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Soil-Structure Interaction for RC Building Resting on Different Foundations: An Overview.

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Abstract : Past earthquake disasters demonstrate that most damages and fatalities have been caused primarily due to ground motion. In traditional method of building design, structural engineers typically assume columns to be supported by fixed foundations, while the calculation of foundation settlements often occurs without factoring in the stiffness of the superstructure. This approach to mathematical modelling often neglects crucial interaction effects, potentially leading to designs that are either overly expensive or compromised in safety. Realistic approach in design is crucial due to the intricate ways in which earth and structure interact, especially when it comes to architectural constructions. Drawing from various sources, this review aims to provide a comprehensive overview in current state of structure-soil-structure interaction issues in tall building frames supported by different types of foundations. Our analysis emphasizes the impact of adjacent structures and highlights the need for further academic research in this area.

***Keywords* - Soil-Structure Interaction, Finite element analysis, Pile foundation, Raft foundation, Piled raft foundation.**

I. INTRODUCTION

Soil-structure interaction (SSI) represents a dynamic relationship between structural and geotechnical engineering disciplines. Pile foundations serve as a prevalent choice for supporting buildings and structures built on soft soil. The traditional design approach typically assumes fixity at the foundation base, disregarding both foundation flexibility and sub-soil compressibility. However, for a more accurate solution, it's imperative to consider the interaction between the superstructure, foundation, and soil as a unified system. Numerous studies have examined soil-structure interaction in framed buildings using raft foundations, integrated footings, or isolated footings as support, as documented in the literature. While many focus on plane frames, only a few delve into the interaction analyses of space frames. Moreover, limited literature existed quantifying the impact of soil-structure interaction on frame comeback when supported by pile foundations.

Group piles are the most common type of deep foundation used for tall structures, with the goal to benefit on the carrying capacity of deeper and more strong soil layers. Piles are subjected to vertical forces caused by gravity, lateral forces, and, on rare occasions, unusual loads such as seismic forces. Analysing pile foundations under such complicated loading conditions is difficult, demanding a reasonable approach achieved by full three-dimensional finite element analysis.

Deformation occurs in foundations resting on deformable soil due to a variety of factors, including soil, superstructure, and foundation rigidity. Although the mathematical approach is made simpler by ignoring the coupling or interaction between soil and structure, which oversimplifies reality. It is important to perform an analysis implementing this interaction into account in order to determine accurate values of these parameters.

II. CORRESPONDING LITERATURE

The relation between soil and structure is a complicated topic. Even a single pile is statically indeterminate structure at a high degree. Thus, it becomes even more complex due to the dynamic forces like lateral ground motion due to earthquakes. It has been a few decades since the assessment of the impact of soil-structure interaction emerged. This paper presents a thorough analysis of the literature on the dynamic behaviour of building structures resting on different types of foundation such as pile, piled raft and raft foundation. The impact of the interaction between the soil and the structure has also been considered.

In mid-1900, S. Chamecki (1956)1 has recognized the importance of soil-structure interaction and suggested that it should be considered for analysis as it is an integral system in substructure as well as superstructure. In his study he established relations by means of coefficients of load transference, making exact possible consideration of rigidity of structure in calculating foundation settlements. Later, D.N. Buragohain et. al., (1977)2 attempted first independent analysis on 3D pile group. In his research he evaluated pile group stiffness by assuming fixidity at base of column. In early 2000, S.C. Dutta and R. Roy (2002)3 made a report on the response of system which comprises more than one component which is always interdependent. They found that to accurately estimate forces acting, soil-structure interaction needs to be considered under both static as well as dynamic loading conditions. In addition, the system should be modelled through rescale it into numbers of elements and assembled using finite element analysis.

Julio. A. Gracia (2008)5 made a report on seismic analysis of reinforced concrete building incorporating soil structure interaction. He used finite element method in computational modelling of the structure. The seismic regulations were referred from El Salvador national building code and it was concluded that by including the stiffness parameters of foundation and subsoil, mechanism such as rocking can be evaluated. He also concluded that due to energy dissipation in soil foundation system, there is increase in system damping which is associated with elastic deformation of the structure. H.S. Chore, et.al. (2008, 2009, 2010 and 2012) has reported more rational approach with realistic assumptions in interaction analysis of structure supported by pile foundation. More studies with mathematical modelling were presented by S.A. Rasal et. al. between 2012 to 2023. Based on different types of foundation, a brief review of literature has been discussed.

2.1 Pile Foundation

H.S. Chore and R.K. Ingle (2008)6 conducted a parametric analysis to investigate how soil structure interaction affects the two-bays single-story space frames that are sitting on a pile group of two piles with flexible caps. The study started with undergoing 3D-FEA for individual frames on premised column basses, this was followed separate work outs. The reaction of the superstructure was examined in relation to the effects of pile configuration and spacing, as evidenced by the bending moment at the top and bottom of the columns and the top displacement in the frame. Comparison of the analysed results revealed that when spacing increases, the difference between the displacements decreases. It was also concluded that the top displacement increases by 42% to 165% as a result of the interaction between soil and structure. There is a significant influence from the way the underlying soil and the pile cap interact. The maximum positive and negative moment in columns is increased by the soil-structure interaction, and it falls between 14.01% and 15.05% and 27.20% and 27.77%.

A year later, the basic single-story and two-bay space framework sitting on a pile group submerged in compacted earth (clay) with a flexible cap was studied by H.S. Chore, et. al., (2009)7. They determine the impact of soil-structure interaction for foundation that was employed in the investigation. It was found that the impact of the soil-structure interaction was determined to be very considerable. They concluded that the range of 4-17 is the percentage variance in the displacement values derived using the coupled and uncoupled analysis, and the range of 3-10 is the current range. It was concluded such that for the kind of foundation utilized in this investigation, it is found that the influence of soil-structure interaction is highly substantial on the reaction of the building frame. Furthermore, there was a reasonable degree of agreement between the outcomes of the coupled and uncoupled analyses, and both approaches yielded comparatively feasible conclusions.

Sandro C. et. al., (2011)8 investigated the effect of soil structure interaction on coupled wall-frame structure resting on pile foundation. In their research a finite element procedure was used in the analysis for dynamic interaction. A typical 6- storey 4 bays building with 2x2 pile configuration was used for the analysis. To assume a torsionally restrained system, the structure also consisted of 4 coupled wall-frame at boundary. Comparisons were made that by decreasing the soil stiffness of deposit, we can increase vertical dynamic pile impedance. In practice, it can be achieved through making plinth beams very stiff or adopting end-bearing piles. Additionally, it was determined that SSI greatly modifies the seismic base shear distribution between the structural parts. Shear pressures migrate from the wall to the frame due to the flexibility of the soil-foundation, and this movement becomes more pronounced as the soil becomes softer. Similarly, because of the flexibility of the foundation, bending moments in the wall are reduced, but moments in beams and columns at lower floors are greatly enhanced. Furthermore, the kinematic interaction is responsible for the gradual and significant pressures in the lowest portions even in the case of a homogenous soil layer.

S.A. Rasal, et. al., (2015)13, conducted a study using three-dimensional finite element analysis to mathematically simulate a typical three-story structure frame that was supported by a pile group of four (2x2) piles embedded in cohesive soft marine clay soil mass. Twenty noded isoparametric continuum elements were used to discretise the elements of the pile foundation, such as the pile and pile cap, and the superstructure frame, such as the beams, slabs, and columns, for modelling purposes. The study concluded that as the embedment depth ratio raised, the displacement at each storey level decreased. The bottom storey experienced the greatest displacement rise as a result of SSI considerations, and as storeys increased, displacement continued to decreased. The expanded pile's passive resistance had shown to have a significant impact on the interaction behaviour. When the embedment depth increased, the displacement at each story level decreased.

V. Srivastava, et. al., (2016)14, worked on A typical building frame resting on a piling group immersed in cohesive soil mass was subjected to physical modeling using full three-dimensional finite element analysis. Numerous factors were taken into consideration when evaluating the superstructure's response, such as the pile's diameter and the spacing between piles within a group. A component of the reaction was the displacement at the top of the frame. The influence of the soil-structure interaction was found to be considerable for the type of soil and foundation that were considered in this study. The investigation also found that the top displacement of the frame was significantly influenced by the contact between the soil and the structure. Displacement increased between 97% and 230% when the impact of SSI was considered, although it was less for the conventional method, or fixed base condition. The displacement at the top of the frame decreased as pile spacing grew.

In 2017, A parametric study focuses on the physical modelling of a typical three-story building frame supported by a pile foundation using 3D finite elements method. For the modelling process, S. A. Rasal et. al., (2017)16 modelled the elements of the superstructure including beams, columns, and slabs. The pile foundation elements such as the pile and pile cap, were considered using twenty-noded isoparametric continuum elements. The interface between the pile and the soil was represented using sixteen-node isoparametric surface elements. The soil was assumed as three different types of elements, which are eight-node, nine-node, and twelve-node continuum elements. The study assumes linear elastic behaviour for the superstructure, substructure (foundation), and soil elements. Additionally, the immediate response of the soil and the total stresses within it were considered.

From the parametric study presented in this paper, several significant conclusions were drawn was as follows, Soil-structure interaction has a notable impact on the displacement of each story in the frame. Displacement is lower in conventional analysis but increases when the nonlinearity of the soil was taken into account. It was also observed that increase in the maximum positive moment in columns located in the middle row of the frame, while columns in the leading and trailing rows show a reduction in positive bending moment. A reduction in negative bending moment was seen in the corner columns, whereas an increase in negative bending moment was also noted in the central rows. Overall, the effect of soil-structure interaction (both linear and nonlinear) significantly influences the response of the specific building frame and type of foundation used in this study.

George M. et. al., (2018)18 made a study to investigate the SSI impact in the context of cyclic loads on a 6-storey building with a piling base. The analysis was performed on structure with shear wall connected to six reinforced concrete slabs and which rests on a pile base with three piles. Class E soil was assumed in their analysis according to ASCE7-10 provisions. The structure was discretized in three dimensions by means of the hexahedral isoparametric finite element and modelled with 8-noded hexahedral elements. Smeared crack approach was used in analysis and it was compared to an equivalent fixed base model. It was concluded that SSI model demonstrates more flexible behaviour and in SSI model, stiffness decreases by 52%. Additionally, base shear was 29.58% lesser than that which was obtained in equivalent FX model.

S. Koparde et. al., (2023)21 Presented a study that deals with modelling a typical building frame comprises five storeys (G+4) with two bays is considered, columns of frames are supported by piles which are assumed to be embedded in cohesive soil mass. They analysed beam and column as 2-noded beam element and slabs and 4-noded shell element. The pile structure was analysed as a 3D 6-noded beam element. The analysed displacement, bending moment, shear force and axial force as response of structure. They concluded that displacement in top storey decreases with increase in pipe diameter and soil subgrade modulus. They also concluded that storey displacement is less in a group of two piles connected in series as compared to that in a group of two piles connected in parallel.

2.2 Raft Foundation

K. Bhattacharya, S. C. Dutta and S. Dasgupta (2004)4 investigated the interaction between the soil and the structure of a low-rise building supported by a raft foundation. The two main dynamic characteristics they examined were the basic torsional-to-lateral period ratio and the lateral natural period. They also analyzed the impact of soil flexibility on the same building and the seismic base shear. They came to the conclusion that soil flexibility alters the building's lateral natural period, which lightens the lateral period and raises base shear for these low-rise structures. Their research also demonstrates how soil structure can change the fundamental ratio of torsional to lateral natural period, which causes lateral torsional coupling. Therefore, while taking soil structure interaction into account, significant mistakes in seismic design can be overlooked.

An effort was made to advance the theoretical analytical techniques. Dr. D. Daniel Thangaraj and K. Ilamparuthi (2012)9 investigated the components influencing the soil-structure interaction analysis and classified them into relative stiffness factors such as ksb and krs. Using the ANSYS finite element program, they carried out interaction analysis on a five-story space frame with a 3x5 bay arrangement. The investigation assessed moments in the raft, forces in the frame components, soil mass settlement, and contact pressure beneath the raft. Comparing the interaction analysis results to the non-interaction analysis, the former revealed lower total and differential settlements. Of the two parameters, ksb had the biggest effect on settlements, indicating how important soil modulus is to the raft's performance.

In 2013, a study of three types of soil and a 10-story moment-resisting building frame situated on a shallow foundation were chosen. The effects on the seismic response of moment-resisting building frames were evaluated by S. Hamid Reza Tabatabaiefar, et. al., (2013)10. Using the FLAC 2D program and the finite-difference approach, the frame sections were modelled and analysed under two distinct boundary conditions: (1) fixed-base (no SSI) and (2) taking the SSI into consideration. It was eventually concluded that when designing concrete moment-resisting building frames that lie on Soil Classes De and Ee, it is crucial to take SSI effects into account for both elastic and inelastic seismic design. Generally speaking, when the subsoil's dynamic properties, including the shear-wave velocity and shear modulus, drop, the inter-storey drifts of the moment-resisting building frames climb proportionately. Without the SSI, the conventional elastic and inelastic design approach cannot provide structural safety for moment-resisting building frames resting on Soil Classes De and Ee.

A. Iqbal and T. M. Al-Hussaini (2014)11 analyzed the performance of soil structure interaction on static and seismic response of tall building resting mat foundation. Simplified numerical models with lumped masses and beam-column elements were used in the study to simulate the mat base and superstructure. In their static analysis, it showed that modelling thick mat slabs with beam-column elements is feasible and realistic by using equivalent springs at the foundation nodes to simulate the soil. Notably, bending moments and settlements in the mat foundation are impacted by the superstructure's stiffness. The research investigates how soil flexibility influences mat and superstructure responses. Parametric studies evaluate the impacts of different variables on building behaviour, highlighting SSI's role in reducing base shear during seismic events. Moreover, SSI proves advantageous for buildings with mass eccentricity, emphasizing its role in managing torsional response.

Research was conducted under lateral stress, on a raft foundation that was submerged in cohesive soil. For the purpose of the analysis, J.P. Nadar et. al., (2015)12 created simplified idealizations in the theory of finite elements. Three-dimensional shell elements with four nodes represented the idealized slab of the frame. The response of the structure was examined in terms of developed deflection, shear force, and bending moments in the independent analysis. The duration and number of cases involving SSI were rapidly increasing. With increasing time, the soil was noted as much softer. Additionally, the time period variation was larger for taller buildings; therefore, the effect of soil increased with storey height. The building's lifespan was shown to extend from a fixed base to a real Raft Spring model. As a result, the true force acting on the structure was underestimated, which could potentially have an impact on the building's stability. By using SSI analysis, the column's bending moment and forces were increased at lower values in comparison to fixed condition analysis.

K. Pratyusha et. al., (2019)19 addresses the behaviour of a five-storey RC framed structure with effects of soil structure interaction. A numerical analysis study was made using finite element analysis to determine effects such as displacement, shear force and bending moment of RC frame structure. They concluded that the analysis of a structure considering soil-structure interaction reveals lower shear forces compared to the analysis excluding this interaction. Additionally, the analysis with soil-structure interaction exhibits varying bending moments relative to the analysis without it. When considering soil-structure interaction, there is an average increase in displacements by 38% compared to when the interaction is not considered. Furthermore, the analysis shows an average decrease of 29.6% in shear forces when soil-structure interaction is included, compared to the analysis without it. They also concluded that design performed using conventional methods is very safe, as it accounts for higher shear forces and bending moments. However, the conventional design method is somewhat uneconomical because it designs the structure for these higher forces and moments. Hence, it is more efficient to design the structure by considering soil-structure interaction.

2.3 Piled Raft Foundation

The physical modeling of a typical three storeyed building frame supported by piled-raft foundation using three dimensional finite elements was conducted by S.A. Rasal et. al., (2017)15. The compact earth mass encased the foundation. Twenty noded isoparametric continuum elements were used in this work to descretize the pile foundation's pile and pile cap as well as the superstructure frame's beams, columns, and slab. The purpose of the parametric study was to determine how soil-structure interaction affected the frame's reaction. The piled-raft foundation was assessed separately to determine the comparable stiffness after the frame was first examined without taking the foundation's influence into account. These results were then utilized in the interaction analysis. It was concluded such that the interaction between the earth and the structure has a considerable impact on the frame's displacement for each floor. When the nonlinearity of the soil was taken into account, displacement increased and was less for the conventional analysis. Soil-structure interaction has a major impact on B.M. Comparing the results with those obtained using conventional analysis, it was observed that the soil-structure interaction analysis increased the absolute maximum positive and negative B.M. in beams B-1, B-3, and B-5 and decreased it in beams B-2, B-4, and B-6. The reaction of the particular building frame under consideration and the type of foundation used in the current investigation were found to be significantly impacted by the soil-structure interaction, both linear and nonlinear.

In a study conducted by Mohsen Bagheri et. al., (2018)17 Numerous numerical simulations were conducted on two distinct types of superstructures and six different types of piled raft foundations in order to determine how seismic soil-pile-structure interaction (SSPSI) affected the seismic responses of the superstructures. This study analyzed the nonlinear structural reactions of the generated two- and three-dimensional (2D and 3D) models after assessing the effectiveness of a piled raft application and estimating the ideal number, placements, and configurations of piles. The project sought to enhance the characteristics of a system of long-short combination stacked raft foundations by gaining a deeper understanding of the dynamics of interaction.

Three-dimensional finite element calculations were performed to determine the effects of the governing parameters on several systems of long-short composite piled raft foundations lying on a soft clay stratum. Three parameters were discovered to have a major impact on the responses of the superstructures subjected to the different earthquakes: configurations, pile lengths and diameters, and structure heights. The greatest lateral displacements in the 2d and 3d models were about equal in high-intensity cases; at low intensities, however, considerably different values were found. It was determined that by adjusting the diameter, length, and layout of a pile, shear force and level movement could be changed, leading to the best possible distribution of shear forces throughout a structure. Geotechnical earthquake engineering typically handles SSPSI, while specific site-to-site variations may occur in the elements of this interaction.

R.M. Swamy et. al., (2019)20 Study deals with mathematical modelling of a G+2 storey consisting of two bays and resting on piled-raft foundation. For analysis purposes, a finite element method was used. The slab of the frame was assumed as 2D plate elements. beams, columns and pile of the sub-structure were assumed as 1D beam-column elements. In their parametric study, the effect of different raft thicknesses with uniform pile diameter was evaluated. A broad conclusion was made in the study was as follows, the Impact of soil-structure interaction on each storey’s displacement was lower in conventional analyses but increases when considering soil nonlinearity. As pile diameter increased, storey displacement decreased across all pile diameters. However, for minimum raft thickness and higher soil modulus, displacement remained on the higher side. The top displacement at each storey was higher when considering four different pile diameters in the interactive analysis, compared to the values obtained in non-interactive analysis.

A study on Nepalese National Building Code, NBC, and the existing lacunae of lack implementation guidelines regarding seismic analysis of structures involving SSI was conducted by Manoj Sitaula, et. al., (2023)22. A 17-story high rise building with piled raft foundation and 2 subterranean floors was considered in this investigation. Action of SSI on buildings dynamic structure was examined. This research provided important insights into importance of SSI in seismic designs. It was concluded such that all other things being equal, structures with SPSI were less responsive than those with fixed bases, irrespective of the soil class taken into account for that particular construction model. A significant reduction in seismic demands was found in structures located on sites D, as evidenced by decreased displacement, drifts, storey shears, overturning moment, and base shear, which decreased by more than 49%. Comparing this change to structures on soil types A, B, and C revealed that it was noticeably more marked. While the effects of elongation in modal periods were more substantial for more flexible foundations, the effect of period elongation varied for different modes. Additionally, when foundation flexibility rose, the number of modes needed to achieve 95% modal mass participation was dramatically reduced, suggesting that SSI can change the way structures deform.

Waleed Dawoud, et. al., (2024)23 in research conducted on direct approach of SSI analysis on 3-dimensional high rise reinforced concrete building over piled-raft foundation. The seismic reactions in the structure were assessed using Plaxis 3D software and nonlinear numerical analysis with the finite element approach, which was confirmed. The impacts of deeper pile embedment and base flexibility (SSI) on the seismic performance of tall buildings were examined. When pile embedment depths are increased by 20% to 80% while El-Centro seismic excitation is present, the building's maximum accelerations range from 15% to 22.8%, which corresponds to a reduction in maximum displacements of 17.5% to 32.2%. Under Hachinohe seismic motion, the maximum displacements dropped by 15.8% to 26.7% and the highest accelerations reduced by 12.6% to 14.3%. The same response was observed. Inter-story drift studies likewise demonstrate a decline, indicating stronger seismic performance in buildings. It is important to note that as pile embedment depths grow, so do base shear and story shear stresses. Piles with 1.4L, 1.6L, and 1.8L lengths were providing approximately identical response. An ideal increase in pile length for enhancing the seismic performance of a building could be 40%. The building height and the subsurface lithology conditions are the primary determinants of this ratio.

III. CONCLUSION

This paper presents a review on analysis of building frames resting on different types of foundation with soil structure interaction. It demonstrates that soil-structure interaction affects the response of the superstructure, which can be significant or minor depending on several parameters of the superstructure and substructure. By including the stiffness parameters of foundation and subsoil, mechanism such as rocking can be evaluated. It is also concluded that due to energy dissipation in soil foundation system, there is increase in system damping which is associated with elastic deformation of the structure. Different approaches are available for the analysis of frame and foundations, depending on the loads imposed. As well as theoretical studies of pile, piled raft and raft foundations, numerous experimental studies have been carried out over the years by different researchers to evaluate the influence of different parameters on the behaviour of structure and foundation. The significant findings and concluding remarks are drawn based on the study for different types of foundation are listed below.

3.1 Pile Foundation.

- Soil-Structure Interaction should be considered for analysis as it is an integral system in substructure as well as superstructure.
- The gradual and significant stresses in the lowest regions are caused by the kinematic interaction when the soil layer is uniform; the soil-foundation flexibility results in the migration of shear forces from the wall to the frame, which increases dramatically with soil softening.
- As the embedment depth ratio is raised, the displacement at storey level decreases.
- With increase in pile spacing, the movement at the top of the frame is reduced.
- It was also observed that increase in the maximum positive moment in columns located in the middle row of the frame, while columns in the leading and trailing rows show a reduction in positive bending moment.
- SSI model demonstrates more flexible behaviour and in SSI model, stiffness decreases significantly.
- Storey displacement is less in a group of two piles connected in series as compared to that in a group of two piles connected in parallel.

3.2 Raft Foundation.

- Lateral torsional coupling results from changes in the fundamental torsional-to-lateral natural period ratio caused by soil structure. Therefore, while taking soil structure interaction into account, significant mistakes in seismic design can be overlooked.
- The interaction analysis showed reduced total and differential settlements compared to non-interaction analysis.
- Among the parameters krs and ksb (Stiffness factors), ksb had a significant impact on settlements, highlighting the crucial role of soil modulus in the performance of the raft.
- Without the SSI, the conventional elastic and inelastic design approach cannot provide structural safety for moment-resisting building frames resting on Soil Classes De and Ee.
- Modelling thick mat slabs with beam-column elements is feasible and realistic by using equivalent springs at the foundation nodes to simulate the soil.
- Bending moments and settlements in the mat foundation are impacted by the superstructure's stiffness.
- The building’s lifespan was shown to extend from a fixed base to a real Raft Spring model.

3.3 Piled Raft Foundation.

- Three factors, structure heights, pile lengths and diameters, and configurations were found to have a substantial impact on the responses of the superstructures to the different earthquakes.
- As pile diameter increased, storey displacement decreased across all pile diameters. However, for minimum raft thickness and higher soil modulus, displacement remained on the higher side.
- Soil-structure interaction can change the way structures deforms.
- Inter-story drift studies likewise demonstrate a decline, indicating stronger seismic performance in buildings.
- It is important to note that as pile embedment depths grow, so do base shear and story shear stresses. The building height and the subsurface lithology conditions are the primary determinants of this ratio.

The review concludes that, of all these methods, the finite element method is the most versatile since it encompasses geometric and material nonlinearities. It not only integrates the best features of other foundation analysis methods, but also incorporates material and geometric nonlinearities.

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