International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 2 Feb 2022, pp: 1522-1533 www.ijaem.net ISSN: 2395-5252

A Study on Numerical Analysis of Soil-Foundation-Structure Interaction

Mohammed Hashir S[1], Dr. K Sudha[2]
[1]PG Student, Government College of Engineering, Salem, Tamilnadu, India
[2]Asso. Professor, Department of Civil Engineering, Government College of Engineering, Salem, Tamilnadu, India

Submitted: 15-02-2022 Revised: 25-02-2022 Accepted: 28-02-2022

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 role of the seismic soil-pile-structure interaction (SSPSI) is usually considered beneficial to the structure system under seismic loading since it lengthens fundamental period and leads to higher damping of system in comparison with the fixed base assumption. When taking a survey from last three decade, the assumption is made to be fixed base but the lessons learned from recent earthquakes show that fixed base assumptions could be misleading and neglecting the influence of SSPSI could lead to unsafe design particularly for structures founded on soft soils. In this project, it has been reviewed the existing literature about Soil Structure Interaction (SSI) and study it's behaviour on structures by considering both linearity and non-linearity parameters of soil. Along with that by the help of application of FEM software, the acceleration of structural system caused by adopting previously recorded earthquake motion to the soil profile has been analysed by performing time history analysis in ABAQUS- DS SIMULIA Suite 2020.

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. In this thesis performed, numerical investigation on Soil-Structure Interaction model by considering physical parameters including seismic response from a journal publication, **Aslan S. Hokmabadi et.al.(2014)** As thelessons learned from recent earthquakes show that fixed-base assumption could be misleading, and neglecting the influence of SSPSI could lead to unsafe design particularly for structures founded on soft soils. Therefore, a fully nonlinear three-dimensional numerical model employing ABAQUS has been adopted to perform time-history analysis. Before commencing the literature review, a brief introduction to Soil Structure Interaction and Pile Foundations are given in the following.

1.1 Soil-Structure Interaction

The seismic design of buildings has been undergoing a critical reappraisal in recent years, with change of emphasis from strength to performance. The development of capacity design principles in the 1970s, was an expression of the realisation that the distribution of strength through a building was more important than the absolute value of the design base shear which can be identified as the key point in the performance-based seismic design, where the overall performance of the building is controlled during the seismic design process.

For determining the seismic response of structures, it is a common practice to assume the structure is fixed at the base. In fact, if the ground is stiff enough (e.g. structure founded on solid rock) it is reasonable to assume that the input motion of the structure due to a design earthquake is essentially identical to the motion of the free field, which is defined as the motion experienced at the same point before the structure is built. However, for structures constructed on soft soils, two modifications need to be considered for determining the seismic response. First, the imposed motion to the structure differs from the free field motion due to the presence of the structure. Secondly, additional dynamic deformations are induced within the structure due to the underneath soft soil. The process, in which response of the soil influences the motion of the structure and response of the structure influences the motion of the soil is referred to as soil–structure interaction.

1.2 Pile Foundation

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. It is evident that the damages occurring at deeper part of piles are inherently difficult to detect and practically impossible to repair. Consequently, adequate provision in the design is indispensable to make such damages as unlikely as possible. A number of approaches have been formulated for the analysis of dynamic soil-pile interaction in the past years. The research work carried out in the area of seismic soil-pile foundation structure interaction could be most generally classified into determination of kinematic seismic response that is determination of pile-head impedance and determination of superstructure seismic response.

II. LITERATURE REVIEW

Cai et al. (2000), A three-dimensional nonlinear (HiSS) finite element sub-system methodology is used for studying the seismic soil–pile–structure interaction effects. From the results it has been concluded that with the plasticity-based soil model, the motion of the pile foundation deviates significantly from the bedrock motion and this departure from the ground motion should not be over looked in evaluating the seismic kinematic response of pile-supported structures.

The effect of soil-structure interaction on a single-storey, two-bay space frame resting on a pile group embedded in the cohesive soil (clay) with flexible cap is studied using the finite element analysis by **Chore et al.** Following conclusions are drawn,

1. The effect of SSI on the top displacement of the frame is quite significant. The displacement is less for fixed base condition and increases by 42 to 103% when the SSI effect is incorporated.
2. With the increase in pile spacing, the top displacement of the frame decreases. With the increase in the number of piles in a group under consideration, the displacement decreases.
3. The effect of SSI is significant on bending moment also. The SSI is found to increase the maximum positive bending moment by 14.98 % and maximum negative bending moment by 27.20 % when compared with the absolute maximum bending moments calculated on the premise of fixed column bases.
4. The parameters like configuration of pile group, number of piles and diameter of pile, and end conditions for the pile tip have significant effects on the variation of bending moment in superstructure columns.

After identifying the areas which are to be addressed in the numerical analysis of pile supported framed buildings, it has been observed that following are playing a major role in dynamic SSI analysis 1. The nonlinearity of soil, 2. Contact between pile and soil and 3. Group effect of neighboring pile supported structures. With the above-mentioned problems the main objectives and scope of this thesis has been given in the following section.

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.

Matinmanesh. H & Saleh Asheghabadi. M (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 beenconsidered 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.

Cristina Medina et.al.(2013) When analysing the seismic behaviour of structures, kinematic and inertial effects associated to soil-structure interaction (SSI) affect the dynamic characteristics of the interacting system and influence the ground motion around the foundation. Thus, it is important to assess the variations of the system period associated with the soil stiffness, as well as the variations of the modal damping associated with the material damping in the soil and especially with the radiation effects. The effects of SSI on the dynamic characteristics of soil-structure systems have been widely studied both for shallow foundations and for embedded foundations using both 3D models and 2D models. Regarding pile-supported buildings, and to the extent of the authors' knowledge, there are few studies in the scientific literature examining the effects of SSI on their dynamic. **Rainer** used a sub structuring methodology to analyse the modal damping of a superstructure supported on piles. On the other hand, **Aguilar and Aviles** analysed piled foundations by extending the **Aviles and Perez Rocha's** procedure for embedded foundations and thus they studied the SSI effects on the system period and damping for a specific configuration of 8 × 8 piles. The aim of this work is to evaluate the influence of SSI on the period and damping of shear structures founded on square pile groups embedded in homogeneous viscoelastic half-spaces subjected to vertically-incident S waves. The analysis is performed by a sub structuring model in the frequency domain that takes into account both kinematic and inertial interaction effects.

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.

Aslan S. Hokmabadi et.al.(2013) A fifteen-storey concrete moment resisting building frame with the total height of 45 m and width of 12 m consisting of three spans, representing the conventional types of mid-rise moment resisting buildings, is selected for the study. The spacing between the frames into the page is 4 m. Natural frequency of the prototype building is 0.384 Hz and its total mass is 953 tonnes. The soil medium beneath the structure is a clayey soil with the shear wave velocity of 200 m/s and density of 1470 kg/m^3. The horizontal distance of the soil lateral boundaries and bedrock depth has been selected to be 60 m and 30 m, respectively. The building is resting on a footing which is 1 m thick and 15 m wide. For the pile foundation case, a 4 x 4 reinforced concrete pile group with pile diameter and length of 1.2 m and 20 m, respectively, and equal spacing of four time the diameter (4d) is considered. The piles are closed-end and have rigid connection with the pile cap representing typical floating pile foundations. In order to achieve a reasonable scale model, a dynamic similitude between the model and the prototype should be applied as described in the literature. Dynamic similitude governs a condition where homologous parts of the model and prototype experience homologous net forces. Although small scale models could save cost, the precision of the results could be substantially reduced. Considering the mentioned specifications of UTS shaking table, scaling factor of 1:30 provides the largest achievable scale model with rational scales, maximum payload, and overturning moment meeting the facility limitations. Thus, geometric scaling factor of 1:30 is adopted for experimental shaking table tests on the scale model in this study. Apart from the geometric scaling which should be imposed to all the components, the required scaled natural frequency for the structural model and the required scaled shear wave velocity and density of the soil mix should be 2.11 Hz, 36 m/s and 1470 kg/m^3, respectively. Moreover, the required scaled natural frequency of the soil mix inside the soil container needs to be 10 Hz which is used as a benchmark to design the laminar soil container.

Chandrakanth Bolisetti et al. (2018), Generally, the Soil-structure interaction (SSI) analysis is generally used to adopt calculation of seismicdemands 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

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.

Hailu Getachew Kabtamu et.al.(2018) In dynamic analysis of a building structure, the base support condition is very essential for calculating its dynamic behaviour useful in estimating structural responses and distribution within structural members. The building base condition will be different depending on the type of supporting ground. Fixed base foundation could be assumed on stiff soil and flexible base foundation on soft soil. Flexibility of base causes decrease in structural stiffness and increase period of vibration during earthquake ground motion. Consequently, the building structural responses such as displacement drift, Story shear, and P-Δ effects will be different from fixed base that could beneficial or detrimental. As a result, in the past the dynamic analysis building on soft soil has gained serious attention in seismic active areas. Many studies showed that soil structure interaction (SSI) has both beneficial and detrimental effect on structure. Because SSI increases flexibility of structure, lengthening of structural vibration period and damping. As a result, in building structures, the base shear decreases; however, at the same time displacement increases. The decrease in base shear may be advantages, but the increment in displacement induces secondary moments P-Δ effect due to high inter-story drift. Moreover, excessive deflection of building could lead to collision of nearby structures. In addition, P-Δ is highly emphasized structural members supporting big axial load such as tall building, and consequence can be catastrophic which leads to instability of the whole structure. Moreover, there are researches those stating that for some special cases fixed base models can lead to an underestimation of seismic response.

Yong Jin et.al.(2021) Due to the randomness and uncertainty of earthquakes, it is necessary to conduct simulated earthquake experiments to understand the dynamic behaviour of soil in controlled environments. Generally, theoretical analysis, model test, and numerical analysis are the three major research methods for seismic responses. As a number of theoretical and numerical analysis results have not been validated due to the complexity of soil, a controlled model test such as the 1 g shaking table test is very useful.

Since the 1980s, the rapid development of computer technology has greatly promoted the development of numerical solutions for ground seismic response analysis. The whole ground system can be calculated dynamically by the finite element method. Many scholars have done finite element analyses to evaluate the seismic response of soil. Andersen presented a numerical model for studying the dynamic evolution of landslides and analysed a simplified slope with houses placed on the top. Faris and Wang performed finite element calculation of seismic acceleration in shear zone of landslide using ABAQUS 2D model. Cheng et al. studied the seismic response characteristics of saturated soft free field ground by a large-scale shaking table test. The nonlinearity coupled numerical model of dynamical effective stress of saturated soft free foundation was established using OpenSEES. Moghadam and Baziar established a numerical model of the effect of a circular subway tunnel on the acceleration at the ground surface through 1 g shaking table test to study the influence of soil shear wave velocity, input motion frequency content, flexibility ratio and depth of the tunnel on the amplification pattern.

III. CONSIDERATION OF PARAMETERS FOR NUMERICAL SIMULATION

3.1. Linear properties

3.1.1. Elasticity modulus

Modulus of elasticity is defined by the ratio of the applied stress to the corresponding strain within the elastic limit. Physically it indicates a material's resistance to being deformed when stress is applied to it.

3.1.2. Poisson's ratio

Poisson's ratio is defined as the ratio of the lateral strain to the axial strain for a uniaxial stress state. For an instance, if a tensile load is applied to a material, the material will elongate on the axis of the load (perpendicular to the tensile stress plane).

3.1.3. Mass density

Density of materials are its mass per unit volume of materials. It is expressed in kg/m3 and shows compactness of building material. Density is also called as unit weight of substance.

3.2. Non-linear properties

3.2.1. Plastic

For stresses beyond the elastic limit, a material exhibits plastic behaviour. This means the material deforms irreversibly and does not return to its original shape and size, even when the load is removed. When stress is gradually increased beyond the elastic limit, the material undergoes plastic deformation.

3.2.2. Yield stress & yield strength

The stress level where the material starts to strain plastically is termed the yield stress. When a material is stressed by an amount that is less than the materials yield stress it will only undergo elastic (reversible) strain, and no permanent deformation of the material will occur.

The level of stress that corresponds to the yield point is referred to as the yield strength of the material.

3.2.3. Plastic strain

Plastic strain also known to be plastic deformation is the permanent distortion that occurs when a material is subjected to tensile, compressive, bending, or torsion stresses that exceed its yield strength and cause it to elongate, compress, buckle, bend, or twist.

3.2.4. Mohr coulomb plasticity

Mohr-Coulomb plasticity model to simulate the hardening behaviour of the material in Abaqus, so that requires cohesion yield stress as function of plastic strain along with angle of friction & dilatancy angle.

3.2.4.a. Cohesion

Cohesion is the force that holds together molecules or like particles within a soil. Cohesion is the component of shear strength of a rock or soil that is independent of interparticle friction.

3.2.4.b. Angle of friction (ϕ)

Soil friction angle is a shear strength parameter of soils. Its definition is derived from the Mohr-Coulomb failure criterion and it is used to describe the friction shear resistance of soils together with the normal effective stress.

3.2.4.c. Dilatancy angle (ψ)

The dilatancy angle is the constant of the Mohr-Coulomb (MC) model, that defines the plastic volumetric strain. Its role in the plastic potential function is analogous to the role of the friction angle, φ, in the yield function.

As for sands, the angle of dilation depends on the angle of internal friction. For non-cohesive soils (sand, gravel) with the angle of internal friction $\varphi>30°$ the value of dilation angle can be estimated as $\psi=\varphi-30°$. A negative value of dilation angle is acceptable only for rather loose sands.

3.2.4.d. Coefficient of friction (μ)

Coefficient of friction is ratio of the frictional force resisting the motion of two surfaces in contact to the normal force pressing the two surfaces together. Mathematically, $\mu = F/N$, where F is the frictional force and N is the normal force.

In relation to frictional angle for soil, coefficient of friction can be,

$$\mu = 2/3*\tan \varphi$$

This expression can be used to value the contact properties of soil to structure components.

3.2.4.e. Cohesion yield stress & absolute plastic strain

The Mohr-Coulomb yield criterion states that, yield occurs when the shear stress on any point in a material reaches a value that depends linearly on the normal stress in the same plane

$$\tau_f = c + \sigma*\tan \phi$$

Generally, for a specified soil c and ϕ do not change with plastic strain provided the soil remains in the same state. Thus, for a normally consolidated soil c will be almost zero and ϕ will be about 30°. However, c and ϕ will change if the soil becomes over consolidated. Thus, c and ϕ will be functions of over consolidation ratio and not necessarily functions of plastic strain. It can be derived of these functional relations using a series of triaxial tests.

With respect to hardening, a material like soil hardens if its shear strength increases. Thus, for an M-C material the hardening parameter may be taken to be the normal stress σ because as it increases τ_f increases also. A purely cohesive soil with $\phi = 0$ cannot harden.

Therefore, from the experimental tests on shear strength of the soil to determine cohesion yield stress to its corresponding plastic strain.

IV. NUMERICAL SIMULATION - SSI MODEL

4.1. Introduction

In this study, three-dimensional explicit finite difference-based program ABAQUS, has been employed for analysis of this project. This program can simulate behaviour of different types of structures and materials by elements which can be adjusted to fit the geometry of the model. Each element behaves according to a prescribed constitutive model in response to the applied forces or boundary restraints. The program offers a wide range of capabilities to solve complex problems in mechanics such as inelastic analysis including plastic moment and simulation of hinges for structural systems. The dimensions of the numerical models were chosen to be similar to the experimental tests as employed by authors to validate data output acquired from results. Therefore, the reasonable scale factors for all parameters were adopted for shake table experiment (ie., geometric scaling factor (λ) of 1:30). The reason for choosing the soil deposit thickness of 30 m for the prototype is that most amplification occurs within the first 30 m of the soil profile, which is in agreement with most modern seismic codes calculating local site effects based on the properties of the top 30 m of the soil profile Rayhani M(2008).

4.2. An overview of prototype

A fifteen-storey concrete moment resisting building frame with the total height of 45 m and width of 12 m consisting of three spans, representing the conventional types of mid-rise moment resisting buildings, is selected for this study as shown in Fig.4.1. Natural frequency of the prototype building is 0.384 Hz and its total mass is 953 tonnes. The soil medium beneath the structure is a clayey soil with the shear wave velocity of 200 m/s and density of 1470 kg/m^3. The horizontal distance of the soil lateral boundaries and bedrock depth has been selected to be 60 m and 30 m, respectively. The building is resting on the pile foundation, a 4 X 4 reinforced concrete pile group with pile diameter, thickness and length of 1.2 m, 165mm and 20 m, respectively, and equal spacing of four time the diameter (4d) is considered. The piles are closed-end and have rigid connection with the pile cap of size 15mx15m with thickness 0.3m representing typical floating frictional pile foundations.

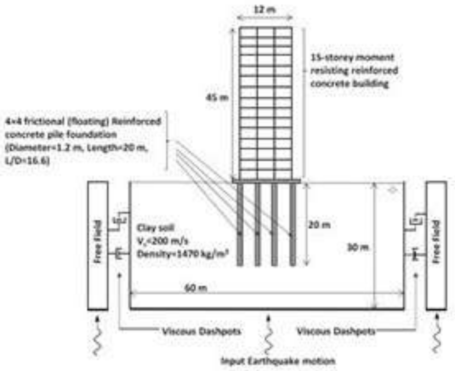

Figure.4.1 Prototype structure supported by floating (frictional) pile foundation.

4.3. Properties of components in SSI model

4.3.1. Soil Profile

In this soil model creation, soil is selected as a soft clay (High plastic clay as referred from plasticity chart) which has mixture of Kaolinite clay with Bentonite mineral. As per the reference shows the soil properties of density of 1450 kg/m^3, shear wave velocity as 36 m/s and Plasticity Index as 42%. Therefore, already existed test result data were taken as the references for value of the property of soil. It has been valued soil density as per the reference at **Aslan S. Hokmabadi et.al.(2013)**, including the elastic property like Elastic modulus and Poisson's ratio of 4 MPa & 0.2 as referred from Geotechdata.info & researchgate journal (Salma Al Kodsi,2017) test result data and for Mohr Coulomb Plasticity values are adopted from reference of Salma Al Kodsi,2017 &eng-tips.comof frictional angle of 20° correspondingly cohesion yield stress of 0.00025 were valued to the soil component.

4.3.2. Raft Foundation&Steel Super-Structure

It consists of two components namely, a Pile and a Pile cap (base plate or raft). The material properties of pile component chosen was similar to be Polyethylene pressure pipe material also known to be HDPE (high density polyethene pipe), where the property data were referred from designerdata.nl as specified in the study shown in Fig 4.8(a).

Whereas the material properties of steel were chosen from Australian standard(AS/NZS 3678:2006) of steel plate grade 250 as it specifies elastic modulus of steel as 200x10^3 MPa, density of 7850 kg/m^3&Poisson's ratio of 0.3 as shown in Fig 4.8(b)(c). From the study report shows that the steel was designed with minimum yield stress of 280 MPa and minimum tensile strength of 410 MPa.

The super structure is built-up by two components namely, steel column of size 3mx 1.2m with thickness 60mm and steel plate of size 12mx12m with thickness 150mm where the material properties adopted as shown in Fig 4.9(a)(b) were similar to Pile cap as mentioned in detail on Raft pile property section.

4.4. Assembling of SSI components

Assembling of structural components were done by connecting the grid points on the surface of one component to another component. Therefore, all components were introduced to contact with other in the assemble module in step-by-step process and using the module operators it has been used for special case of assemble the components like multiplying a pile to the pile group and level up the storey shown in Fig. 4.2.

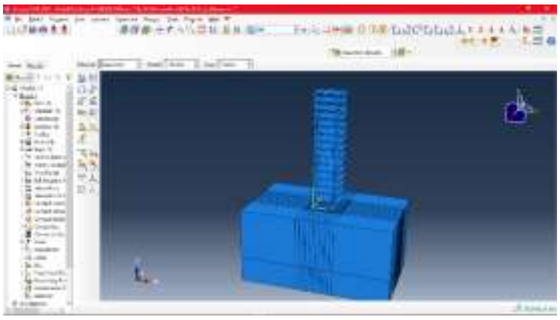

Figure.4.2Assembling entire structures over soil profile.

4.5. Meshing of SSI components

As many parametric studies helped in approach of type of meshing and mesh size, which could balance and optimize the computation speed and accuracy. In this simulation of model, the appropriate mesh has been provided to reduce the time taken for evaluation for all components of the structural system as shown in Fig 4.3 to 4.7

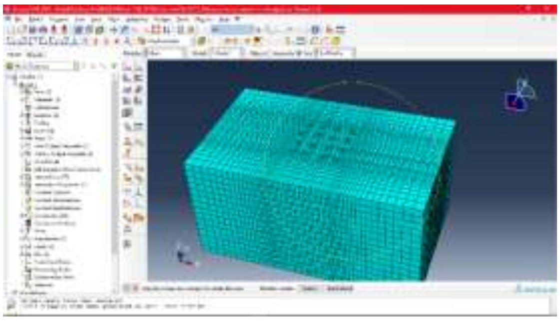

Figure.4.3Final view of meshing to soil profile

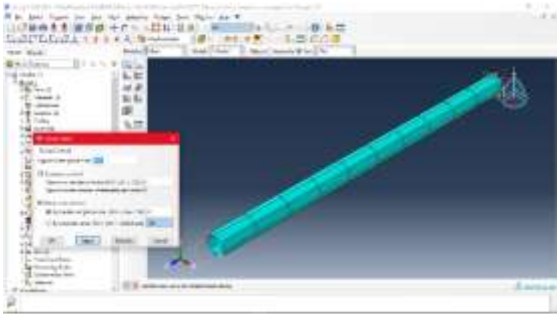

Figure.4.4Final view of meshing to Pile component showing mesh seeding

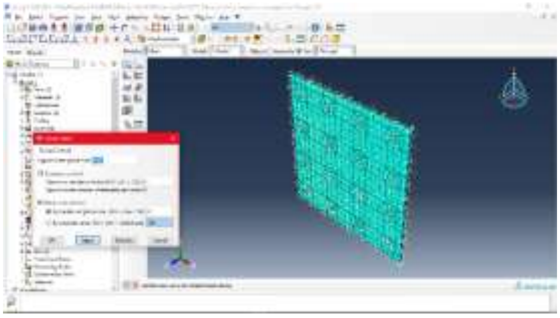

Figure.4.5 Final view of meshing to Pile cap component showing mesh seeding

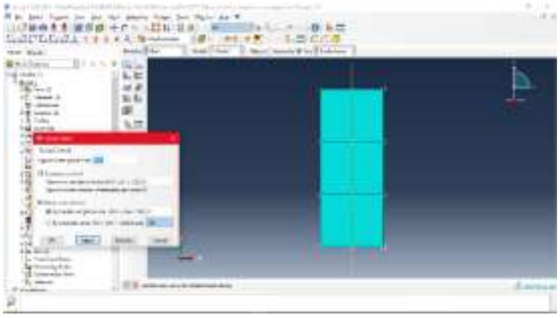

Figure.4.6 Final view of meshing to steel column component showing mesh seeding

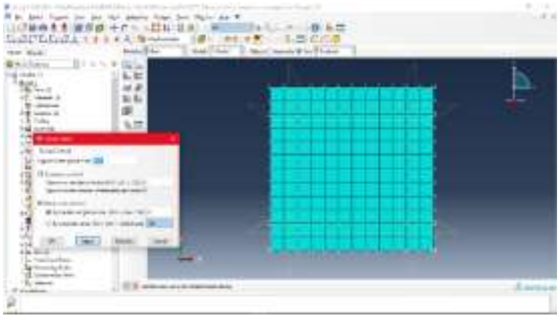

Figure.4.7 Final view of meshing to steel plate component showing mesh seeding

4.6. Application of load and boundary conditions

It has been performed two conditions: at first, boundary conditions are provided for the soil profile as it has been restrained on each node in all direction except the loading direction(U1) where it was denoted as viscous boundary condition.

Secondly, for the loading conditions both gravity and seismic (time history analysis) loads were adopted in the analysis. As for the gravity load the entire structural system was considered in which the analysis performed for 1 s of time period, whereas the seismic load was adopted as previously recorded earthquake motion ie. El-Centro (horizontal-1 component ie. x-direction is selected) which was obtained from PEER as per the reference as shown in Fig 4.8 to 4.10. And recorded value as shown in Table 4.1. of earthquake motion is scaled to 1 sec for the time period of 10 sec.

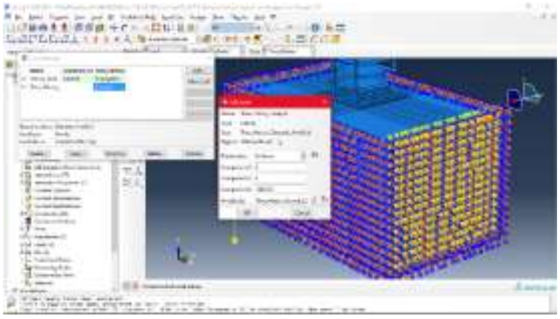

Figure.4.8 Creation of loading condition – dynamic load

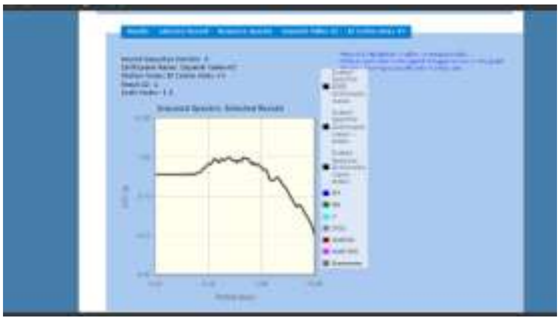

Figure.4.9 Portal view of PEER showing El-Centro Earthquake motion detail

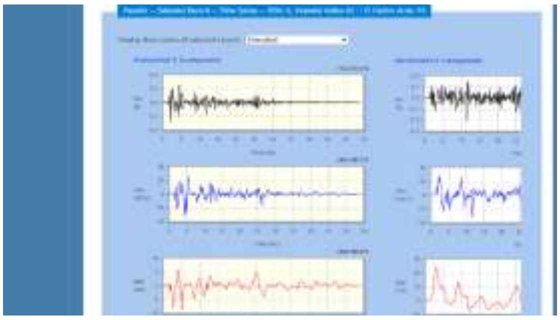

Figure.4.10 Portal view of PEER showing El-Centro Earthquake motion record

Time(sec)	Acceleration(g)	Time(sec)	Acceleration(g)
0.00	-1.43E-03	5.50	-2.75E-03
0.50	1.44E-02	6.00	2.60E-02
1.00	4.20E-02	6.50	-4.29E-02
1.50	9.10E-02	7.00	-2.23E-02
2.00	1.63E-01	7.50	9.38E-03
2.50	-1.03E-01	8.00	-2.12E-02
3.00	6.86E-02	8.50	3.92E-02
3.50	-1.09E-01	9.00	-3.73E-02
4.00	2.96E-03	9.50	1.20E-01
4.50	-2.07E-01	10.00	-8.06E-03
5.00	-1.65E-01		

Table.4.1 El-Centro earthquake motion record in Acceleration vs Time

4.7. Application of load and boundary conditions

Surface interaction and constraints at every surface-to-surface contact of one component over another were adopted to avoid any slippage of the components. Soil friction over foundation as a contact property was provided using coefficient of friction value as a tangential behaviour and pressure overclosure as a normal behaviour for adopted soil condition as shown in Fig. 4.11 & 4.12. And constraint between each structural component was assumed to be Tie as referred to be a fixed support.

Figure.4.11 Contact property – tangential behaviour

Figure.4.12 Contact property – normal behaviour

4.8. Results and Discussion

It has been observed that for every acceleration caused by (El Centro) earthquake motion at each node over the soil profile excides the entire super structure starting from the base (at storey 1). At initial state (when time period, t=0 sec), soil profile and structure are at rest as there is no acceleration has been distributed to the soil profile as shown in Fig. 4.13(a). But after the input earthquake motion starts to oscillate (as accelerate) the soil profile, it tends to distribute the same effect to the structural system, as a cause of interaction effect caused by soil to entire structural system. From the observation, it can be seen that for each time period(T) whenever of soil profile is oscillated by an earthquake motion which tends to isolate base of the super structure also, as it can be seen in the Fig. 4.13(b)to(e)

- At time period, t_1= 1.29x10^{-3} sec, soil profile is oscillating with acceleration of 2.026x10^{3} g and the structure at base responses negative acceleration of 2.7x10^{3} g.
- At time period, t_2= 1.33055x10^{-3} sec, soil profile is oscillating with negative acceleration of 4.7x10^{6} g and the structure at base responses acceleration of 2.73x10^{8} g.
- At time period, t_3= 1.33059x10^{-3} sec, soil profile is oscillating with negative acceleration

of 1.256×10^{10} g and the structure responses acceleration of 5.9×10^{10} g.

- At time period, $t_4 = 1.33062 \times 10^{-3}$ sec, soil profile is oscillating with negative acceleration of 2.64×10^{11} g and the structure responses acceleration of 1.69×10^{12} g.

On observing the results of analysis, acceleration on base of superstructure is intensified and it starts to distributed throughout the top of the structure and also it is inferred that both soil and structure cannot be stable for this peak ground acceleration, as the seismic loading is given as near field response earthquake motion. Therefore, the well distributed seismic waves need to use for further analysis. From the above responses it is also understood that the **inertial interactionis acting due to floating pile foundation as a proof of opposite acceleration of structure (at base) is shown against earthquake motion on soil profile**. And also, as the earthquake motion is provided at right face of soil profile, response of superstructure starts at base from the same zone.

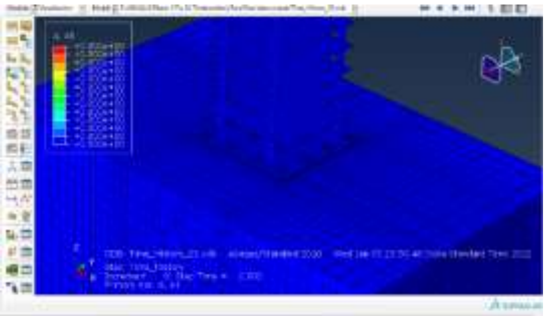

Figure.4.13(a) Field output data – Acceleration at initial state

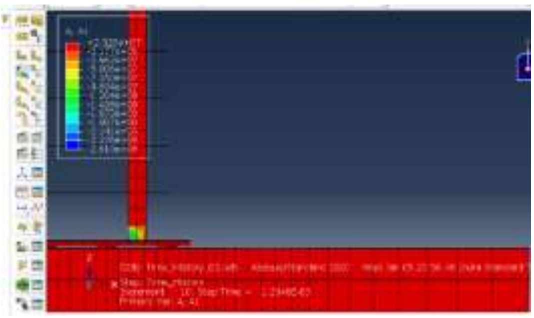

Figure.4.13(b) Field output data – Acceleration at time period 1.29×10^{-3} sec

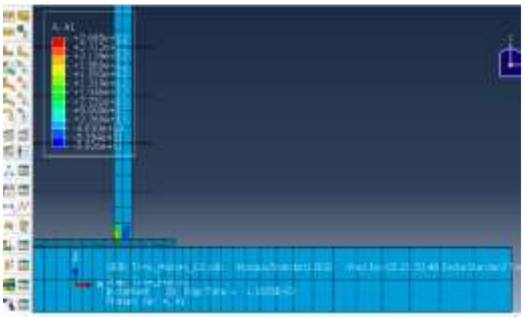

Figure.4.13(c) Field output data – Acceleration at time period 1.33055×10^{-3} sec

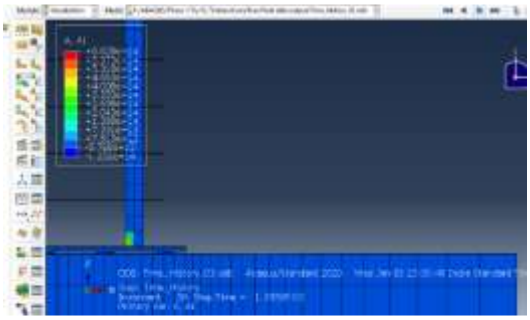

Figure.4.13(d) Field output data – Acceleration at time period 1.33059×10^{-3} sec

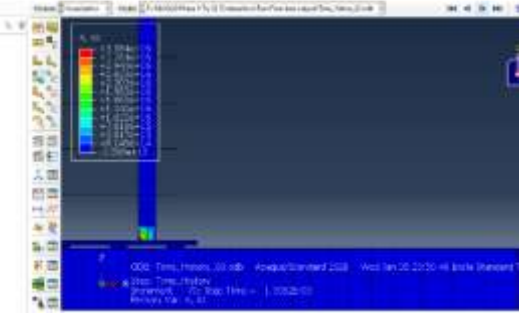

Figure.4.13(e) Field output data – Acceleration at time period 1.33062×10^{-3} sec

V. CONCLUSIONS

1. From this literature review, it has been gained knowledge about soil structure interaction (SSI) and factors responsible for SSI effects. Also studied the behavior (dynamic)of the super-structure due to SSI effects during seismic excitation.
2. It has been studied about the input parameters which was required to model the components needed for numerical simulation using ABAQUS software and also studied the responses of structures for different type of foundation for various seismic loads.

3. A 3D simulation model for SSI has been created and necessary input parameters has been selected and applied for the structure; following responses has been observed from the investigation,
   a) At initial state, soil profile and structure are at rest in condition.
   b) After the input earthquake motion starts to oscillate the soil profile, which tends to isolates the structural system starting at its base (storey 1).
   c) From each time interval, the super structure (at base) is accelerated due to the oscillation of soil profile caused by earthquake motion.
   d) It is also understood that the inertial interaction is acting due to floating pile foundation as a proof of opposite acceleration of structure (at base) is shown against earthquake motion on soil profile, as the earthquake motion is provided at right face of soil profile, response of superstructure starts at base from the same zone.
   e) The acceleration on base of superstructure is intensified and it starts to distributed throughout the top of the structure. This study has been carried out for the restricted time period; but if the time period for analysis is increased, more accurate response can be achieved throughout the structure.
4. To speed up the analysis process, number of mesh has to be reduced in investigation without affecting the accuracy of the response in the analysis.

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