International Journal of Engineering Research ISSN:2319-6890)(online),2347-5013(print)
Volume No.5 Issue: Special 3, pp: 737-741 27-28 Feb. 2016

Study on Soil-Structure Interaction: A Review

Prakash M. Yesane, Y. M. Ghugal, R. L. Wankhade
Department of Applied Mechanics, Government College of Engineering, Karad, India
E-mail- yesaneprakash@gmail.com

Abstract*-The concept of soil–structure interaction was introduced, and the research methods were discussed. Based on several documents, a systematic summary of the history and status of the soil–structure interaction research that considers adjacent structures was proposed as a reference for researchers. This study is in the growing stage, given its complexity and excessive simplification of the model for soil and structures, and should be carried forward for its significance. An attempt was made to summarize the all terms in this area of study. Furthermore Parametric study on soil structure interaction behaviour by various researchers is tabulated. The existing problems and the future research trend in this field were also examined..

Keywords Soil-Structure Interaction, static loading, seismic loading, nonlinear, finite element analysis, space frame, isolated footing, raft footing.

1. Introduction

The scales of socioïeconomic 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.

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).

The estimation of earthquake motions at the site of a structure is the most important phase of seismic design as well as retrofit of a structure. In classical methods used in structural analysis, it is assumed that, the motion in the foundation level of structure is equal to ground free field motion. This assumption is correct only for the structures resting on rock or very stiff soils. For the structures constructed on soft soils, foundation motion is usually different from the free field motion and a rocking component caused by the support flexibility on horizontal motion of foundation has been added. Traditionally, in analysis of the rigid base structures, input motion at the base of the structure is taken as equal to the free field ground motion. In the case of a flexible-base structure, in addition to the added rocking component to the horizontal motion of the structure, a part of the structureȩs vibrating energy will transmit to the soil layer and can be dissipated due to radiation damping resulting from the wave propagation and hysteresis damping of the soil materials. However, in classical methods, for the rigid base structures, this energy dissipation is not considered.

The effect of soil on the response of structures depends on the properties of soil, structure and the nature of the excitation.

The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as Soil-Structure Interaction (SSI). Implementing Soil-Structure Interaction effects enables the designer to assess the inertial forces and real displacements of the soil-foundation structure system precisely under the influence of free field motion.

2. Kinematic and Inertial Effects

Structure on soil exhibits two kinds of interaction effects known as kinematic and inertial effects.

I. Kinematic interaction effects exist due to change in wave propagation media as a result of change in density and elasticity of the media. It changes the wave propagation velocity and leads to reflection and refraction of incoming seismic waves. 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 doesnȩt depend on the mass of structure and is affected by the geometry and configuration of structure, the foundation embedment, the composition of incident free-field waves, and the angle of incidence of these waves. Kinematic interaction can be neglected for structures with no embedment excited by vertically propagating shear waves.

II. Inertial effects result from the combined dynamic behavior of structure, foundation, and supporting soil media. Soil media, owing to its elastic and inertial properties, increases the degrees of freedom of structure and makes it possible to dissipate energy of incoming seismic waves by the radiation of waves away from the structure and hysteretic deformation of supporting soil media. Inertial effect depends on the relative flexibility of supporting soil media to the structure, which implies that the effect is not significant for regular structure founded on stiff soils or rock, but could be significant for stiff and massive structures.

3. Soil–structure interaction under static loading:

Numerous studies have been made on the effect of soilï structure interaction under static loading. These studies have considered the effect in a very simplified manner and demonstrated that the force quantities are revised due to such interaction. A limited number of studies have been conducted on soilïstructure interaction effect considering three dimensional space frames. The studies clearly indicated that a two-dimensional plane frame analysis might substantially overestimate or underestimate the actual interaction effect in a space frame. From these studies, it becomes obvious that the consideration of the interaction effect significantly alters the design force quantities. These studies, may be quantitatively approximate, but clearly emphasize the need for studying the soilï structure interaction to estimate the realistic force quantities in the structural members, accounting for their three dimensional behaviour.

4. Soil–structure interaction under dynamic loading

Structures are generally assumed to be fixed at their bases in the process of analysis and design under dynamic loading. But the consideration of actual support flexibility reduces the overall stiffness of the structure and increases the period of the system. Considerable change in spectral acceleration with natural period is observed from the response spectrum curve. Thus the change in natural period may alter the seismic response of any structure considerably. In addition to this, soil medium imparts damping due to its inherent characteristics. The issues of increasing the natural period and involvement of high damping in soil due to soilï structure interaction in building structures are also discussed in some of the studies. Moreover, the relationship between the periods of vibration of structure and that of supporting soil is profoundly important regarding the seismic response of the structure. The demolition of a part of a factory in 1970 earthquake at Gediz, Turkey; destruction of buildings at Carcas earthquake (1967) raised the importance of this issue.
These show that the soilï structure interaction should be accounted for in the analysis of dynamic behavior of structures, in practice. Hence, soilï structure interaction under dynamic loads is an important aspect to predict the overall structural response.

The dynamic equation of motion of the soil and structure system can be written as:

[M]{ü}+[C]{Ţ}+[K]{u}=[M]{m}üg+{Fv}

where,{u},{Ţ} and {ü} are the nodal displacements, velocities and accelerations with respect to the underlying soil foundation, respectively. [M], [C] and [K] are the mass matrix, damping matrix and stiffness matrix of the structure, respectively. It is more appropriate to use the incremental form of Eq. (1) when plasticity is included, and then the matrix [K] should be the tangential matrix and g U&& is the earthquake induced acceleration at the level of the bed rock. If only the horizontal acceleration is considered, for instance, then {m}= [1,0,1,0, ...,1,0]^T. Fv is the force vector corresponding to the viscous boundaries. The above mentioned method, where the entire soil-structure system is modelled in a single step, is called Direct Method. The use of direct method requires a computer program that can treat the behaviour of both soil and structure with equal rigor (Kramer 1996). The methods to solve the soil structure interaction problem can be grouped as direct approach, substructure approach.

(A)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 causes 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.

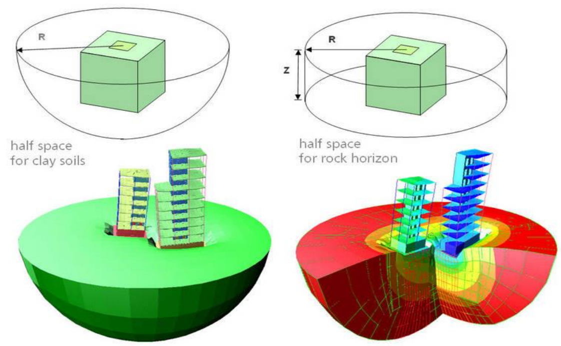

Fig. 1. Elastic half space model (Direct approach)

(B) Substructure Approach

Substructure method is one in which the analysis broken down into several steps that is the principal of superposition is used to isolate the two primary causes of soil structure interaction that is inability of foundation to match the free field deformation and the effect of dynamic response of structure foundation system on the movement of supporting soil. In the analysis and design of engineered structures in the past, it was assumed that the foundation of structure was fixed to a rigid underlying medium. In the last few decades, however, it has been recognized that Soil Structure Interaction (SSI) altered the response characteristics of a structural system because of massive and stiff nature of structure and, often, soil softness. Various studies have appeared in the literature to study the effect of SSI on dynamic response of structures such as nuclear power plants, high-rise structures and elevated highways.

5. Analytical methods

Analytical methods to predict lateral deflections, rotations and stresses can be grouped under the following four headings

1) Winkler Approach
2) P-Y Method
3) Elastic Continuum Approach
4) Finite Element Method

Viladkar et al.[2] presented a new approach for the physical and material modelling of a space frame-raft-soil system. The soil-structure interaction effect in framed structures with proper physical modeling of the structure foundation and the soil mass is evaluated by Noorzaei et al. [3]. The effects of horizontal stresses and horizontal displacements in loaded raft foundation are studied by Swamy Rajashekhar et al. [4]. The effect of the differential settlement on design force quantities for frame members of building frames with isolated footings is studied by Roy and Dutta [5]. A finite element procedure for the general problem of three-dimensional soil-structure interaction involving nonlinearities caused by material behavior, geometrical changes, and interface behaviour is presented by Desai et al. [6]. The formulation was based on the updated Lagrangian or approximate Eulerian approach with appropriate provision for constitutive laws. Hora [7] presented the computational methodology adopted for nonlinear soil-structure interaction analysis of infilled frame-foundation-soil system.

Similarly study done by researchers in ssi under dynamic loading. Brown and Yu [8] examined the effect of progressive loading during the construction of the frame on the frame-foundation-soil interaction. Kutanis and Elmas [9] presented an idealized 2-dimensional plane strain seismic soil-structure interaction analysis based on a substructure method. Lu et al. [10] carried out three-dimensional finite element analysis in time domain on dynamic soil-pile-structure interaction of a tall building.

Parametric study on Effect of soil ï structure interaction by various researchers is depicted in following table

Sr. No.	Parameter	Particulars	Studies by various researchers
1.	**Forms of structure**	**Plane Frame**	**Duncan and Chang [33], Jardine et al. [], Hora [7], Kutanis and Elmas [9], Agrawal and Hora [39]**
		Space Frame	**Noorzaei [29], Viladkar et al. [2], Noorzaei et al. [3], Swamy Rajashekhar et al. [4], Roy and Dutta [5], Brown and Yu [8], Chore et al. [31], Xiujuan et al. [], Desai et al. [34] Viladkar et al. [36], Nataralan and Vidivelli [], Bhattacharya et al. [37], Livaoglu [38],**
2.	**Geometry of superstructure**	**R. C. Frame**	**A. Massumi and Tabatabaiefar [15], Muberra ESER AYDEMIR,[16], Shiji P.[19]**
		Infill wall	**Hora [7], Chrysostomou and Asteris [30], Agrawal *et al*[31]**
		Tall	**Pallavi Ravishankar,[21], Lu et al. [10], S.T. Karapetrou *et al* [26]**
		Elevated tanks	**Ramazan *et al* [12]**
		Chimney	**Ganesh Kumar T[40]**
		nuclear reactor	**Dan M. Ghiocel, Roger G. Ghanem[12] Ostadan, F *et al*[24]**
		Bridge	**Shamsabadi *et al* [21], Bezih *et al* [27]**
3.	**Types of foundation**	**Pile**	**Y.X. Cai, P.L. Gould , C.S. Desai [34], Hokmabadi A.S.,[20], Pulikanti *et al* [29], Medina *et al,* [25],**
		Isolated	**Al-Shamrani and Al-Mashary [30], Roy and Dutta [5], Bhattacharya et al. [37], Agrawal and Hora [39]**
		Raft	**j Rajasankar *et al,* [18], Noorzaei [29], Thangaraj and Ilamparuthi [32], Viladkar et al. [36], Wang et al. [35]**
4	**Domain**	**Time Domain**	**Y.X. Cai, P.L. Gould , C.S. Desai [11], Viladkar et al. [36], Kutanis and Elmas [9],**
		Frequency domain	**Suleyman Kocak a, Yalcin Mengi b [14]**
5.	**Other**	**stochastic processes**	**Dan and Roger [12], Veletsos and Prasad,[13]**

6. Conclusions

The review of the current practice as applied in soil-structure interaction analysis leads to the following broad conclusions.

1. To accurately estimate the response of structure, the effect of soil structure interaction is needed to be considered under the influence of both static and dynamic loading.
2. The forces in superstructure, foundation and soil mass are significantly altered due to the effect of soil-structure interaction. For accurate estimation of the design force quantities, the interaction effect is needed to be considered.
3. Load redistribution significantly modifies the total and differential settlements. Settlements are found more in the non-linear analysis.
4. Numerous investigators analysed the interaction behaviour considering foundations as raft foundation, isolated footing, grid foundation and pile foundation etc.
5. The investigators have considered the soil mass as homogenous, isotropic and behaving in linear and nonlinear manner in the interaction analysis.
6. A limited number of studies have been conducted considering the soil mass as elasto-plastic, visco-elastic and visco plastic in interaction analyses.
7. 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, nonhomogeneity and interface modeling of soil and foundation.
8. To perform nonlinear soil-structure interaction analysis, incremental iterative technique is found to be the most suitable and general one.
9. For practical purpose Winkler hypothesis should at least be employed instead of carrying out an analysis with fixed base idealization of structures.
10. Soil-structure interaction may cause considerable increase in seismic base shear of low-rise building frames resting on isolated footings.

REFERENCES

i. Kramer, S. L. "Geotechnical Earthquake Engineering", Prentice Hall, Inc., Upper Saddle River,New Jersey (1996)

ii. M.N. Viladkar, J. Noorzaei, and P.N. Godbole, Interactive analysis of a space frame-raft-soil system considering soil nonlinearity Comput. Struct., 51, (1994), 343-356.

iii. J. Noorzaei, M.N. Viladkar, and P.N. Godbole, Nonlinear soil-structure interaction in plane frames, Eng. Comput., 11, 1994, 303-316.

iv. H.M. Rajashekhar Swamy, Krishnamoorthy, D.L. Prabakhara, and S.S. Bhavikatti, Relevance of interface elements in soil structure interaction analysis of three dimensional and multiscale structure on raft foundation, Electron. J. Geotech. Eng., 16, 2011, 199-218.

v. R. Roy, and S.C. Dutta, Differential settlement among isolated footings of building frames: the problem, its estimation and possible measures, Int. J. Appl. Mech. Eng., 6(1), 2001, 165-186.

vi. C.S. Desai, H.V. Phan, and J.V. Perumpral, Mechanics of three-dimensional soil-structure interaction, J. Eng. Mech., ASCE, 108(5), 1982, 731-747.

vii. M. Hora, Nonlinear interaction analysis of infilled building frame-soil system, J. Struct. Eng., 33(4), 2006, 309-318.

viii. P.T. Brown, and Si K.R. Yu, Load sequence and structure-foundation Interaction J. Struct. Eng., ASCE, 112(3), 1986, 481-488.

ix. M. Kutanis, and M. Elmas, Non-linear seismic soil structure interaction analysis based on the substructure method in the time domain, Turk. J. Eng. Environ. Sci., 25, 2001, 617-626.

x. X. Lu, B. Chen, P. Li and Y. Chen, Numerical Analysis of Tall Buildings Considering Dynamic Soil-Structure Interaction, J. Asian Archit. Build., 2(1), 2003, 1-8

xi. Y.X. Cai a,, P.L. Gould b, C.S. Desai c Nonlinear analysis of 3D seismic interaction of soil–pile–structure, systems and application Engineering Structures 22 (2000) 191–199*

xii. Dan M. Ghiocel, and Roger G. Ghanem, Stochastic Finite-Element Analysis of Seismic Soil–Structure Interaction Journal of Engineering Mechanics, Vol. 128, No. 1, January 1, 2002. ©ASCE, ISSN 0733-9399/2002/1-66

xiii. Anestis S. Veletsos,1 Member, ASCE, and Aiumolu M. Prasad, Journal of Structural Engineering, Vol. 115, No.1.4, April, 1989. ©ASCE, ISSN 0733-9445/89/0004-0935

xiv. Suleyman Kocak a,, Yalcin Mengi b A simple soil structure interaction model Applied Mathematical Modelling 24 (2000) 607-635*

xv. Massumi1 and H.R. Tabatabaiefar2 A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil–structure interaction, Soil Dynamics and Earthquake Engineering 30 (2010) 1259–1267

xvi. Muberra E.A., "Soil Structure Interaction Effects On Multistorey R/C Structures", International Journal Of Electronics; Mechanical And Mechatronics Engineering Vol. 2 Num.3 pp.(298-303).

xvii. Rajasankar J., Iyer N. R., Yerraya Swamy B., Gopalakrishnan N., Chellapandi P., "SSI analysis of a massive concrete structure based on a novel convolution/deconvolution technique", Sādhanā Vol. 32, Part 3, June 2007, pp. 215–234.

xviii. Shiji P. V., Suresh S., Joseph G., "Effect of Soil Structure Interaction in Seismic Loads of Framed Structures", International Journal of Scientific & Engineering Research Vol. 4, Issue 5, May-2013.

xix. Hokmabadi A.S., Fatahi B., Samali B. Seismic Response of Superstructure on Soft Soil Considering Soil-Pile-Structure Interaction, Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013

xx. pallavi ravishankar, dr d neelima satyam, numerical modelling to study soil structure interaction for tall asymetrical building, international conference on earthquake geotechnical engineering istanbul, turkey

xxi. anoosh shamsabadi1 and mike kapuskar, nonlinear seismic soil-abutment-structure interaction analysis of skewed bridges

xxii. ramazan livaoğlu1 and adem doğangün an investigation about the soil-structure interaction effects on sloshing response of the elevated tanks the 14th world conference on earthquake engineering october 12-17, 2008, beijing, china

xxiii. Ostadan, F., Arango, I., Oberholtzer, G., Hsiu, F., Radially Loaded Circular Tunnel Structure, IX Pan american

Conference on Soil Mechanics and Foundation Engineering, Vina del Mar, Chile, August 1991

xxiv. *c. medina, j. j. aznárez, l. a. padrón, Orlando maeso effects of soil–structure interaction on the dynamic properties and seismic response of piled structures soil dynamics and earthquake engineering 53(2013)160–175*

xxv. *S.T. Karapetrou n, S.D. Fotopoulou, K. D. Pitilakis, Seismic vulnerability assessment of high-rise non-ductile RC buildings considering soil–structure interaction effects, Soil Dynamics and Earthquake Engineering73(2015)42–57*

xxvi. *Cristina Medina, JuanJ. A znárez, Luis A. Padrón n, Orlando Maeso, Effects of soil–structure interaction on the dynamic properties and seismic response of piled structures Soil Dynamics and Earthquake Engineering 53(2013)160–175*

xxvii. *Kamel Bezih a,b,*, Alaa Chateauneuf d,e, Mahdi Kalla c, Claude Bacconnet d,e Effect of soil–structure interaction on the reliability of reinforced concrete bridges Ain Shams Engineering Journal (2015)*

xxviii. *Sushma Pulikanti, Ramancharla P. K., "SSI Analysis of Framed Structure Supported on Pile Foundations -With and Without Interface Elements", Frontier in Geotechnical Engineering (FGE) Vol. 3 Issue 1, March 2014.*

xxix. *J. Noorzaei, Concepts and application of three dimensional infinite elements to soil-structure-interaction problems, Int. J. Eng., 9(3), 1996, 131-142.*

xxx. *M.A. Al-Shamrani, and F.A. Al-Mashary, A simplified computation of the interactive behavior between soils and framed structures, Eng. Sci., 16(1), 2003, 37-60.*

xxxi. *H.S. Chore, R.K. Ingle, and V.A. Sawant, Building frame - pile foundation - soil interaction analysis: a parametric study, J. Interact. Multiscale Mech., 3(1), 2010, 55-79.*

xxxii. *D. Thangaraj and K. Ilamparuthi, Parametric study on the performance of raft foundation with interaction of frame, Electron. J. Geotech. Eng., 15, 2010, 861-878.*

xxxiii. *J.M. Duncan, and C.Y. Chang, Nonlinear analysis of stress and strain in soils, J. Soil Mech. Found. Eng. Div. ASCE, 96(5), 1970, 1629-1653.*

xxxiv. *C.S. Desai, H.V. Phan, and J.V. Perumpral, Mechanics of three-dimensional soil-structure interaction, J. Eng. Mech., ASCE, 108(5), 1982, 731-747.*

xxxv. *C.M. Wang, Y.K. Chow, and Y.C. How, Analysis of rectangular thick rafts on an elastic half-space, Comput. Geotech., 28(3), 2001, 161-184.*

xxxvi. *M.N. Viladkar, G. Ranjan, and R.P. Sharma, Soil-structure interaction in the time domain, Comput. Struct., 46(3), 1993, 429-442.*

xxxvii. *K. Bhattacharya, S.C. Dutta, and R. Roy, Seismic design aids for buildings incorporating soil-flexibility effect, J. Asian Archit. Build., 5(2), 2006, 341-348.*

xxxviii. *R. Livaoglu, Some approximations on considering fluid-structure-soil interaction effects by using ansys, Proc. of 11th conference for computer-aided engineering and system modeling, Abant, Bolu, 2006, 1-9.*

xxxix. *R. Agrawal, and M.S. Hora, Nonlinear interaction behaviour of plane frame-layered soil system subjected to seismic loading, Int. J. Struct. Eng. Mech., 11(6), 2012, 711-734.*

xl. *Ganesh Kumar T.,Shruthi H.K, "Soil Structure Interaction Effect On 200m Tall Industrial Chimney Under Seismic Load"*