape
- Coefficient of friction between foundation and soil
- Depth below the ground surface
- Boundary conditions
- Foundation construction methods
- Group interaction effects

Elastic Continuum Approach- In elastic continuum model, the continuous behavior of soil is idealized as three dimensional continuous elastic solid where the soil surface deflections due to loading will occur under and around the loaded region. In this case some continuous function is assumed to represent the behavior of soil medium. In continuum idealization, soil is assumed to be semi-infinite and isotropic for the sake of simplicity. However, the effect of soil layering and anisotropy may be conveniently accounted for in the analysis.

Finite Element Method – The finite element method makes use of the variation principle to obtain the solution to a particular governing equation and prescribed boundary conditions. Since, each particular model can be divided in to many smaller elements, the geometrical configuration of the model does not present many difficulties. This method is ease for solving large class of practical problems.

Summary

The following concluding remarks may be drawn based on the study for *direct approach*-

a. The effect of soil-structure interaction on the dynamic response of building can reduce the resonant frequency.
b. The interaction effect is significant for shear wave velocity less than 305m/sec and foundation medium is having shear wave velocity more than 305m/sec.
c. Contribution of rocking is more for tall structures founded on soft soils and in significant for buildings on stiff soils.
d. The stiffness and damping characteristics of the foundation medium are frequency dependent and may be assumed to be constant for practical purposes.

The *indirect approach* uses the discrete model in which the half-space is represented by springs and dashpots which permits a solution in an approximate manner but accurate for practical purposes. Following conclusions may be drawn-

a. The principal effect of soil-structure interaction can reduce the resonant frequencies of the structure and to modify the effective damping.
b. The interaction effect is significantly greater for tall structures than for short structures.
c. The FFT approach is computationally efficient particularly when large quantities of computations are required.

The concluding remarks may be drawn for the *analytical and numerical approach as-*

a. The finite element method has proved to be a very useful method for studying soil-structure interaction effect with rigor. In fact, the technique becomes useful to incorporate the effect of material nonlinearity, non-homogeneity and interface modeling of soil and foundation.
b. For practical purpose Winkler hypothesis should at least be employed instead of carrying out an analysis with fixed base idealization of structures.

Both the half-space and numerical methods have advantages and limitations. The half-space method may be used for near-surface structures and the other are used for deeply embedded structures.

Limitations of Half-Space Approach-

a. Solutions do not incorporate material damping which is high in soils for ground motions from 0.2 to 0.25g
b. Analysis is available for deposits of 1 or 2 layers and this analysis is very complicated.
c. Solutions cannot take into account the effects of adjacent structures on building response.

Limitations of Finite Element Analysis-

a. Choosing proper element size is more complicated.
b. Results of numerical analysis of wave propagation phenomenon are very sensitive to boundary conditions.
c. Obtains only approximate solutions.

Many investigators and regulatory agencies attempt to decide finite element analysis to be the best tool to solve soil-structure interaction problems.

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