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Analysis of Soil-Structure Interaction – A Review

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ABSTRACT -With the rapid development of society and economy and the global explosion of population, the construction of the cluster of high buildings is on the rise gradually due to the lack of space in cities. Thus, numerous high-rise buildings are emerging in cities and even more complex structures were constructed in worldwide countries. The concept of structure–soil interaction was introduced to study about the dynamic behaviour of adjacent structures as there were closely spaced and also to study the soil and structure contact behaviour on various conditions. Many unresolved problems in soil dynamics are the study of the interaction of nearby masses on the ground. It will be recalled that analytical studies of problems in soil dynamics have often started by considering the simpler problem relating to an elastic half space. Later these studies lead in analysing the structure with non-linear parameters to solve with accuracy. In this study it has been reviewed the existing literature about SSI and study it's behaviour on structures by considering both linearity and non-linearity of soil. Furthermore, an attempt has been made to review and summaries the necessities for numerically analysing a 3D modal for a structural system using FEM.

Key Words: Soil, Soil-Structure Interaction, Seismic Analysis, Dynamic loads,Foundation, Linear & Non-linear analysis.

I. INTRODUCTION

After the emergence of earthquake of above -M 7 from Richart scale, it was evident that damage to the structure not only depends on the behavior of super structure but also on the sub-soil below it. Since then, many researchers have studied the behavior of the soil subjected to the dynamic loading and /or Seismic loading. Investigations were done experimentally, analytically, numerically and also field observations. From these investigations, it was understood that the response of soil to dynamic loads plays a major role in the damage of structures as the structure is interconnected to soil to any existing adjacent structures which shares the same response. The behavior of soil becomes much complex and several factors needs to be considered. Before starting the actual literature review a brief introduction to Soil Structure Interaction and Pile Foundations are given in the following sections.

1.1 Soil-Structure Interaction

Soil-Structure Interaction (SSI) has been recognized as an important factor that may significantly affect the relative building response, the motion of base and motion of surrounding soil. In general, building-soil interaction consists of two parts; kinematic and dynamic (or inertial) interaction. The former is a result of wave nature of excitation and is manifested through the scattering of incident waves from building foundation and through filtering effect of the foundation that may be stiffer than the soil and therefore may not follow the higher frequency deformations of soil. This interaction depends on frequency, angle of incidence and type of incident waves, as well as shape of foundation and on the depth of embedment.

1.2Foundation

Foundation is part of a structural system that supports and anchors the superstructure of a building and transmits its loads directly to the earth. Foundation types – (1) Shallow Foundation & (2) Pile Foundation. Shallow foundation distributes loads from the building into the upper layers of the ground. A shallow foundation is one in which the depth from ground surface to the underside of the foundation is less then five times the width of the foundation. Shallow foundations perform very well on sites with strong soils, sufficiently thick natural gravel rafts overlying weaker soils or where robust, engineered ground improvement is carried out. Shallow foundation are susceptible to any seismic effect that changes the ground contour, such as settlement or lateral movement, or alters the bearing capacity of the upper soil, such as liquefaction.Pile foundation is a popular method of construction for overcoming the difficulties of foundation on soft soils. But, until nineteenth century the design was entirely based on experience. It is only too convenient for an engineer to divide the design of major buildings into two components: the design of the structure and the design of foundations. But in reality, the loads on foundation determine their movement, but this movement affects the loads imposed by the structure; inevitably interaction between structure, foundation and soil or rock forming the founding material together comprise one interacting structural system (Poulos and Davis, 1980). Significant damage to pile supported structures during major earthquakes (such as 1906 San Francisco earthquake, 1964 Niigata and Alaska earthquakes) led to an increase in demand to reliably predict the response of piles. Since then, extensive research has been carried out and several analytical and numerical procedures have been developed to determine the static and dynamic response of piles subjected to horizontal or vertical loads. Also, full scale experimental observations on the pile's behaviour and numerous model testing have been carried out.

Observations of damage to pile foundation of buildings in recent major earthquakes also indicate substantial instances of the damage at deeper part of the piles. Generally, such damages tend to be common at interfaces of soil layers with prominent stiffness contrast.

II. LITERATURE REVIEW

Hung Leung Wong (1975), The dynamic response of foundations placed on top of a semi-infinite medium is of considerable interest in the fields of applied mechanics, wave propagation and in the design of machine bases. During shaking of an earthquake, seismic waves are transferred through the soil from the fault rupture to a structure of interest. The wave motion of the soil excites the structure which in turn modifies the input motion by its movement relative to the ground. These interaction phenomena will be called soil-foundation-superstructure interaction or simply soil-structure interaction. Depending on the material properties of the soil medium, the source of dynamic excitation and the particular type of foundation considered the response of the structural system can be quite different from the case where the supporting is rigid. This interaction effect may be especially significant in the frequency band near the resonant frequencies of the superstructure because the soft foundation can provide the means for energy absorption. Because of this, the interaction is generally considered to be favorable in earthquake engineering design. A well-controlled analysis of creating 2D model to find the exact series solutions from this we could infer the dynamic characteristic of interaction between soil and structures. As a result, we could study the effect of embedment, shape of foundation, seismic waves intensity and interaction with other structures along with soil along with this in a simplified manner we could infer topographical study, effect of soil damping. Therefore, 3D model is constructed for approximate method of solving the study, and the results can be super positioned, here the foundation can be restricted to flat foundation. This 3D Analysing is tested experimentally and finally can infer the vibration data on full scale structure. Method for analysing: (1) FEM – For solving Superstructure and (2) Continuum principle – For solving soil medium of semi-infinite or layered half spaced.

Buragohain et al. (1977), who evaluated the space frames resting on pile foundation by means of the stiffness matrix method in order to quantify the effect of soil-structure interaction using simplified assumptions. In that study, the pile cap was considered to be rigid. The stiffness matrix for the entire pile group was derived from the principle of superposition using the rigid body transformation. The foundation stiffness matrix was then combined with the superstructure matrix to perform the interactive analysis which was carried out in a single step to assess the effect of soil-structure interaction on the response of structure in terms of change in member forces and settlements.

Cai et al. (2000), work in 2000 the analysis was carried out on fixed boundary conditions and also damping in the foundation subsystem was neglected. Moreover, the effects of soil nonlinearity were not analysed.

Later **Yingcai in 2002** studied the seismic behaviour of tall building by considering the non-linear soil-pile interaction, in which a 20-storey building is examined as a typical structure supported on a pile foundation using DYNAN computer program, leading to the conclusion that the theoretical prediction for tall buildings fixed on a rigid base without soil-structure interaction fails

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to represent the real seismic response, since the stiffness is overestimated and the damping is underestimated.

Ingle and Chore (2007), reviewed the soil-structure interaction (SSI) analysis of framed structures and the problems related to pile foundations, and underscored the necessity of interactive analysis to build frames resting on pile foundations by more rational approach and realistic assumptions. It was suggested that flexible pile caps along with their stiffness should be considered and the stiffness matrix for the sub-structure should be derived by considering the effect of all piles in each group. But, the basic problem of the building frame is three dimensional in nature. Although a complex three-dimensional finite element approach, when adopted for the analysis, is quite expensive in terms of time and memory, it facilitates realistic modelling of all the parameters involved. Along these lines, Chore and Ingle (2008 a) presented a methodology for the comprehensive analysis of building frames supported by pile groups embedded in soft marine clay using the 3-D finite element method. The effect of various foundation parameters, such as the configuration of the pile group, spacing and number of piles, and pile diameter, has been evaluated on the response of the frame. The analysis also considered the interaction between pile cap and soil. It has been concluded that with the increase in pile spacing and number of piles in a group, displacement at top of frame decreases. In addition, with the increase in diameter of piles, displacement at top of frame decreases for any spacing owing to the increased stiffness of pile group at higher diameter. Also, the effect of soil-structure interaction (SSI) is significant on bending moment, i.e., SSI is found to increase the maximum positive bending moment by 14.01 % and maximum negative bending moment by 27.77 %.

M.D. Lee,et al. (2008), Dissipation of energy by the yielding of soils and the foundations they support can influence the performance of a structural system. The degree and nature of these effects are not well defined by documented field evidence or by experimental testing. The interaction between vertical and horizontal foundation response is not understood well either. To account for this lack of understanding and to eliminate inelastic structural deformation in the foundation, designers often create very expensive designs for new construction or seismic retrofits for existing, deficient construction. Soil response is often idealized as being linear for soil-structure interaction problems, yet design-level loading will generally induce nonlinear soil response. The accurate evaluation of the seismic response of structures is limited by the ability to model the behaviour and interactions among a structure, its foundation, and the supporting soil. Earthquake engineers use laboratory experiments to understand the performance of the key components of structural and foundation systems under controlled loading conditions. Experiments and the data collected therein are used to calibrate and validate computational models of component behaviour. Although past research has produced significant knowledge about the behaviour of components, the earthquake performance of complete structural systems is less well understood. The experimental, computational, and information technology resources were used to resolve the interaction problems with absolute accuracy compared to past research works. They have chosen a continuous bridge on drilled shaft foundations as the prototype structure to study soil foundation-structure-interaction (SFSI). This structure was selected because it represents a common construction type in regions of moderate and high seismicity. To account for the size and complexity of the prototype system, bridge performance was studied through a series of four, complementary experimental programs: centrifuge tests of individual bridge bents to evaluate the nonlinear response of the soil and foundation system; field tests of individual bents to evaluate the linear response of the soil, foundation, and structure in situ; shaking table tests of a two-span model to evaluate the nonlinear response of the structure subjected to bi-directional, incoherent support motion; and static tests of bents and individual columns to evaluate size effects and strength degradation in shear under cyclic loads.

H. Matinmanesh& M. Saleh Asheghabadi (2011), this paper finite element method has been used for seismic analysis of soil-structure interaction. Two different sandy soils (dense and loose sand) have been considered as the hypothetical site soil in order to investigate the effect of sandy soil properties on the seismic response of the soil-structure system. ABAQUS v. 6.8 program has been used for two-dimensional finite element simulation of the whole project including the local soil and the building structure. The simulated buildings are two dimensional 5 and 20 storey buildings with moment resisting frames representing low- and high-rise buildings. The earthquakes are selected from three actual ground motion records representing seismic motions with low, intermediate and high magnitudes of a/v (pick ground acceleration in m^2/s to pick ground velocity in m/s) so as to investigate the effect of frequency content on soil-structure interaction. As conclusion, the soil-structure models including dense sand has shorter period in comparison with loose sand and high-rise buildings have longer period in comparison with low-rise buildings. Shorter period soil-structure systems (5 storey building over dense sand) demonstrated the highest amplification for Hav earthquake and lowest maximum acceleration (on the soil-structure interface) on Lav earthquake. Longer period soil-structure system (20 storey building over loose sand) presented the highest amplification in Lav earthquake and lowest in Hav earthquake. Maximum principal stress on the soil-foundation interface in all models occurred beneath the columns while the lowest stress was in the middle of foundation. The 20 storey buildings generated higher principal stresses during the earthquake in the soil-structure interfaces in each earthquake for both soils.

Lou Menglin,et al. (2011), as in the metropolitans, the building structures are built closely to each other over the soft soil deposit. Under such circumstances, the dynamic interaction among building structures must occur through the radiation energy emitted from a vibrating structure to other structures. Hence, the dynamical characteristics as well as the earthquake response characteristics of a structure are unable to be independent of those of the adjacent structures. Those two buildings with distance less than 2.5 times of width of foundation are interacting with each other. And when the distance was less than one time of width of foundation, the response of structures may increase or decrease tens of percent. Soil–structure interaction, one of the most major subjects in the domain of earthquake engineering, has been paid comprehensive attention by international in recent decades. Soil– structure interaction phenomena concern the wave propagation in a coupled system: buildings erected on the soil surface. SSSI effects turn out to be significant, and one immediate consequence is that erecting or dismantling a building or a group of buildings could change the seismic hazard for the neighbourhood. This leads to significant conceptual changes, especially concerning seismic micro zonation studies, land-use planning, and insurance policies. Deep foundations (including pile foundation). For simplification and calculability, most of those works to date are restricted to shallow foundations and surface foundations. With the continual increase of superstructure height, deep foundations are widely used and the depth is augmenting. The study of dynamic interaction of deep foundations is of essential importance. Non-linear analysis- As mentioned above, the effect of soil and structures usually exceeds the linear elastic phase and requires elastoplastic analysis. And to solve the problem of SSSI successfully, nonlinear analysis of both soil and structure must be considered. Many SSSI researches are just theoretical derivation and numerical calculation. There are few SSSI experiment. As the technique of shaking table and centrifuge is getting increasingly mature, plenty of field tests and laboratory tests are yet to be done.

Fig.1. Cluster of high-rise building closely spaced

Domenico Lombardi &Subhamoy Bhattacharya (2013), in this paper, investigates the effects of liquefaction on modal parameters (frequency and damping) of pile-supported structures. Four physical models, consisting of two single piles and two 2 × 2 pile groups, were tested in a shaking table where the soil surrounding the pile liquefied because of seismic shaking. The experimental results showed that the natural frequency of pile-supported structures may decrease considerably owing to the loss of lateral support offered by the soil to the pile. On the other hand, the damping ratio of structure may increase to values in excess of 20%. These findings have important design consequences: (a) for low-period structures, substantial reduction of spectral acceleration is expected; (b) during and after liquefaction, the response of the system may be dictated by the interactions of multiple loadings, that is, horizontal, axial and overturning moment, which were negligible prior to liquefaction; and (c) with the onset of liquefaction due to increased flexibility of pile-supported structure, larger spectral displacement may be expected, which in turn may enhance P-delta effects and consequently amplification of overturning moment. The experimental results showed that the natural frequencies of the systems are strongly dependent on the excess pore water pressures developing in the soil. Specifically, the natural frequencies reduced considerably with the onset of liquefaction. At full liquefaction, the frequency may be reduced by more than half of the initial value (ie. 50% - 60%), which was measured before liquefaction. The damping ratio of the system is increased significantly as the pore water pressure builds up. At full liquefaction, damping ratios of higher than 20% were estimated. The liquefaction of the soil causes a reduction of the response spectrum particularly for low periods of vibrations. At full liquefaction, the inertial force acting on the system may reduce considerably because of the combined effects of the reduction of the spectral acceleration and lengthening of the fundamental period of vibration of the systems. However, the maximum bending moments decreased in magnitude as the soil liquefied. The models were constructed in the finite element programme SAP2000, and the soil–pile interaction was modelled using a set of nonlinear springs distributed along the pile length. The comparison showed a good agreement between measured and computed values.

Cristina Medina et al. (2013), In this paper, an analysis of the SSI effects on the period and damping of pile-supported structures is accomplished. For this purpose, an equivalence between the interacting system and a SDOF system which reproduces, as accurately as possible, the coupled system response within the range where the peak response occurs is established. The coupled-system response is obtained by using a sub structuring model in which the structure is considered as a SDOF shear structure that represents, from a general point of view, one mode of vibration of multi-storey buildings. Both, dynamic and kinematic interaction effects are included in the analysis of this coupled system. Impedances and kinematic interaction factors of the piles configurations studied in this paper, are calculated using a BEM-FEM methodology. In order to determine the dynamic characteristics of this equivalent SDOF system, a simplified and stable procedure, which takes into account all the elements of the matrix of impedances, is developed herein. Results for different configurations are obtained in order to accomplish an analysis of the influence of the main parameters of the problem for the cases. All the results obtained herein have a dimensionless character, thus their physical interpretation must be carefully done and requires a specific data processing taking into account the influence of every dimensionless parameter. They have concluded that piles configurations which imply stiffer foundations yield a reduction on the effective period of the coupled system: larger number of piles or embedment ratio, and lower pile slenderness ratio. The obtained results show that this conclusion is not applicable for short and squat buildings, case in which the opposite occurs. The effective damping increases with the foundation stiffness. Slender buildings as well as soft soils magnify the SSI effects for a particular configuration. This trend can be reversed for very stiff foundations or very short and squat buildings. The effective damping for slender buildings is close to that corresponding to fixed-base condition or lower. The foundation horizontal displacement and rocking increase for softer soils as well as for more flexible geometric configurations. Results in terms of period and damping for different pile configurations are provided in ready-to-use graphs that can be used to build modified response spectra that include SSI effects.

ChandrakanthBolisetti et al. (2018), Generally, the Soil-structure Interaction (SSI) analysis is generally used to adopt calculation of seismic demands in nuclear structures, where currently it is performed using linear methods in the frequency domain. Such methods avail to result in accurate predictions of response for low-intensity earthquake, but results of extreme shaking in highly nonlinear soil, structure or foundation response is unproven for some period. This Nonlinear (time-domain) SSI analysis in large cases is rarely performed due to a lack of experience on the part of analysts, engineers or any other scientists. A nonlinear, time-domain SSI analysis procedure using a commercial finite-element code which invades the frequency-domain code, SASSI, for linear SSI analysis and low intensity earthquake shaking. Nonlinear analysis using the time-domain finite-element code, LS-DYNA, and results are compared with those from equivalent-linear analysis in SASSI for high intensity shaking. The equivalent-linear and nonlinear responses are showing significantly alternative results or it showing slight similarity depends on usage of computer programs. This type of approach has been incorporated in order to safety and protective measures to surroundings for building like Nuclear Power plants, Factory buildings, Industrial buildings, etc., which might cause environment and people if such disasters or accidents occurs. Therefore, through this approach the nuclear building is designed of such seismic consideration

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LINEAR APPROACH OF ANALYSING	NON-LINEAR APPROACH OF ANALYSING
Frequency-Domain codes – SASSI, SAP2000	Time- Domain codes – LS-DYNA, ANSYS, ABAQUS
Strain-Compatible properties - used to represent the soil	Large soil strains and possible gapping and sliding at the foundation-soil interface
Low Intensity ground earthquake shaking	High Intensity ground earthquake shaking

Table.2.1 Differentiate between the entities of Linear & Non-Linear Approach of analysis

Depending on various computer codes results varies from significantly alternate to slight similar values. Many researchers came upon various results when comparing the linear and nonlinear values using different codes which is shown above. But they came out with analysing two primary codes like SASSI and LS-DYNA. Both are capable for analysing in 2D and 3D of any foundation shapes or Superstructures. The frequency-domain code, SASSI and the time-domain code, LS- DYNA, result in almost identical responses for SSI analyses of linear models. This is an important result in the benchmarking of time domain codes against the frequency-domain codes for linear analyses. Nonlinear SSI predictions can be significantly different from those made using linear frequency-domain codes. The differences are greatest for cases with significant nonlinearities, such as nonlinear site response (primary nonlinearities) and nonlinear behaviour at the foundation (secondary nonlinearities), namely, soil hysteresis, and gapping and sliding underneath the foundation.

III. CONCLUSIONS

From this literature review, it has been gained knowledge about soil-structure interaction (SSI) and factors responsible for SSI effects. Also learned what are all the challenges involved to structures and its behaviour due to SSI effects during seismic excitation including the dynamic behaviour of super structure. It has been studied about the parameters which was required to model the components needed for numerical investigation on analysis of both theoretically and in modelling an interface using ABAQUS software. Non-linear analysis- As mentioned above, the effect of soil and structures usually exceeds the linear elastic phase and requires elastoplastic analysis. And to solve the problem of SSI successfully, nonlinear analysis of both soil and structure must be considered. Therefore, in future, non-linear analysis of SSI effect on structure is studied and evaluated.Additionally, the experimental analysis is also a main concern in study and analysis of SSI effects on structures which was evaluated in a journal by Domenico Lombardi &Subhamoy Bhattacharya.

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