International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 09 Issue: 07 | July 2022 www.irjet.net p-ISSN: 2395-0072

EFFECT OF SOIL STRUCTURE INTERACTION ON DYNAMIC BEHAVIOUR OF STRUCTURES- A REVIEW

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Abstract - *Response of soil which results motion within the structure during seismic activity is usually overlooked as most of the structures are assumed to be resting on fixed base, which sometimes leads to unsafe design after doing post failure analysis. Observations from some of the past seismic events such as 1989 Loma Prieta earthquake and 1995 Kobe earthquake where SSI is one of the main reasons for the collapse of the Hanshin Expressway show evidences of adverse nature of SSI in certain circumstances. Soil flexibility should be considered especially during the analysis of high-rise buildings or structures resting on soft soil or located in high seismic zones to avoid any sort of failure and ensure safe service. This study is at the growing stage, given its complexity and inadequate detailed guidelines to calculate effect of SSI within the standard codes which should be advanced with easier methods to resolve soil-structure interaction problems with greater ease in the coming future. Current paper attempts to review the state of art about various methods of soil structure interaction analysis conducted by various researchers using some of the popular finite element analysis softwares and some of the provisions mentioned in different International seismic codes.*

Key Words: Soil-Structure Interaction (SSI), fixed base, flexible base, seismic loading, soil flexibility, Kinematic interaction, Inertial interaction

1. INTRODUCTION

All structures are built over soil and at times maybe subjected to seismic force during an earthquake, the intensity depending on seismic zones. The waves that arrive at foundation during an earthquake produce motions in the structure itself. Motions depend on the structural or building layout & the vibrational characteristics. For the structure to response to the motion, it needs to overcome its own inertia, which result in an interaction between the structure and the soil. Such an interdependent behaviour between soil and structure regulating the overall response is referred as Soil-Structure Interaction (SSI) behaviour in the present context. Soil-structure interaction broadly can be divided into two phenomena:

a) kinematic interaction

b) inertial interaction

Earthquake ground motion causes soil displacement known as free-field motion. However, the foundation embedded into the soil will not follow the free field motion. This inability of the foundation to match the free field motion causes the kinematic interaction. On the other hand, the mass of the superstructure transmits the inertial force to the soil, causing further deformation in the soil is termed as inertial interaction.

It is often seen that to carry out soil-structure interaction analysis in FEM software is represented as mat foundation considered as a slab resting on equivalently spaced springs of suitable stiffness value. Conventional practice considers the analysis of structure and foundation separately, assuming that the base of structure is fixed means the base of the foundation transfers the load by direct bearing on solid rocky stratum or soil and subsequently load distributing within the building frames are calculated. This assumption is applicable when the superstructure is highly flexible than the underlying soil stratum upon which the foundation rests. SSI plays a critical role when the behaviour of structure is considered under static or dynamic loading. It influences the behaviour of soil, as well as the response of pile under loading. The analysis is highly essential for predicting a more accurate structural behaviour so as to improve the safety of structures under extreme loading conditions.

2. HISTORY OF SSI

Soil–Structure Interaction is an interdisciplinary field of study which lies at the intersection of soil and structural mechanics, soil and structural dynamics, earthquake engineering, geophysics and geomechanics, computational and numerical methods, and various other technical field of study. Its origin can be traced back to the late 19th century which evolved and further advanced gradually in the upcoming decades and also in the first half of the 20th century and progressed rapidly in the second half of the 20th century accelerated mainly by the needs of the nuclear power and offshore industries and with the launch of powerful computers and simulation tools such as finite elements with the need for improvements in seismic resistant design of structures.

Roesset[37] and Kausel[38] presented reviews of the early-stage developments in field of Soil-Structure Interaction after extensive research. In addition to the two components of SSI- kinematic and inertial originally coined by Whitman, Roesset [37] also discussed about the direct and substructure approaches to perform SSI analysis. He also reported previous works by Reissner and Bycroft, Veletsos and Wei, Luco and Westman, and Novak in field of dynamic stiffness of foundations, as well as effects of deposits in the form of layers or strata, embedment and pile group. On the other hand, Kausel [38] presented the development in SSI sequentially with starting from fundamental solutions commonly termed as green's functions proposed by mathematicians and scientists' way back in early 19th century. He reported notable contributions in static SSI by Boussinesq, Steinbrenner, Reissner and Hanson just to name a few. Erich Reissner, in 1936, put founding stones for dynamic SSI with a publication where he explored the behaviour of circular disks on elastic half-spaces subjected to time-harmonic vertical loads, which was further carved by notable work done by Luco, Bycroft, Housner, Newmark, Veletsos, Whitman and many others. Kausel[38] himself initiated development of substructure approach to solve SSI problems. But the beginning of the modern era and rapid growth of Soil-Structure Interaction took place some four decades ago with the publication of some renowned influential papers by Veletsos and Wei in 1971 and Luco and Westmann in 1971 and 1972 respectively, which provided a complete rigorous solution to the problem of circular plates underlain by elastic half-spaces excited dynamically over a wide range of frequencies, and for a wide set of Poisson's ratios.

3. IMPORTANCE OF SSI

It is usually seen that considering SSI proves to be beneficial on seismic response of a structure since structures analysed using SSI are more flexible increasing its natural period and damping ratio thus leading to a reduction in base shear of a structure as compared to a structure with fixed base. Due to these reasons SSI has always been ignored by structural engineers to reduce the complexities involved in the analysis. But, observations from effect of 1971 San Fernando earthquake and 1989 Loma Preita earthquake shows a different story. Badry et al[39] conducted SSI analysis for asymmetrical buildings supported on piled raft which was damaged during 2015 Nepal Earthquake which was observed that adverse effects of SSI can increase with asymmetry in geometry of superstructure.

Ray Chowdhury[40] highlighted the possibility of differential settlement arising out of soil flexibility for low-rise steel moment resisting building frames where SSI needs to be carefully applied for heavily loaded footings owing to high inertial effects. Hence there is a compulsion to develop a rational basis for seismic design incorporating SSI. Saez et al[40] researched on the influence posed by dynamic SSI on inelastic response of moment-resisting frame buildings founded on dry and fully saturated sands. They showed a noticeable effect of dynamic SSI in case of fully saturated sands owing to the increase in pore water pressure. This suggests that the importance of taking SSI into account can vary depending on site conditions. Contrary to elastic structures, SSI can increase ductility demands and total displacements in case of inelastic structures. Given that structures are expected to be inelastic in the event of severe earthquakes, the current seismic provisions are inadequate. Jarernprasert S. et al[42] has also designed an approach to integrate SSI by using a modified seismic design coefficient that allows the structure to reach its target ductility. It can therefore be observed that SSI needs to be taken into account when designing non-elastic structures. Despite considerable amount of research in this field of SSI but considering SSI while designing real life structures at site very rare given the inadequate provision of SSI in standard seismic codes. Thus, it is necessary to develop a procedure to analyze the SSI problem in a simple way but quite precise.

4. CURRENT PRACTICE OF SSI RESEARCH

Several researchers worked on the response of soil structure interaction in framed structures and also the influence of structure under dynamic loading considering parameters such as story drift, base shear, etc.

Elasto-plastic interaction analysis of two-bay, two-storey plane frame with foundation beam-soil system developed by Hora M.[1] using the finite element method to make superstructure behave in linear elastic manner and the soil mass in elasto-plastic manner according to various yield criteria. Settlements in soil mass, contact pressure below foundation beam, forces in the frame members and the foundation beam are evaluated and collapse load is determined since analysing interaction system in this way, yields a rational structural behaviour as the shear forces and bending moments get significantly altered due to the resulting differential settlements of soil mass. Meanwhile, forces and moments get transferred from the exterior columns towards the interior ones due to elasto-plastic interaction analysis and soil remaining in elastic state, although the soil mass below the outer edges has fully yielded.

Two numerical models where model 1 simulates seismic soil-structure interaction including the structure, foundation modeled with finite elements and the subsoil conditions modeled with springs and dampers whereas model 2 is generated for comparison purposes considering fixed base were developed by using ANSYS software of a 6 storied RC building with basement to study the influence of soil-structure interaction by Garcia J.A.[2]. Results show that upon considering the influence of soil-structure interaction in the dynamic behaviour of the structure reflects in an increase in the vibration period as well as an increase in system damping compared to the fixed base model. Moreover, economic designs are obtained by including the soil in the structural analysis and design as there is a reduction in seismic loads.

Analyzing a building by varying number of stories as 5,10,15 by Kumar D.N. et al[3] and Kumar A. et al [4] of a 30-storey building with both defining the soil medium by springs considering effect of foundation soil settlement with main objective to study the effect of soil-structure interaction on horizontal displacement of each floor and vertical displacement at the supports and the bending moment and shear forces at the interior middle frame of building. Wind loading is taken as 55 m/s, 50 m/s, 33 m/s by [3] with both varying sub grade modulus of foundation soil from 12,000 kN/m^3 to 60,000 kN/m^3. It was put forward that with decreasing sub grade modulus, displacement increases in x & y directions and horizontal displacement & vertical displacement increases with increase in number of stories & so the effect of soil – structure interaction has to be considered especially for lower sub grade modulus of soil at higher seismic intensities.

Usually, flexibility of the soil results in the decrease of stiffness which in turn increases the natural period of the structure, so Bhojegowda et al[5] using ETABS software studied the effect of soil flexibility on the natural period besides identifying spring stiffness for different regular and irregular storey buildings with isolated, mat and pile foundations for different soil conditions. Response spectrum analysis has been adopted which showed an increase of bending moment and displacement from fixed base analysis to flexible base analysis, but not much variation for 15 storey frame with pile resting on hard and medium soil compared to 5,10 storey frame as framed structure with pile foundation behaves as a fixed support for homogeneous non liquefiable soil. Base shear for mat foundation increases as famed structure with mat foundation possesses high foundation stiffness in comparison with isolated foundation but when other parameters are compared with isolated footing displacement, bending moment and time period reduces.

Analysing the dynamic behaviour of building frames over raft footing with and without soil flexibility where the soil beneath raft footing is a true soil model or continuum model and to evaluate the responses in terms of lateral natural period, seismic base shear, lateral displacement or story drift was the main focus of Kuladeepu M N et al[6]. Space frame, foundation and soil was taken part of a single compatible unit with soil model considered as homogeneous, isotropic and elastic of half space taking dynamic shear modulus and poisson's ratio as the inputs in SAP2000 software. The observations indicate that considering the soil structure interaction as well as increase in the number of stories, the fundamental natural period and base shear increases in a structure resulting in the decrease of shear modulus of soil. But with the reduction of shear modulus of soil as well as number of stories, the maximum lateral displacement is found to be increasing.

Modelling soil by Winkler approach or spring model and elastic continuum approach termed as FEM on an irregular 15 storey with analysis carried forward using SAP2000 building by Nirav et al[7] to study the effect of soil flexibility. The analysis concluded replacing fixed base by spring or modelling soil as a FEM, change in the response of structure is observed in case of soft soil and the base shear increases compared to the spring and FEM model, but displacement increases in X and Y direction of a FEM model compared to spring and fixed base models with an increase in soil flexibility.

To incorporate the effect of soil flexibility of significant design variables, G.V. Rama Rao et al[8] studied on the seismic response of chimney structures with raft footing using staad pro v8i software. Since there is a large difference in the foundation input motion during the earthquake for soft soils compared to free field ground motion which exists in the absence of structure with the assumption of a fixed support resulting in significant variation in frequency and amplitude values of structures during actual seismic activity from what the analysis provides treating the structure to be on fixed base. The final analysis shows decreasing trend of lateral & support displacement with increase in soil subgrade modulus also increase in soil flexibility decreases natural frequency significantly.

To assess the differences in the design response and analysis outputs arising due to inconsideration of soil structure interaction in the analysis for reinforced concrete building frames supported on pile foundation and embedded in loose sand using the Open SEES program where five types of analysis has been carried out to estimate the different design response and analysis output parameters being the main focus of study of Sharma Nishant et al[9]. He highlighted the fact that it may not always be feasible to ignore time history analysis in cases where site response influences the overall response of the building-foundation-soil system. Also, lowest estimate of forces & drift values is found by equivalent static method but fixed base analysis using spectrum compatible ground motion shows the largest values. Estimates of force obtained using linear soil structure interaction and non-linear soil structure interaction are significantly lesser than that obtained by fixed base analysis but slightly larger than equivalent static method. Although effect of soil deposit is considered here by modifying the ground motion, direct application of motion is not recommended for estimating the design forces. Instead, the foundation soil medium should be modelled to obtain the realistic estimate of design forces. Hence, Equivalent Static Method & Fixed Base Analysis may not always provide a realistic estimate.

To determine the change in various seismic response quantities due to consideration of flexibility of soil and the effect of seismic zones, Venkatesh M. B. et al[10] did effective modelling of a multiple bay regular RC building of eight storeys with the soil beneath the structure modelled as equivalent soil springs connected to the raft foundation in staad pro software thereby carrying out modal analysis of building system and response spectrum analysis of the soil-structure model. The results showed an increase in natural period with soil flexibility but reduction in base shear is seen for flexible base compared to fixed base analysis. An increase in response of structure with change in soil type from hard to soft with change of seismic zone from III to V irrespective of height of structure. Also, a significant variation is observed in raft shear stress and bending moment for soft and medium soil type compared to hard soil depicting considerable settlement of raft in soft soil.

RC building of 20 storey with three types of soil is considered resting on raft foundation underneath incorporating the effects of soil flexibility based on shear modulus, poisson's ratio and modulus of elasticity. Patel Bhavik et al[11] studied soil structure interaction analysis of the same using equivalent static method, response spectrum method and time history method for rigid base and flexible base. Actual record of accelerogram of bhuj earthquake is invoked for time history method, carrying out the entire analysis in SAP2000 software. Results conveyed modelling the soil as solid object gives more deflection compared to when soil is modelled as spring. Observation is also made for base shear which is almost same when soil is modelled as spring but a significant difference is seen when soil is modelled as solid but base shear for flexible base decreases as compared to fixed base.

Analyzing the effect of soil-structure interaction on the elastic response of moment resisting framed reinforced concrete structures founded on embedded raft in an elastic half-space to accelerograms compatible to design spectra carried out by Anand Vishwajit et al[12] with a need to understand elastic response of structure-soil systems subjected to harmonic excitations and Design Basis Earthquake obtained using the substructure approach. Analysis was performed on MATLAB 2015 using Newmark γ-β method which was adopted for analysis thus showing soil-structure interaction makes an elastic structure more flexible leading to an increase of natural time period and damping of the structure-soil system. There is a reduced base reaction in case of structures which exhibit elastic behaviour under design basis earthquakes considering SSI.

Replacing the fixed support at base by a spring of equivalent foundation stiffness of a multistoried reinforced concrete residential building frame supported on isolated footings founded on different types of sandy soil located in seismic zone V to perform flexible support analysis by researcher Verma V.K. et al[13]. Significant maximum vertical and differential settlement between footings is observed in flexible support analysis. Compressibility of soil leads to the redistribution of the forces in beams and columns and reversal in the nature of these forces thereby increasing vertical support reaction and support moment for a building supported on the less stiff soil.

To study the effect of strong ground motion on joint displacement, axial force and time period and mass participating factors on a G+10 reinforced concrete irregular multi-storeyed building, Singh S.K. et al[14] utilized three different software namely ETABS, STAAD PRO & SAP2000 as per design response spectrum curve suggested by IS 1893-1[31] to perform dynamic analysis. Based on the response spectra study, he highlighted that the modal mass participating factor is more than 75% in the higher mode & the considered structure is stiff for earthquake excitation. The frequency in first mode of vibration is found between 0.44 Hz to 0.57 Hz by different programs, which shows building much stiffer. Meanwhile, the joint displacement in X- direction is found more as compared to Y and Z directions due to the fact that the earthquake motion was applied in X-direction which depicts uplift in Y- direction and displacement in Z-direction.

The effect of variation in slope angles of 15,30,45 degrees for a 15m height building resting on sloping ground, considering fixed base and taking soil structure interaction into consideration was done by Ghosh Rahul et al[15] implementing equivalent static force method, response spectrum method, time history method, nonlinear static method & nonlinear time history method. While, linear analysis is conducted using ETABS software but nonlinear analysis using SAP2000 software. Results of the analysis indicate that structures resting on sloping ground reflects differential movement on either side of the structure since the taller side moves more than the shorter side in the direction of force indicating stiffness concentration on the shorter side of the structure on the higher level of the slopes. Thus, the columns on the higher side of the slope are subjected to heavy torsional force and also subjected to increased bending moment due to reduction of column height. Meanwhile, bending moment of the columns on shorter side of the structure at higher level of slopes increases with the rising storey level as well as slope angle, even if there is no reduction of column length. It was also observed for structures analyzed without considering soil structure interaction, forces are overestimated such as base shear and bending moment but underestimates responses such as time period, displacement and torsion.

Comparative study of a G+10 building resting on sloping ground at an angle of 0,10,20 degrees and plane ground carried out by Manjunath H V et al[16] using ETABS software performing equivalent static analysis and response spectrum analysis to do a comparison of results of displacement, story drift, base shear between IS code1893:2002 and IS code 1893:2016. Analysis results shows an increase in displacement and story drift values for models analyzed using IS code 1893:2016 as compared to IS code 1893:2002 whereas displacement and story shear value reduces with increase in sloping angle. Also, it is observed that base shear is lesser for models analyzed using IS code 1893:2016 compared to IS code 1893:2002.

Municipal solid waste finer fraction (MSW-FF) utilized as a sustainable structural fill material to improve the bearing capacity and reduce settlement below foundations supported on weak soils or when foundations are supported on filled up soil & also to evaluate the bearing capacity, settlement and modulus of subgrade reaction for the shallow foundation of different sizes and shapes resting on soil with low subgrade modulus and with a layer of MSW-FF as structural fill. To understand the effect of soil and foundation stiffness on the base pressure, settlement, bending moment and shear stress in shallow foundations for both cases of natural soil & with MSW-FF as structural fill, Patil M.et al[17] undergone a soil-structure interaction analysis using staad pro software. From the soil-structure interaction analysis, it is observed that the effect of soil subgrade modulus on foundation base pressure and settlement is prominent, while having a negligible effect of bending moment and shear stress in the foundation. Further, the relative stiffness of foundation and soil has a significant effect on the foundation design parameters, which showed a promising potential of utilizing MSW-FF as a sustainable structural fill.

Considering effect of infill stiffness using modelling approach given by Hendry for fixed base and flexible base, a G+7 infill masonry RC building is considered. Rajput Harsh et al[18] carried out equivalent static analysis for the two building models and to compare the performance of infill masonry building resting on raft foundation with fixed base and flexible base along with soil structure interaction for seismic loading considering the parameters of story shear, floor displacement, story drift, time period and settlement of raft using staad pro software. After the analysis is carried out it was reported maximum value of story shear for flexible base about 1.23 times of fixed base infill frame model. Floor displacement is about 4.03 to 5.04 times of fixed base infill frame model whereas, story drift is about 1.26 to 4.86 times of fixed base model. Besides, the study conveyed, considering the soil structure interaction in dynamic analysis of RC building frame the time period increases about 1.7 times of fixed base infill model and settlement to increase by 62.07 mm more than fixed base infill model with a differential settlement of magnitude 5.28 mm occurring between centre and corner of raft foundation.

Two support conditions mainly, fixed support and other supported on elastic mat supported on soil springs proposed by Winkler, where a mat foundation with thickness 850 mm further resting on three types of subgrade modulus of soil on a 10-storied RC building. Alkari A.K. et al[19] analyzed the same using Response Spectrum method in staad pro software to compare the results of storey displacement, column end forces and bending moments in beams for different soil conditions. Analysis results conveyed the fact that on considering realistic support condition changes the column & beams forces in the structure. The relative displacements between successive floors are less for structure on soft soils since, the structure on soft soil deflects as a whole body. Hence, the effect of soil structure interaction in soft soils is more as compared to medium and hard.

Finite element modelling of an existing underground water tank has been done in ETABS software to understand the behaviour when subjected to seismic loading considering dynamic soil pressure & soil structure interaction using Winkler's spring method. Dubey Rahul et al[20] considered two different soil condition such as Clay of high Compressibility (CL) and Silt of high Compressibility (MH) where CL is categorized under medium or stiff soil and MH is under soft soil to carry forward the analysis. He highlighted that although soil conditions do not influence design forces significantly but on considering seismic forces the moments in walls along both X and Y directions at the base exceeds moments in walls of existing tank. Further, shear force parameter is seen dominating the thickness of wall but on considering seismic forces, shear force increases which tends to redesign thickness of slab. Whereas, upon considering effect of soil structure interaction which is modelled with elastic spring at base, design forces increase compared to seismic design with rigid base. Although, effect of soil structure interaction is not very much significant.

5. CODAL PROVISIONS ON SSI

Inspite of a vast array of solution techniques discussed in Section 4, very few international codes had given some guidelines for incorporating Soil-Structure Interaction. This is generally due to lack of consent among researchers regarding the effects of Soil-Structure Interaction posed on seismic response of structures during analysis. Considering the significance of considering SSI in structural design, there is a need to include SSI provisions in seismic codes around the globe. To enable the people in various code committees, this section makes a general attempt to discuss about the guidelines regarding SSI in some of the existing international seismic codes.

5.1 India

IS code 1893-3[21] & IS code 1893-part 4[22] spoken about considering Soil-Structure Interaction while designing bridges and industrial structures. But it's also necessary that Soil-Structure Interaction needs to be considered while designing structures which are bound to be supported upon deep foundations in soft soil. Though past analyses shows that Soil-Structure Interaction would lead to reduced seismic forces further enhancing lateral deflections, still neither guidelines spoken about for computing Soil-Structure Interaction effects nor specialist literature have been mentioned. Meanwhile seismic codes for general buildings and liquid retaining structures, IS 1893-1[31] and IS 1893-2[23] are completely silent about the phenomenon.

5.2 United States of America

SSI provisions was first inducted by Applied Technology Council ATC 3-06[25] calling for a reduction in design base shear to counter longer natural period and a higher damping shown by structure-soil system as compared to fixed base. So, ASCE 7-10[30] introduced a cap on base shear reduction by suggesting modified design base shear to be no less than 70% of the original value. On the other hand, reduction in equivalent lateral force was established on elastic structural response and further research shows that effect of SSI on structural response dwindles with the intensity of inelasticity experienced by the structure resulting in structural design not performing up to the desired mark during seismic event. National Earthquake Hazard Reduction Program (NEHRP) developed some provisions in the form of FEMA[26] which basically put a limit on reduction of base shear as a function of response modification factor. Hence, these provisions recommend reduction in design base shear for systems with larger response modification factor which means those structures with larger inelastic deformation capacity which were later incorporated in ASCE 7-16[24].

Besides, the procedure of equivalent lateral force, ASCE 7-16[24] suggests a linear dynamic analysis using either of the two methods-

a) SSI modified general design response spectrum as given in the code

b) SSI modified site-specific response spectrum which have to be developed by the concerned design engineer

Meanwhile, effects of kinematic interaction cannot be incorporated with the linear dynamic procedure. But if kinematic interaction is found to be predominant then, a nonlinear response history procedure using acceleration histories scaled to a site-specific response spectrum for kinematic interaction method should be adopted. Kinematic SSI effects are represented by the response spectral modification factors for base slab averaging and with the product of embedment not less than 0.7. Khosravikia et al[32] evaluated the importance of using FEMA[26] and ASCE 7-10[30] which form the basis of ASCE 7-16[24] and showed that SSI provisions of both FEMA[26] and ASCE 7-10[24] results in unsafe designs for structures with surface foundation on moderately soft soils, but FEMA[26] slightly improves upon the current provisions being more conservative out of the other two provisions specified.

5.3 Japan

Dynamic interaction between the structure and the ground should be taken into consideration while designing bridge abutments, retaining walls, underground structures and foundation structures such as piles and caissons as put forward by JSCE 15[33]. But for other structures, SSI can be ignored or can be modelled appropriately depending on the type and characteristics of structure and ground. The choice of modelling the structure and soil-foundation system simultaneously or separately either by direct approach or substructure approach is left to the judgement of structural designer.

5.4 Europe

EN 1998-5[34] code recommends considering dynamic SSI for structures which are either slender or have significant second order ($P-\delta$) effects. Those structures founded either on pile foundation or those with massive or deep-seated foundations such as bridge piers, offshore caissons and silos also permits including SSI in their design process. EN 1998-1[35] code specifically mentions a typical ground type with extremely low shear strength and high plasticity index and EN 1998-5[34] authorizes SSI consideration in design of any structure to be built on such deposits. Though EN 1998-5[34] identifies the structures for which SSI must be included in design practice but it does not give any specific guidelines to compute the effect of SSI.

5.5 New Zealand

NZS 1170.5[36], similar to Eurocode, Indian Standard code and Japanese guidelines, did not designate any sort of guidelines to incorporate the effect of SSI in design practice. However, it mentions the use of an entity termed as structural performance factor which depends on material, form and period of the seismic resisting system, damping of the structure, and interaction of the structure with the ground parameters. NZS 1170.5[36] also requires consideration of foundation deformations when calculating building deflection. But since there is no guidance on how to include foundation flexibility, structural designers have frequently ignored foundation flexibility while designing based on NZS 1170.5[36].

Among the various standards discussed above, it is seen that ASCE 7-16[24] appears to be the most evolved while implementing the effect of SSI in structural design practice. Moreover, it is also a noticeable fact that most of the well-known seismic codes do contain conditions for including SSI effects in design practice but still lack guidelines on evaluation and accommodation of SSI effects in design practice. Such gap accompanied by a communication gap between structural and geotechnical engineers can make a structure susceptible to unsatisfactory performance during an earthquake. This highlights a greater importance of considering SSI in present day where good sites for construction are rare and construction on soft soils and landfills are quite common. In this context, NIST [27] suggests proper guidelines and procedures to evaluate SSI effects which could be utilised between structural and geotechnical engineers for certain project modifications.

6. CONCLUSION

The phenomenon comprising of various mechanisms which leads to the interdependence of soil and structural displacements is basically soil-structure interaction which is broadly classified under either kinematic and inertial component of soil-structure interaction. The present study is based on reviewing past research over last few years on soil-structure interaction and effect of soil flexibility on response of structures. Soil-Structure Interaction may prove to be either beneficial or detrimental to structural response during real seismic event contrast to the structure-soil stiffness. But actual response is a function of frequency which depends on the earthquake intensity. It shows that rigid and heavy structures founded on soft soils are the worst hit. The response of any structure is analysed considering fundamental natural period, lateral displacement, storey drift, lateral deflection and seismic base shear as the main parameters highlighting the influence of soil-structure interaction on dynamic behaviour of the building and must be considered in the design of earthquake resistant buildings. It is also recommended to consider soil structure interaction analysis with increase of height of building and in case of soft soil to achieve accurate estimation for the different straining actions.

a) Building total drift- The Base flexibility behaviour, which is generated from the soil structure interaction analysis, influences the total drift of the building as it is clear through each storey displacement. So, it can be clearly mentioned that fixed base or stiff soil assumptions can lead to greater underestimation of the storey drifts of building. Moreover, the study also confirms considerable effect of base flexibility on the inter-storey drift ratios leading to superior serviceably limits.

b) Base shear and base moments- Accordingly from the conducted study it is also confirmed that the building base shear and moments diminishes with medium and soft soils as compared to stiff soils.

So far, researchers who had analysed the interaction behaviour using the latest software packages considered the foundation as raft foundation, isolated footing, pile foundation and mat foundation with the soil mass as homogenous, isotropic behaving as linear and nonlinear manner in the interaction analysis. For practical purposes, Winkler model should at least be employed, assigning area springs in the local z axis of finite element software to make the foundation flexible there by creating the effect of soil structure interaction instead of idealizing structures as fixed base to carry out the analysis.

From the SSI provisions listed in some of the reputed seismic codes as discussed in section 4, it is seen that ASCE 7-16[24] is the only standard code with guidelines on implementing soil-structure interaction in design and analysis of structures whereas other standard codes just suggest conditions for performing soil-structure interaction analysis in design practice but do not establish proper procedure for the same. Considering structures often being constructed on soft soils and landfills, this gap needs to be fulfilled in form of well-drafted guidelines to ensure inclusion of soil-structure interaction in regular design practice in the coming future. A limited number of studies have been conducted so far considering the soil mass as elasto-plastic, visco-elastic and visco-plastic in interaction analyses and effect of soil-structure interaction on basement shear walls of the building due to various parameters which should be taken into consideration for carrying out research on SSI in the future. Also, transmission and consideration of seismic waves at the interface between soil layers should be a further scope of study including the vertical wave propagation and its effect on building response. Likewise, another field of study which is SSSI (structure-soil-structure interaction) and associated phenomena of structural pounding is gaining popularity in the coming times.

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