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Soil-Structure Interaction: A Critical Review

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ABSTRACT:-This paper provides an insight and the role of the dynamics soil structure interaction analysis depending upon the past studies. As a result of population boom and scarcity of land, buildings are constructed very close to each other. This is the major issue especially in the case of developing country where housing colonies are developing in the big cities as well as in the countryside, making the study of soil-structure interaction as an essential part of structural design process. The effect of soil, on which the structures stands, especially in the highly seismic zones, the dynamicbehaviour of soil as wellstructureshouldbe well known by the designer. The effects of structures standing in a close vicinity to each other is the main issue of soil-structure interactions as well as structure-soil-structure interactions. In this paper, variousmethods of soil-structure interactions carried out by various researchers in various regionare reviewed.

Key words: - Population boom, Countryside, Soil-Structure Interaction, Seismic Zones

I. INTRODUCTION

Civil engineering structures generally require some type of structural element which is in direct contactwith soil. In order to estimate the accurate response of the superstructure it is necessary to consider the response of the soilsupporting structure, and is well explained by the soilstructure interaction (SSI) analysis. Various attempts have beenmade by various researchers to model the SSI problem analytically; however thesoil nonlinearity, foundation interfaces and boundary conditions make the problem more complex and computationally costlier.

Most efficient and accurate modeling of the unbounded soil medium hasbeen of long-standing interest in the mind of researchers for the dynamic soil structure interaction (SSI) problems. The methods availablefor the analysis of SSI problems can be classified into two groups:i.e. direct method and substructure method. In the direct method of SSIanalysis, the artificial boundary has to be placed sufficiently far fromthe soil-structure interface because approximate or local boundaryconditions are imposed on this boundary. This leads to an increase inthe number of degrees of freedom (DOF) and the computationaleffort, although the direct method itself is computationally efficient because the interaction force-displacement relationship involved is local in time and space. On the contrary, in the substructuremethod, the boundary conditions imposed on the interaction horizonare rigorous, making the force-displacement relationship global bothspatially and temporally. A large amount of data also need to be processed,which results in expensive computations, especially for large-scaleproblems.

II. REVIEW OF AVAILABLE LITERATURES

Jonathan et al. (1999) proposed the well-definedprocedures for simulating the inertial soil structure interaction effects with respect to seismic structural response. Their analysis procedure and data's are similar to that of provisions provided in standard building codes along with the consideration of the site influence conditions, foundation embedment, flexibility, and shape of the foundationimpedance. The process of implementing their analysis procedures and techniques is well illustrated using the data of Northridge earthquake (1994). Their analyses empirically evaluate SSI effects using available strong motion data from a broad range of sites conditions.

Zhang et al. (1999) developed a three-dimensional dynamic SSI analysis program (DSSIA-3D) for SSI analysis in the time domain. DSSIA-3D is based on the substructure method, wherein the unbounded media is modelled by the SBFEM. Approximation schemes in both time and space were implemented for computational efficiency in calculating the unit-impulse response matrix with no major loss of accuracy. Also, in order to calculate the interaction forces using convolution integrals an efficient scheme has been implemented. DSSIA-3D can be used for SSI analysis considering seismic waves as well as externally applied dynamic loading.

Wegner and Zhang (2001) proposed a procedure using FEM-SBFEM coupling for the free-vibration analysis of a soil-structure system. Using inverse iteration for solving the nonlinear eigenvalue problem, the fundamental frequency of the soil structure system and the corresponding mode shapes as well as the radiation-damping ratio are calculated.

Genes M. C. and Kocak S. (2005) presented a computational model for dynamic response of soil–structure interaction analysisusing the FE–BE–SBFEM coupled model. In their analysis they first developed and tested the FE–BEM and FE–SBFEM models and later, the FE–BE–SBFEM model is implemented in analysis. In their proposed model,the finite region, which might be considered as the structure, is modelled by the FEM. On thesoil–structure interface, the boundary at the bottom of the finite medium, which is extending toinfinity in vertical direction, is modelled by the BEM, and the vertical boundary of the layers,which is extending to infinity in horizontal direction, is modelled by the SBFEM. This coupledmodel combines the three methods by using them whenever they are advantageous; for example,the use of SBFEM on the vertical boundary eliminates the need for discretization of freesurfaces, and SBFEM represents the layered medium on the vertical boundary more efficientlythan the BEM. SBFEM satisfies the boundary conditions on free, fixed and inter-materialsurfaces without discretization. Also, there are no singular integrals to be evaluated as in BEM.

Their analyses are conducted in frequency space. Dynamic stiffness matrices pertaining to relatedregions of the SSI system are calculated by three methods and combined by using sub structuring method. In the SBFEM, for the dynamic stiffness matrix calculations Bulirsch–Stoer integrationalgorithm is used to integrate the resulting ODE. Since Bulirsch–Stoer integration algorithmdictates the frequencies at which dynamic stiffness matrix is calculated, related dynamic stiffnesscalculations are conducted by BEM and FEM at corresponding frequencies. Their finding shows that the coupled FE–BE–SBFEM model can be used in SSI analyses efficiently and accurately. Their results also demonstrated the importance of using coupled models for analysing complex structures and non-homogeneous unbounded mediums.

Julio A. G. (2008)proposed that the influence of soil-structure interaction in the dynamic behaviour of the structure is reflected in anincrease in the vibration period as well as an increase in system damping compared to the fixed basemodel. He observed that the increase in vibration period is about 7.6% as compared with the fixed-base model. He also observed that the increase inthe system damping is 166% as compared to the fixed-base model.

His observation shows that the influence of soil-structure interaction in the seismic design of the structure is reflected in a decrease inthe horizontal values of spectral acceleration and reduction in the acceleration values for the fundamentalperiod of the structure is 29.6% as compared with the fixed base model. He recommended to reduce the spectral acceleration of the structure corresponding to thefundamental period by 20% over the acceleration value for the fixed base model. He observed that the inclusion of the soil in the structural analysis provides results, stresses and deformations, closest to theactual behaviour of the structure, in comparison with those provided by the analysis of a fixed-basestructure. He also suggested that, mechanisms such as rocking can be investigated by including the stiffness parameters offoundation and subsoil. His finding suggests that the increase in system damping is associated with a reduction in the elasticdeformation of the structure due to the energy dissipated in the soil-foundation system. Besides, moreeconomic designs are obtained by including the soil in the structural analysis and design, due to thereduction in seismic loads.

Sanaz et al. (2011) worked on coupled scaled boundary finite element-finite element model to examine the dynamic response of the structure considering soil-structure interaction. They used substructure method to analyse the soil-structure interaction problem. Their analysis is performed in time domain were material behaviour of soil and structure is assumed to be linear. They used scaled boundary finite element method to calculate the dynamic stiffness of the soil, and the finite element method to analyse the dynamic behaviour of the structure. 2D frames have been analysed by them using their proposed model and results were compared with those obtained by cone model. In analysis they observed that, consideration of SSI effect leads to reduction in displacement and base shear. It was also observed that when the soil structure system was subjected to an earthquake whose predominant period is close to natural period of the structure, considering SSI effects leads to more significant reduction, and the dynamic response of the structure was more affected. From their analysis it was observed that considering SSI effects results in more effective design without decreasing safety margin.

Syed, N. M. and Maheshwari, B. K. (2012) presented the work on coupled FEM-SBFEM approach for the nonlinear dynamic SSI analysis. In their study the nonlinearity of soil is modelled using HiSS constitutive model. After verification of developed algorithm, an axisymmetric problem of an elastic half-space under dynamic load was addressed by them. Their results highlighted the importance of radiation damping in the SSI analysis. They suggested that their approach can be used in the dynamic SSI analysis of highly nonlinear problems, since the full Newton-Raphson iteration is considered in the nonlinear HHT-α method of integration. They also stressed that, their algorithm can be extended to deal with soil liquefaction.

Chen, X., Birk C. and Song, C. (2013). They developed a new algorithm which will be useful for the solution of dynamic soil-structure interaction problems in the time domain. The traditional SBFEM is based on approximating the acceleration unit-impulse response by a piece-wise constant function. Two essential improvements proposed by them are: (1) the displacement unit-impulse response is calculated instead of the acceleration unit-impulse response based on a piece-wise linear approximation; (2) the convolution integral in the soil-structure interaction force vector is truncated after a few steps. This leads to a significant reduction of computational effort. The accuracy and computational efficiency of the proposed algorithm have been verified by them using various numerical examples.

Syed, N. M. and Maheshwari, B. K. (2014). The FEM-SBFEM approach was compared by them with the direct method of the SSI analysis using viscous dashpots. They found that the FEM-SBFEM approach is computationally efficient compared with viscous dashpots, which uses large FEM mesh (increasing computation) and still gives approximate results. In their study free-field amplification factors were calculated using the FEM-SBFEM approach and compared with those calculated using viscous boundary and Kelvin elements. The results of the dynamic SSI analysis of a building with unbounded domain modeled using the SBFEM verified a well-established fact that the response of the structure depends conjointly on the dynamic characteristics of the structure and the supporting soil.

Badry P, Satyam N (2016).has observed that the effect of introducinginteraction effect deviates the system response. Thedeviation so observed was less for the bottom floor andincreases as the storey height increases. The response was about 15 - 20 % on an average in the case of SSIanalysis than the fixed base analysis. Thus, it signifies thatthe effect of interaction plays important role in superstructure response. They have also observed that, the asymmetrical building responseat all points located at the same level is not same and clearlyshows that the asymmetrical building has different movement at different location on the same vertical level. Thisdeviation is found to be within the range of 2–4 % for different corners which indicates the effect the structure.

Lu, Yang (2016). Developed simplified nonlinear sway-rocking model to capture the coupled sway-rocking behaviour of shallow mat foundations supporting heavily-loaded buildings under earthquake ground motions. Their spring-type model utilised a single normalised backbone curve for each of the swaying and rocking degrees of freedom. They also developed normalised backbone curves depending upon their results of a series of static displacement-control finite-difference analyses which was carried out using the FLAC^{3D} program. The effect of soil non-homogeneity on the stiffness and capacity of the soil-foundation system was also considered in their analysis.

The effectiveness and efficiency of their proposed model were validated against resultsfrom dynamic analyses performed using a FLAC^{3D} model by utilising two artificial input motions and one real earthquake acceleration record. The simplified model was capable of efficiently capturing the foundation load-displacement behaviour, including the maximum and residual displacements, with good accuracy.

Although their proposed simplified model has some limitations, though their model able to provide parameters necessary for preliminary design of buildings on weak soil while achieving a good balance between simplicity and accuracy. In addition, the concept of the model allows engineers to select appropriate model properties in accordance with specific site conditions.

Kwag, S., Ju, B and Jung, W. (2018) explored the SSI effect on the overall risk of a PWR containment building structure with respect to two failure modes: strength and displacement. Such an exploration is based on the current SPRA framework which integrates seismic hazard and fragility information. For the fragility analysis purpose, the factor of the safety method and the MLE-based statistical approach are employed by them. The seismic responses of the containment structure supported on the three soil conditions: fixed, hard, and soft, are obtained by using site response analyses and inelastic time-history analyses, and results are then utilized for basic information in the fragility quantification. The discrete seismic hazard information in the site of interest and the log-log linear approximation are utilized for the conservative risk assessment. Finally, the seismic fragility and risk results in the three different soil conditions are compared for each failure mod

A summary of SSI researches through analytical, experimental and numerical studies

III. CONCLUSION(S)

From the literature review, author wants to conclude that it is very important to direct research towards the ways of examining the effects of SSI on the structure and figure out the conditions that produce adverse effects on SSI. This review article will provide a good understanding of the origin and development related to the various problems that existed in the context of soil structure interaction. It is apparent that great dealof work has been done to understand the effects of dynamic SSI. It has been hypothesized that in many cases SSI can be considered beneficial for multi-purpose residential and / or commercial buildings and other types of civil engineering structures. Many investigators have shown that this hypothesis is flawed in different contexts. Numerous evidence is available that demonstrates the effects of soil structure interactions on the structural response and highlighted the important contributions due to SSI. In addition, ground motion amplification plays a major role in the structural response. There are various ways to evaluate the effects of seismic SSI and each method has its own usefulness and scope. Various issues related to soil modelling and foundation interaction have been discussed and it is considered that a limited amount of research has been done on nonlinear modelling of soil and foundation interaction for seismic soil structure interaction studies. The natural period of the structure plays a major role in the structural responsefor seismic SSI studies. It has been observed that the validity of the fixed base for flexible bases is limited to the stiff soil foundation systems. The behaviour of low-rise and high-rise structures are different from each other. In the same way, the behaviourof moment resisting framed structures is different from those of the wall frame structure where the rocking plays an important role. The type of foundation plays a major role in determining the response of the superstructure. The behaviour of structures supported on shallow foundation is different than that supported on the piles. Site features and ground motion have a significant impact and produces a destructive response to the structures during an earthquake. It is understood that there are many issues involved with dynamism and that need to be known for a better understanding of the seismic SSI.

From this review article, it is clear that many studies have carried out which give idea about the effects of SSI. However, studies that focus on the application of different approaches to a particular issue is limited. Such studies should be developed to understand local effects and specific effects of SSI which will be useful in understanding the realistic scenarios or causes that may arise due to SSI.

Researcher	ear	Contribution	Foundation	Analysis
Analytical Studies				
Lin and Miranda	009	4-story asymmetrical building	Springs and dashpot	Arithmetic sum method
Olariu and Movila	014	2-story asymmetrical building	Springs and dashpot	Spectral acceleration method
Experimental studies				
Todorvska	002	45m Hollywood storage building	Pile	Ambient vibration test
Mason, Trombetta, Chen, Bray, Hutchinson and Kuttar	013	Asymmetrical group of symmetrical building	Isolated	Scale down model, Centrifuge testing
Numerical studies				
Venkatesh, Gupta and Pandit	012	Asymmetrical loading	Raft	and 2 3-D nonlinear analysis of soil - D analysis for structure
Tehrani and Khoshnoudian	014	Planar asymmetry. 5 to 15 story buildings	Shallow	Pushover analysis
Sharma and punit	014	Different shear wall configuration in tall asymmetrical building	Shallow	3-D nonlinear dynamic analysis
Isbiliroglu and Taborda	014	Group of asymmetrical small structure	Isolated	3-D nonlinear analysis
Yigti	013	Asymmetrical cluster of buildings	Shallow	3-D dynamic nonlinear analysis
Irfan, Sunandan Reddy and Mythili	014	Soft story effect including interaction	Isolated	3-D dynamic non

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