A review on interaction behaviour of structure-foundation-soil system

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Abstract

Soil-structure interaction is interdisciplinary field which involves structural and geotechnical engineering. In the conventional non-interaction analysis of building frame structural designer assumed that columns are resting on unyielding support. Similarly, in foundation design, foundation settlements are calculated without considering the influence of the structural stiffness. Although, interaction effect is ignored to simplify the mathematical model but neglecting the interaction between soils and structures may result in a design that is either unnecessarily costly or unsafe. A more rational solution of soil-structure interaction problem can be achieved with computational validity and accuracy by appropriate analysis. The present study makes an attempt to study the possible alternative solutions proposed by various researchers to evaluate the effect of soil-structure interaction from time to time.

Keywords: soil-structure interaction, static loading, seismic loading, nonlinear, finite element analysis, space frame, isolated footing.

1. Introduction

Several studies have been made on the effect of soil-structure interaction problems to obtain more realistic analysis. They have quantified the effect of interaction behaviour and established that there is redistribution of forces in the structure and soil mass. Hence, structures and their supporting soils should be considered as a single compatible unit. The interaction effects are found quite significant, particularly for the structures resting on highly compressible soils. The flexibility of soil mass causes the differential settlement and rotation of footings under the application of load. The relative stiffness of structure, foundation and soil influence the interaction behaviour of structure-foundation-soil system

2. Linear soil-structure interaction under static loading

The interaction behaviour of plane frames with an elastic foundation of the Winkler's type, having normal and shear moduli of sub-grade reactions is studied by Aljanabi et al. [1]. An exact stiffness matrix for a beam element on an elastic foundation having only a normal modulus of sub-grade reaction was modified to include the shear modulus of sub-grade reaction of the foundation as well as the axial force in the beam. The results indicated that bending moments might be considerably affected according to the type of frame and loading.

The efficiency of the coupled finite-infinite elements formulation with respect to computational effort, data preparation and the far field representation of the unbounded domain is investigated by Noorzaei [2].

Al-Shamrani and Al-Mashary [3] presented a simplified procedure for the analysis of soil-structure interaction behavior of two-dimensional skeletal steel or reinforced concrete frame structures resting on isolated footings that are supported by different types of soil. The main program was made of two major modules; one for soil settlement calculations and another for the analysis of structure. They evaluated the effect of interaction on the predicted settlements, footing loads, and internal bending moments of the structural members.

Roy et al. [4] performed an analysis on an idealized model consisting of multi-storey 3-D frame structure with grid foundation. The grid foundation is assumed to rest on springs, which idealize the soil behaviour.

The effect of soil-structure interaction on a space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap is examined by Chore et al. [5]. They evaluated the effects of pile spacing, pile configuration, and pile diameter of the pile group on the response of superstructure. The effect of soil structure interaction is found to be quite significant.

The effect of contact between strap beam and bearing stratum is studied by Guzman [6]. The results indicate that when a strap footing is used as part of a foundation system, a detail that allow for pressure to be relieved from the strap beam is necessary on construction documents. Without it, a considerable unforeseen load path could be created that may result in the failure of strap beam followed by overstress of the soil under the eccentric footing.

The interaction and non-interaction analyses for the space frame-raft foundation-soil system using

ANSYS finite element code is compared by Thangaraj and Ilamparuthi [7]. The soil was treated as an isotropic, homogenous and elastic half space medium. A detailed parametric study was conducted by varying the soil and raft stiffness for a constant building stiffness. The interaction analysis showed less total and differential settlements than the non-interaction analysis and relative stiffness of soil plays major role in the performance of the raft.

The stress and settlement distribution of a tank foundation by using the finite element analysis software (ANSYS) is studied by Xiujuan et al. [8]. The results indicate that finite element method can simulate the settlement of a tank foundation reliably. The operation of finite element analysis is convenient and needs less equipment than the traditional method of experiment; the result of this method is identical to that of the traditional method. They conclude that it is a practical and valuable method for analyzing and studying the stress and settlement distribution of a tank foundation, which can also be used to study other foundation types.

The effects of horizontal stresses and horizontal displacements in loaded raft foundation are studied by Swamy Rajashekhar et al. [9]. The numerical experiments are performed on three dimensional mathematical models. The results of uncoupled analysis i.e., complete slip/frictionless interface between foundation and soil and the coupled analysis i.e., complete welding/bonding of joints between foundation and soil elements were compared with the results of non-interactive analysis. They concluded that the response of the structure does change in soil-structure-interaction analysis when compared to non-interactive analysis but member end actions for beams and columns are almost same in coupled and uncoupled analysis.

3. Nonlinear soil-structure interaction under static loading

A simplified, practical nonlinear stress-strain relationship for soils which is convenient for use with the finite element method of analysis is described by Duncan and Chang [10]. The Mohr-Coulomb strength parameters, cohesion and angle of internal friction are involved in this relationship.

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. [11]. The formulation was based on the updated Lagrangian or approximate Eulerian approach with appropriate provision for constitutive laws.

The influence of small strain non-linearity of low plasticity clay in comparison with linear elastic behaviour is studied by Jardine et al. [12]. They found that non-linear behaviour results in the concentration of strain and deformation towards the loading boundaries.

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. [13]. Hyperbolic stress strain model has been used to consider the soil non-linearity. The interactive behaviour of a five storey two bay plane frame has been studied in detail and the results are compared with those obtained from a conventional and a linear interactive analysis.

Viladkar et al. [14] presented a new approach for the physical and material modelling of a space frame-raft-soil system. The beams and columns of the superstructure is discretized by a modified Timoshenko beam bending element with six degrees of freedom per node and structural slabs and raft are discretized by a modified Mindlin's plate bending element with five degrees of freedom per node. The soil media is represented by the coupled finite-infinite elements with three degrees of freedom per node. The constitutive modelling involves the use of the hyperbolic model to account for the soil nonlinearity. They compared the behaviour of the space frame-raft-soil system under the linear and nonlinear interaction.

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 [15]. They presented various representative case studies for frames resting on sandy soil and clayey soil by idealising the soil medium below the footing as linear and nonlinear respectively.

Wang et al. [16] used the Ritz method to solve the bending problem of a transversely loaded rectangular thick raft with free edges, resting on an elastic half-space.

The possible alternative models for the structure-foundation-soil interaction system available in the literature are studied by Dutta and Roy [17]. Emphasis was given on the physical modeling of the soil media. For practical purpose it is found that Winkler hypothesis, despite its limitations, yields reasonable performance and it is very easy to exercise. Finite element modeling with nonlinear idealization of soil media found to be the most powerful and versatile tool for solving soil-structure interaction problem which can incorporate the effect of material nonlinearity, nonhomogeneity and anisotropy of the supporting soil media. To perform such an analysis, incremental iterative technique was found to be the most suitable and general one.

Hora [18] presented the computational methodology adopted for nonlinear soil-structure interaction analysis of infilled frame-foundation-soil system. The unbounded domain of the soil mass has been discretized with coupled finite-infinite elements to achieve computational economy. The nonlinear behaviour of the soil mass was modelled using hyperbolic model. The incremental-iterative nonlinear solution algorithm was adopted for carrying out the nonlinear elastic interaction analysis. The interaction analysis showed that the nonlinearity of soil mass plays an important role in redistribution of forces in the superstructure.

Pender et al. [19] compared two ways of modelling shallow foundation stiffness. One method assumes that the soil beneath the foundation can be idealized as an elastic continuum and the other that the soil can be represented as a bed of independent springs. They concluded that the rotational stiffness of a bed of springs is less than that of a continuous elastic material and nonlinear soil behaviour has a greater effect on the rotational stiffness than the vertical stiffness.

The influence of column spacing on the behavior of a space frame-raft-soil system under static load is studied by Nataralan and Vidivelli [20]. The analyses were carried out for linear and non-linear conditions, in which soil was treated as a homogeneous and isotropic continuum. Settlement was greater in the non-linear analysis and the settlements were higher for higher column spacing. Contact pressure distribution was more uniform in the non-linear case and its magnitude was less than that of linear soil, particularly in the end panels of the raft.

4. Elasto-plastic soil-structure interaction under static loading

Desai and Lightner [21] evaluated hybrid finite element procedure for nonlinear elastic and elasto-plastic soil-structure interaction analysis including simulation of construction sequences.

The elastic-perfectly plastic behaviour of the compressible subsoil is studied by Noorzaei et al. [22]. Interaction analysis is performed on plane frame-combined footing-soil system. Comparison of the interactive behaviour has also been made with the non-interactive behaviour and also with behaviour of the system when the sub-soil is considered as behaving in a linear elastic and non-linear elastic manner. Hyperbolic representation of the stress-strain behaviour of the soil mass has been used for the non-linear analysis. The elasto-plastic analysis has been carried out using six different yield criteria for soils.

5. Visco-elastic/plastic soil-structure interaction under static loading

A three-dimensional visco-elastic finite element formulation for studying the interactive behaviour of space frames, taking into account the stress/strain-time response of supporting soil medium is presents by Viladkar et al. [23]. The methodology for evaluating time-dependent visco-elastic constants for the soil mass is given. The results are compared with the structural behaviour with that when interaction is neglected.

The principles of elasto/viscoplastic finite element analysis are presented by Abdullah [24]. Plasticity models such as Drucker-Prager, Von-Mises, Tresca and Mohr-Coulomb models with associated and non-associated flow rules were incorporated in the viscoplastic algorithm. The ultimate bearing capacity of a rigid surface footing resting on weightless clayey soil predicted by Tresca model agrees very well with that obtained by Prandtl exact solution.

6. Soil-structure interaction under dynamic loading

The effect of progressive loading during the construction of the frame on the frame-foundation-soil interaction is examined by Brown and Yu [25]. The interaction analysis results of plane and space frames shows that the effective stiffness for interaction purposes, of a building that is loaded progressively during construction, is about half the stiffness of the completed building.

An idealized 2-dimensional plane strain seismic soil-structure interaction analysis based on a substructure method is presented by Kutanis and Elmas [26]. To investigate the interaction effect non-interaction analysis and linear and nonlinear analyses were performed. Computations were made by taking different peak acceleration and shear wave velocity. The soil plasticity was modelled with the Von Mises failure criteria.

Three-dimensional finite element analysis in time domain on dynamic soil-pile-structure interaction of a tall building is carried out by Lu et al. [27] The viscous boundary of soil is implemented in general-purpose finite element program (ANSYS) used in the analysis. The influences of parameters, such as soil property, excitation, buried depth and the rigidity of the structure, on dynamic characteristics, seismic response and interaction effect of soil-structure interaction system are discussed.

The effect of soil flexibility on base shear and uncoupled torsional-to-lateral natural period ratio is examined by Bhattacharya et al. [28]. The results of the study conclude that the effect of soil-structure interaction may cause considerable increase in seismic base shear of low-rise building frames, particularly those with isolated footings.

The effect of soil-structure interaction and fluid-structure interaction on elevated water tank under seismic loading is studied by Livaoglu [29].

The important contribution of infill walls in the resistance of earthquake loads along with a presentation of the behavior modes of the infill and the bounding frame is documented by Chrysostomou and Asteris [30]. Recommendations are made for the in-plane material properties, failure modes, strength and stiffness as well as deformation characteristics of infilled frames.

The interaction effect of frame, isolated footing and soil media under seismic loading is studied by Agrawal and Hora [31]. Various analyses are performed on frame-footing-soil system by considering plane frame, infill frame, homogeneous soil and layered soil mass. The frame is considered to act in linear elastic manner while the soil mass to act as nonlinear elastic manner. They concluded that the shear forces and bending moments in superstructure get significantly altered due to differential settlements of the soil mass.

7. Experimental study on interaction behaviour

A computational iterative scheme for studying the effect of soil-structure interaction on axial force and column moments is presented by Mandal et al. [32]. The results obtained from the computational scheme were validated from experimental study. A small scale two-storey two-bay frame made of perspex was analysed. The frame was placed on a kaolin bed with adequate arrangement of drainage. The proposed computational scheme could be used to predict increase in axial force and moments in structural members due to the effect of soil-structure interaction.

8. Parametric study on interaction behaviour

The particular parameter considered in the interaction analysis of structure-foundation-soil system is depicted in Table 1.

Table 1 Parametric study on interaction behaviour by various researchers

Sr. No.	Parameter	Particulars	Interaction studies by various researchers
1	Geometry of superstructure	Plane frame	Aljanabi et al. [1], Al-Shamrani and Al-Mashary [3], Duncan and Chang [10], Jardine et al. [12], Hora [18], Noorzaei et al. [22], Kutanis and Elmas [26], Agrawal and Hora [31]
		Space frame	Noorzaei [2], Roy et al. [4], Chore et al. [5], Thangaraj and Ilamparuthi [7], Xiujuan et al. [8], Swamy Rajashekhar et al. [9], Desai et al. [11], Noorzaei et al. [13], Viladkar et al. [14], Roy and Dutta [15], Nataralan and Vidivelli [20], Viladkar et al. [23], Brown and Yu [25], Lu et al. [27], Bhattacharya et al. [28], Livaoglu [29], Mandal et al. [32]
		Infill wall	Hora [18], Chrysostomou and Asteris [30], Agrawal and Hora [31]
		Tall building	Lu et al. [27]
2	Type of foundation	Elastic beam	Aljanabi et al. [1], Noorzaei et al. [13], Hora [18]
		Isolated footing	Al-Shamrani and Al-Mashary [3], Roy and Dutta [15], Bhattacharya et al. [28], Agrawal and Hora [31]
		Raft foundation	Noorzaei [2], Thangaraj and Ilamparuthi [7], Swamy Rajashekhar et al. [9], Viladkar et al. [14], Wang et al. [16], Nataralan and Vidivelli [20]
		Pile foundation	Chore et al. [5], Jardine et al. [12], Lu et al. [27]
		Grid foundation	Roy et al. [4]
		Strap footing	Guzman [6]
3	Type of soil	Sandy	Roy and Dutta [15], Nataralan and Vidivelli [20]
		Clayey	Chore et al. [5], Jardine et al. [12], Roy and Dutta [15], Abdullah [24], Bhattacharya et al. [28]
		Layered	Xiujuan et al. [8], Desai and Lightner [21], Agrawal and Hora [31]
4	Interface behaviour	Foundation-soil	Desai et al. [11], Rajashekhar et al. [9]
5	Settlement	Effect of the differential settlement	Roy and Dutta [15], Agrawal and Hora [31]

9. Conclusions

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

a) 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.
b) Load redistribution significantly modifies the total and differential settlements. Settlements are found more in the non-linear analysis.

c) Numerous investigators analysed the interaction behaviour considering foundations as raft foundation, isolated footing, grid foundation and pile foundation etc.
d) The investigators have considered the soil mass as homogenous, isotropic and behaving in linear and nonlinear manner in the interaction analysis.
e) A limited number of studies have been conducted considering the soil mass as elasto-plastic, visco-elastic and visco plastic in interaction analyses.
f) The finite element method has proved to be a very useful method for studying the effect of soil-structure interaction.
g) To perform nonlinear soil-structure interaction analysis, incremental iterative technique is found to be the most suitable and general one.
h) For practical purpose Winkler hypothesis should at least be employed instead of carrying out an analysis with fixed base idealization of structures.
i) Soil-structure interaction may cause considerable increase in seismic base shear of low-rise building frames resting on isolated footings.

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