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# Structural And Seismic Response Analysis of The Structure-Soil-Structure Interaction in A 3-Layered Soil System

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**ABSTRACT**

Structure-soil-structure interactions (SSSI) are among the most studied field in the recent years as the strength of a structure depends upon its foundation and the bearing capacity of the soil over which it is built. These interactions are studied in the form of structure's deformation, stresses, building frequency and deformation during seismic vibration etc. Conventionally, a single layer soil foundation has been used for building structures. In this thesis, a three layered soil system comprising of Silt sand, clay as well as stiff clay has been used with 6m, 18m and 21m of respective layer thickness, to build a G+9 multistory building. Different cases have then been analysed with modifications in the design of the pile foundations, i.e., a simple pile foundation as well as pile foundations with one, two and three bulbs. The structural analysis shows that the equivalent stress as well as total deformation of the building structure is least in case of 3 layered soil foundation structure with 3 bulbs on the piles, with a value of 3.2262e$^{7}$ Pa and 0.0781m, respectively. The 3 layered soil foundation also showed an increase in the frequency of the structure in the vibration analysis while the deformations due to the accelerations of the storeys show a decreasing trend with a little to no effect due to the design modifications of the piles with bulbs. However, the equivalent stresses in the vibration analysis have been observed to be directly proportional to the number of bulbs in the pile foundation design as the maximum equivalent stresses have been measured in the case of the pile foundation with 3 bulbs and minimum in the case of simple pile foundation.

**Keywords:** Structure-soil-structure interactions (SSSI), multistory building, vibration analysis, maximum equivalent stresses, pile foundation, three layered soil system

**INTRODUCTION**

In order to build a building, you must have a solid foundation. As the portion of a building responsible for distributing loads across a broad area of soil in a manner that doesn't exceed ultimate bearing capacity and keeps settling of the whole structure within a reasonable range, it is known as a foundation. The section of the structure on which a building rests is known as the foundation. Known as the "foundation bed," the firm ground on which it sits. The building's foundation will be affected by the kind of soil it is built on. There are several factors to consider while choosing the soil for a building's foundation. Soil foundations used in building may be classified in a number of ways.

Clay is a poor choice for constructing foundations because of its propensity to move when it dries or becomes wet. This might lead to uneven flooring as a consequence of fractures or fissures in the structure. The deeper the foundation is buried in a clay soil, the more stable the structure will be. When it comes to the clay soil, a slab-on-grade foundation or a drilled pier foundation are the greatest options for building a home. In order to provide more structural stability, pier foundations are drilled into the clay and anchored into the ground, while slab-on-grade structures are placed on top of it. Similarly, silt's propensity to hold water for an extended period makes it an unsuitable foundation material. Silt expands and shifts as a result of this property; the construction is left without support and subjected to recurrent, long-term stress. Structural damage or failure might result as a result of this. Construction should be done using dirt that is more appropriate for the project.

When constructing on sand or any other soft soil, then deep foundations are necessary to support the weight of the structure. Foundations should instead be built deep below or even underwater so that they may make touch with the earth's stronger layers. Examples include bridges, piers, dams, and other structures that have to be built underwater while maintaining their integrity. Large constructions need the use of deep foundations in this situation. As a means of reducing costs and ensuring that loads are transmitted to the deeper layers of the earth, pile foundations are employed. Pile is a thin component having a limited area of cross-section relative to its length. Because the carrying capacity of the soil at the surface is very limited, it is used to transmit foundation loads to considerably deeper rock or soil layer. Pile transfers weight either through skin friction or the bearing. Piles are also used to protect the structures from uplift as well as provide structural stability against lateral or overturning forces.

Pile foundations should be used when- (a) If there is a possibility of irrigation canal building in the region, (b) When a severely concentrated load is applied to the foundation, (c) High-bearing-capacity soil is found at a higher depth, (d) If there is greater scouring in the riverbed in the case of bridges, (e) When providing raft or grillage is prohibitively costly, (f) In swampy areas, (g) Whenever the topsoil layer is naturally compressible.

The main objectives of this work are:

- To study the soil-foundation-structure interaction (SFSI) of a G+9 multistorey building with pile foundations in a 3 layered soil system.
- To conduct a Finite Element Analysis of the building with different design modification of pile foundation on 3 layered soil using ANSYS software.
- To study the effect of seismic vibration on the “soil-foundation-structure interaction” of these different foundation designs.
- To compare the results in the form total equivalent stresses, deformations as well as frequencies of the structures of different footings with time.

In order to achieve the above objectives, a 3D model of the three layer soil system along with the pile foundation will be prepared and imported to ANSYS workbench. ANSYS is one of the best student friendly software available for analysis projects providing accurate and precise results than the older versions. The 3D model generated would then be meshed to break it into a number of finite elements. The material properities along with all the other boundary conditions are then fed into the software based on which the simulation results will be generated.

## LITERATURE REVIEW

[1] (Wang et al., 2013) explored the “dynamic through-soil interaction” between subterranean station and neighbouring pile supported structure on the “viscous–elastic soil layer” is computationally, under vertically incident S wave. To this end, ANSYS, a commercial "finite element analysis software", has been further developed as well as enhanced for the calculations of frequency domain, in which “hysteretic damping” can be considered for both the soil as well as the structures, allowing for the direct investigation of the "structure–soil–structure interaction" (SSSI). Different pile lengths, styles, stiffnesses, and numbers of storeys as well as structures have been considered for the ground structure. Maximum acceleration responses for a 12 seismic inputs are also shown. Two of the most significant elements are the arrangement as well as shaking direction. The system reaction can be enhanced or dampened depending on the distance between nearby buildings, that has been linked to the overall system's dynamic features. Those low-slung structures near the subsurface structure are severely impacted.

[2] (Madani et al., 2015) saw powerful earthquakes strike, nearby constructions with insufficient clear spacing crash. Along with such hammering, cross-interaction of nearby structures through the soil can transfer vibration energy across the buildings, complicating the situation. The impact of both of the above events on the inelastic response of chosen steel constructions are investigated in this work. The number of storeys ranged from three to twelve, with various clear distances up to the seismic code's specified value being evaluated. Within Opensees, the hammering is modelled. For "through-the-soil interaction" of neighbouring buildings in two types of soft soils, a coupled model of the springs as well as dashpots is used. As the maximum reactions averaged across seven consecutive earthquakes, the pounding force, the story shears, the plastic hinge rotations, as well as the relative displacements of stories are examined under different situations. As a consequence, the impacts of pounding as well as the "structure–soil–structure interaction" are explored simultaneously.

[3] (Nazarimofrad et al. 2016) calculated the “seismic response of an irregular multi-story structure with active tendons” using a mathematical model presented in this research. Changes in the stiffness, structural mass, as well as damping matrices are then used to create the SSI effect. Using active tendon and the LQR method, the model is used to calculate the “seismic response of ten-story structures”. At each storey, the building is described as a structure made up of components connected by stiff floor diaphragms that have 3 degrees of freedom: lateral displacements in the 2 perpendicular directions as well as rotation around a vertical axis. When a building is built on soft soils, the results reveal that the active tendons have little influence on the lowering of structural reaction.

[4] (Schepers et al. 2017) considered the interplay between unbounded soil as well as the foundation's flexibility while designing mitigating measures against the railway traffic-induced vibrations. Computational expenses make common numerical systems such as Transmitting Boundaries, Boundary Elements, and Perfectly Matched Layer difficult to use. Because of its simplicity, the Dynamic Winkler Foundation (DWF) idea is appealing, but it overlooks certain crucial aspects of the soil-structure

interaction. As a result, the DWF coefficients should be carefully determined, taking into consideration the qualities of both the foundation soil and the building. They estimate these coefficients and examine their applicability using evaluations of a real-world building for which mitigation strategies have been deployed as part of an ongoing research project.

[5] (Bolisetti et al. 2018) conducted "Soil-structure interaction" (SSI) analysis using the linear techniques in frequency domain as well as an essential step in the computation of the seismic demands in the nuclear structures. For low-intensity shaking, these approaches should provide accurate response forecasts, but their suitability for intense shaking which results in a highly “nonlinear soil, structure, or the foundation response” is unknown. For such circumstances, nonlinear (time-domain) SSI analysis may be used, although it is rarely done owing to a lack of knowledge among the engineers, analysts, and regulators. The study describes a "nonlinear time-domain SSI analysis" approach that uses a commercial “finite-element code”. For a linear SSI analysis including low intensity earthquake shaking, it is compared to SASSI, a frequency-domain algorithm. For a high intensity shaking, a nonlinear analysis using the "time-domain finite-element code" LS-DYNA is explained, and the findings are compared to those from the “equivalent-linear analysis” in SASSI. The nonlinear as well as the equivalent-linear responses are vastly different. The nonlinear effects of strong shaking, such as sliding, gapping, and elevation, are the greatest near soil-structure interface, as these can be represented by equivalent-linear approaches.

[6] (Al-Adly et al. 2019) determined the “bearing capacity of an isolated square footing” lying on either clean or oil-contaminated sand in their paper. It is the goal of this research to figure out how much oil content in the sand and how deep the oil-contaminated sand layer extends under the footing affect bearing ability. Sand was subjected to a number of standard laboratory tests to determine its mechanical, physical, as well as chemical characteristics. As a means of contamination, the crude oil is used. Loading experiments were conducted on an isolated square footing model which rested on clean as well as oil-contaminated sand to complete the investigation. To mimic real-world circumstances, contaminated sand layers were created by adding crude oil to dried sand at concentrations of 10-20% by weight. According to the (d/B) ratio, the (d/B) ratio of the contaminated sand layer (d) beneath the footing was selected and modified as (0.5, 1, 1.5, & 2) to imitate field circumstances. There was a decrease in the bearing capability of the material as a consequence of the pollution. The footing's bearing capacity drops dramatically as the percentage of the oil content as well as the depth of contaminated sand layer increase. When oil is present in sand, shear failure beneath footings shifts from the “local shear failure to punching shear failure”, according to findings.

[7] (Qaftan et al. 2020) examined the scaling process and design of a “multi-story concrete wall-frame building”, using a scale factor of 1:50. This investigation used a particularly chosen dry sand with the round particles as well as a precise grain size distribution. To depict the behaviour of the soil border during time-history seismic excitations, a “flexible soil container” was conceived and constructed. A fixed-base structure with no soil interaction was investigated, followed by a soil container with no structure, and finally a structure with the raft as well as the pile foundations in soil container was examined in detail in all three phases. Ultimately, a 3D finite element programme was used to numerically simulate the identical experimental steps. There is excellent agreement between the finite element simulations as well as the experimental data, and these numerical models may be used in future dynamic research.

[8] (Rahmaninezhad et al. 2021) made the goal of their work was to create a technique for estimating the lateral deflections of the GRR walls under the footing loads. Stability in 68 GRR walls with the wrap-around as well as the modular block facing has been studied in order to meet the above stated target. It was decided to employ a modified Bishop approach to determine the safety factors for these walls, rather than the limit equilibrium method. There was a bigger lateral facing deflection in the GRR walls exposed to footing stress with the lower safety factors than those with the higher safety factors, according to the calculated as well as measured data. Based on this conclusion, a data analysis was done to establish an exponential connection between the safety factors estimated using the "modified Bishop method" as well as the "maximum lateral facing deflection" of GRR walls under footing stress.

[9] (Jaiswal et al. 2021) attempted to use finite element modelling to assess qu of strip footing sitting on a rock mass, that was assumed to follow the most recent variant of the “Hoek-Brown failure criteria” due to a paucity of information in the existing literature. Findings for the “bearing capacity factors” (Nr0) for a footing supported by weightless rock mass were used to verify these findings. As part of a thorough investigation, researchers looked at elements influencing the strength of rock mass underneath, including the "Geological Strength Index" (GSI) and the “disturbance factor” (D) at 0 & 1, along with footing embedment depth (Df). Analysis and discussion of numerical models' reported possible failure zones is carried out in order to identify the qu. According to the findings, the qu was significantly impacted.

[10] (Burd et al. 2022) performed damage assessment evaluations of structures at risk of the tunnelling damage using a simplified, 1D soil-foundation interaction model. Urban infrastructure projects may benefit from the use of simplified models like this one. An embedded shallow foundation with a typical load-bearing masonry structure is the primary target of the proposed soil-foundation interaction model. They employed a non-linear Winkler model to describe the soil-foundation interaction, as well as the model allows us to define ground motions caused by tunnelling. The model includes shear as well as normal tractions operating on the foundation, along with the frictional sliding as well as gapping under the footing. With the use of a two-dimensional plane stress model, the soil-foundation model can be shown to produce an accurate depiction of how the facade responds when subjected to the tunnel-induced ground movement, albeit at a fraction of the computing cost of an equivalent 3D finite element model.

In our literature survey, it has been noticed that very little work has been conducted to analyse the soil-foundation-structure interaction (SFSI) of different types of footings in rock soils. Rocks, sand and gravel, hard sound chalk, sand and gravel with limited clay content, and thick silty sand are all found in this kind of soil. Even less analysis has been performed on ANSYS, which is a widely used and easily available software now, used by many researchers and students.

## MATERIALS AND METHODOLOGY

### 1. Design Of The Building With Pile Foundation

A G+9 storey building with pile foundation having the dimensions as mentioned below has been used for the present research work

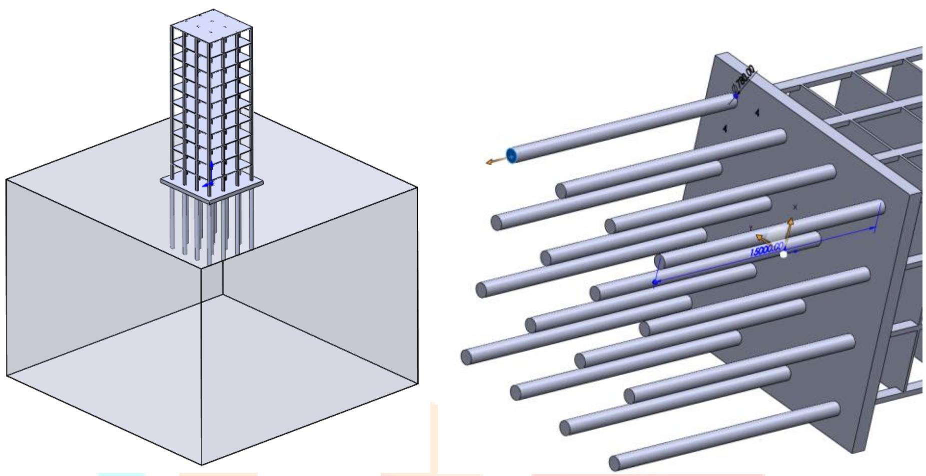


*Figure -1 The Design of the G+9 Building with pile foundation*

- Base dimension 12m x 12m
- Column – 300 x 600mm
- Beam – 300 x 500mm
- Floor slab – 150mm
- Cross-section properties of foundation elements raft – 850mm
- Pile diameter – 750 mm & pile depth – 15m
- soil volume is 60 x 60 x 45 m
- G+9 storey building is designed

The foundation soil of the building comprises of 3 layers as shown in the figure 3-3 below with their thickness.

- **Silty Sand – 6m**
- **Clay – 18m**
- **Stiff Clay – 21m**

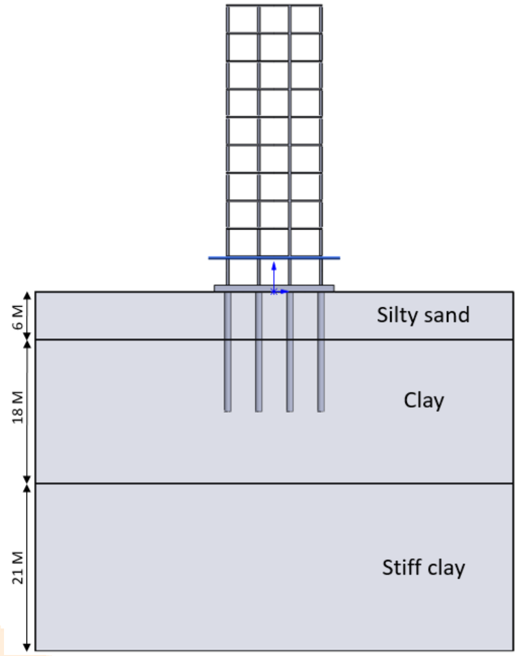



**Figure -2 Addition Of Soil Layers**

## 2. Materials

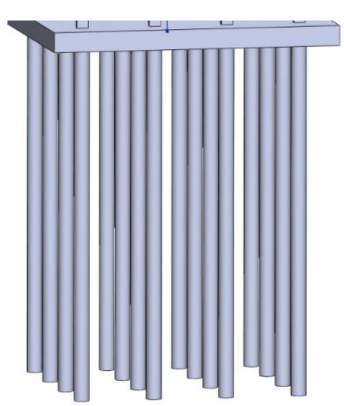
The table 1 below shows the material properities of the material of the building as well as the foundation soil layers.

***Table -1 Material properities of the building materials and the foundation soil***

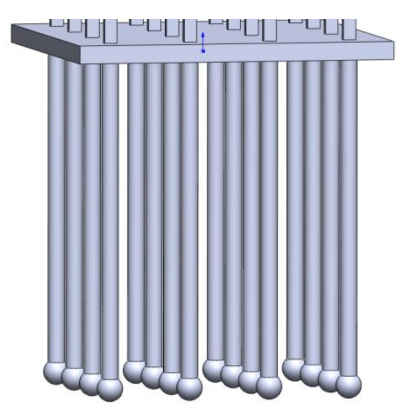
| Material properties | | | | | |
|---|---|---|---|---|---|
| **Material** | concrete | soft soil | silty sand | clay | stiff |
| **Young's Modulus, E (Pa)** | 2.90E+10 | 2.50E+07 | 2.05E+08 | 1.65E+07 | 6.00E+07 |
| **Poisson's ratio** | 0.15 | 0.25 | 0.35 | 0.45 | 0.39 |
| **Density, ρ (kg/m3 )** | 2500 | 1900 | 2039.43 | 1672.33 | 1937.46 |

## 3. Modification In Pile Foundation

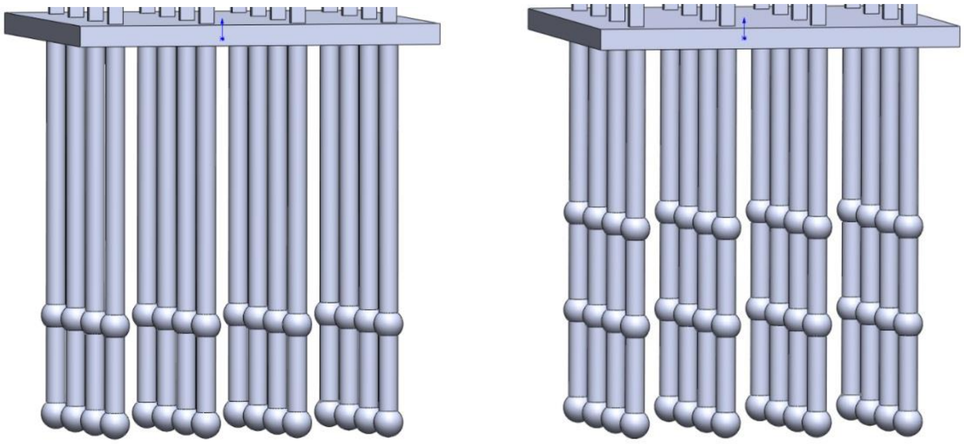
The following modifications in the pile foundation structure have been carried out as mentioned in the different cases.



**(a)**



**(b)**



(c) (d)

*Figure 3 (a) Without bulb, (b) With 1 bulb, (c) With 2 bulb and (d) With 3 bulbs*

*Table 2 Cases In The Present Research Work*

| CASES | TYPE |
|---|---|
| Case-1 | Standard design |
| Case-2 | With 3 layers of sand |
| Case-3 | With 1 bulb in each pile |
| Case-4 | With 2 bulb in each pile |
| Case-5 | With 3 bulb in each pile |

## 4. Mesh Generation

To accurately characterise an item's physical shape, its continuous geometric space is split down into thousands or more unique shapes. The 3D CAD model will be more accurate and also allow for more accurate simulations if the mesh density is increased. Meshing is the process of dividing a complex shape into distinct components. To discretize a domain into 2 or 3, mesh generation might be utilised. Because meshing takes up a significant portion of the time it takes to generate simulation results, the automated meshing methods may provide faster and more accurate answers. The mesh generation for the standard building design and for the modified designs with 3 layers of foundation have shown below in the figure 4.

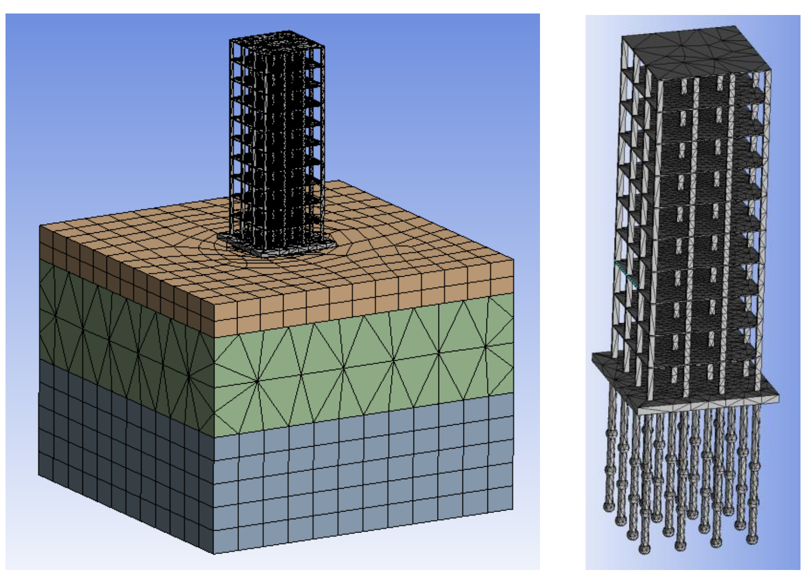


*Figure -4 Mesh Generation for the Modified Designs*

The standard design consists of 76086 nodes and 39231 elements while the modified design with 3 layers of foundation and 3 bulbs in the pile foundation consists of 105438 nodes and 52840 elements.

### 5. Boundary Conditions

The buildings have been considered fixed at bottom surface at A and the pressure is applied perpendicular in downwards direction at B as shown in the figure 5 below.

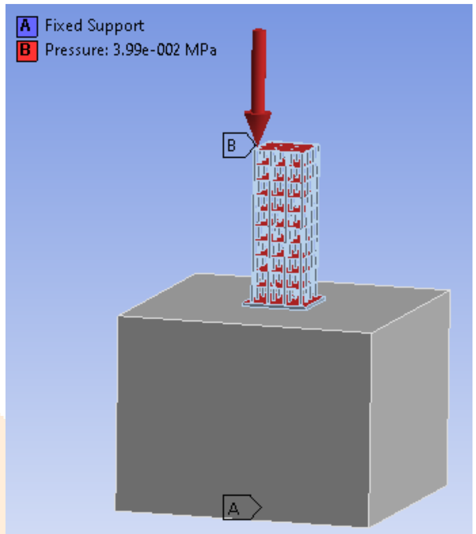



*Figure 5 Boundary conditions on the model*

### Acceleration Boundary Condition

The boundary conditions for the accelerations at different time periods during the seismic vibration is mentioned in the figure 6 below.

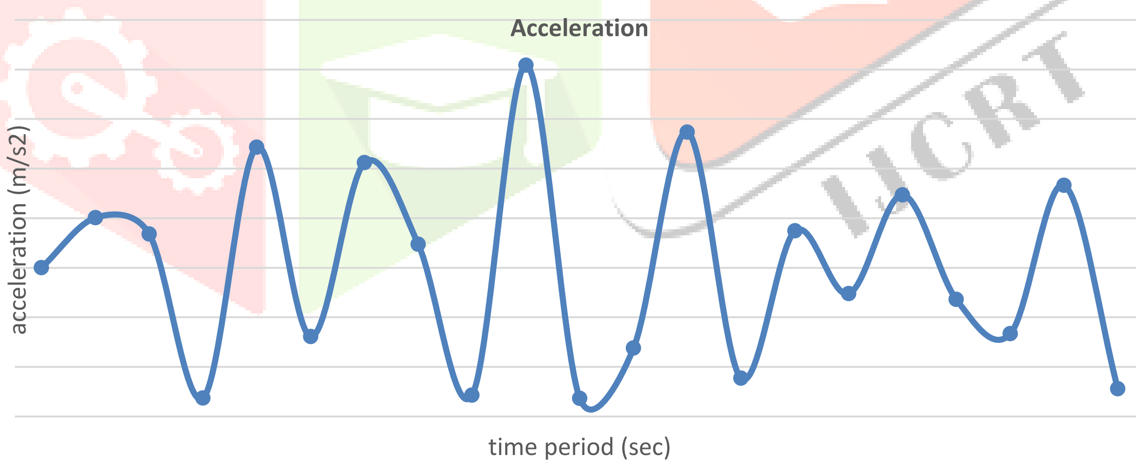
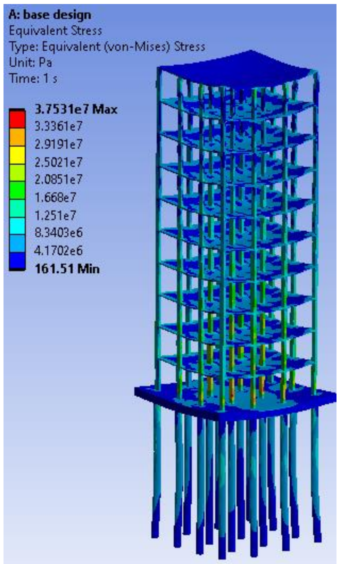


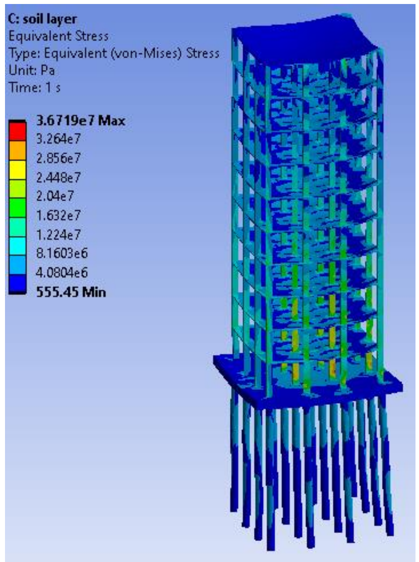

*Figure 6 Graph for acceleration vs. time period*

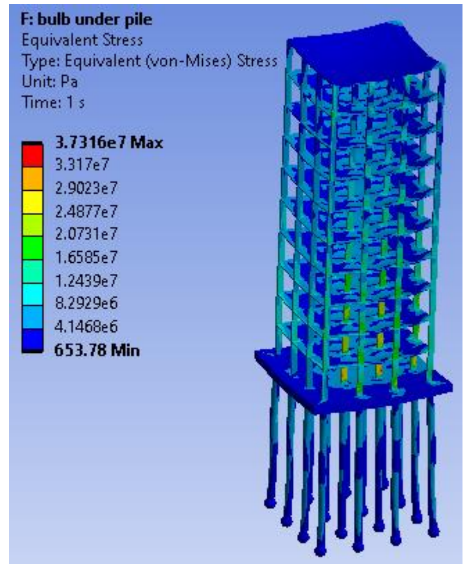
## RESULTS AND DISCUSSIONS

### 1. Equivalent Stresses

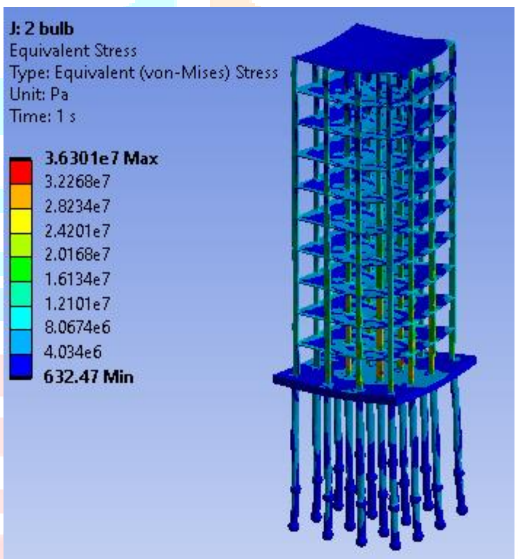
The results of the equivalent stresses obtained in the analysis have been shown below in the figure 7. The maximum equivalent stress obtained for the G+9 building structure in case 1, i.e. standard design is 3.7531 $e^7$ Pa, in case 2 with 3 layers of different sand in the foundation is 3.6719 $e^7$ Pa, in case 3 with 1 bulb in each pile in the foundation is 3.7316$e^7$ Pa, in case 4 with 2 bulb in each pile in the foundation is 3.6301$e^7$ Pa and in case 5 with 3 bulb in each pile in the foundation is 3.2262$e^7$ Pa.

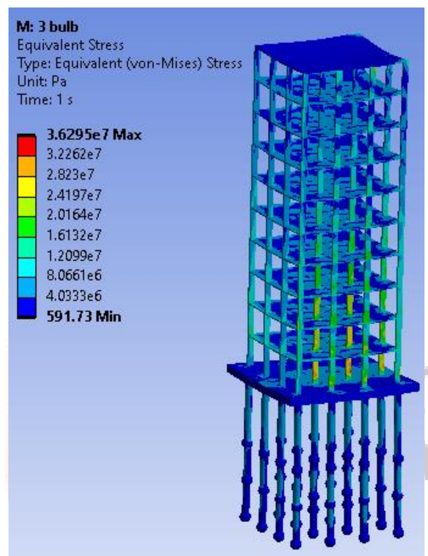



(a) (b) (c)

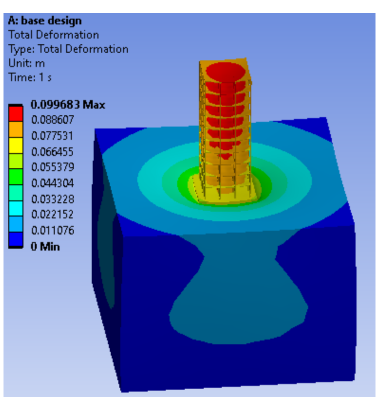


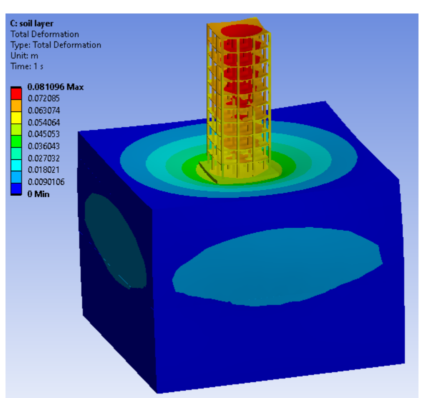



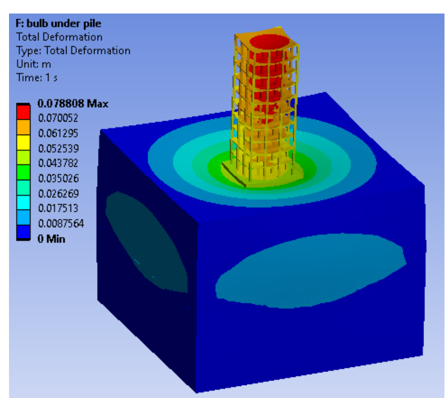

(d) (e)

*Figure 7 Equivalent Stresses for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5*

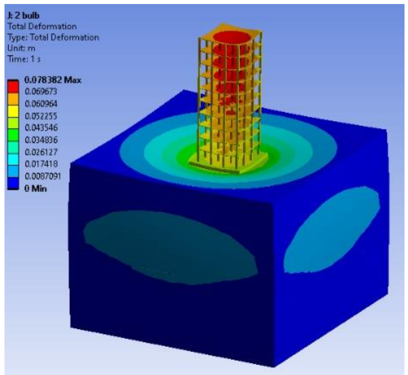
## 2. Total Deformation

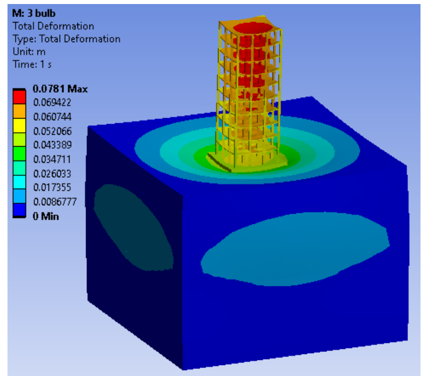



(a) (b) (c)




**(d)** **(e)**

*Figure 8 Total Deformation for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5*

The results of the total deformation obtained in the analysis have been shown below in the figure 8. The maximum total deformation obtained for the G+9 building structure in case 1, i.e. standard design is 0.099683m, in case 2 with 3 layers of different sand in the foundation is 0.081096m, in case 3 with 1 bulb in each pile in the foundation is 0.078808m, in case 4 with 2 bulb in each pile in the foundation is 0.078382m and in case 5 with 3 bulb in each pile in the foundation is 0.0781m.

### 3. Frequency Of Each Case

The comparison of the frequency of the building structure with different types of foundations during a seismic vibration, obtained for all the G+9 storeys in the all the cases have been shown below in the figure 8.

As observed, the frequencies obtained is minimum in the case 1, i.e., a simple soil foundation structure with pile foundation while the other cases show almost the frequencies, indicating that the frequency of the structure is increased due to a 3 layered soil foundation but the effect of the design modifications in the pile foundation is almost negligible.

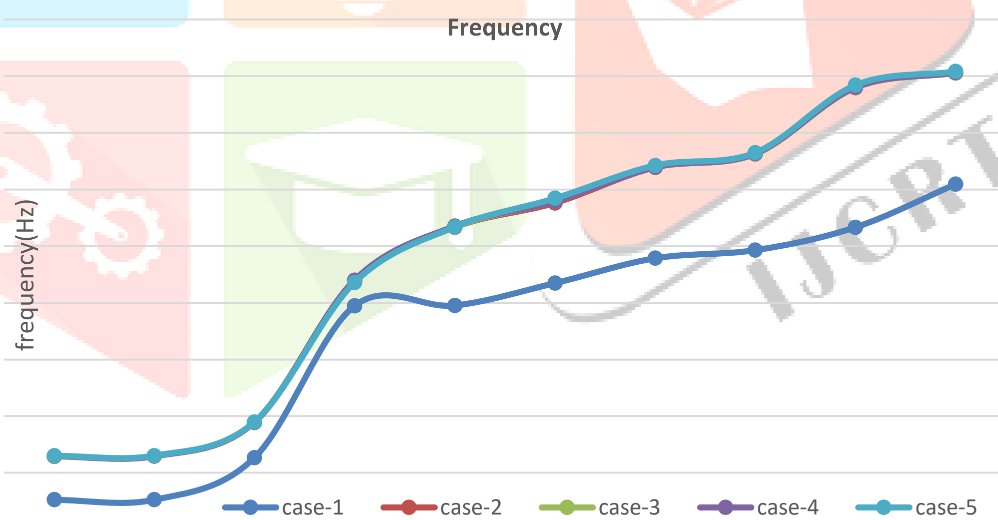



*Figure 9 Frequencies obtained at each storey of the building structure in all the cases*

### 4. Deformation Due To Acceleration

The comparison of deformations of the building structure with different types of foundations at different accelerations during a seismic vibration, obtained for all the G+9 storeys in the all the cases have been shown below in the figure 10 below.

As observed, the deformations obtained at different accelerations due to vibration is maximum in the case 1, i.e., a simple soil foundation structure with pile foundation while the other cases show almost the same deformations, indicating that the deformation of the structure is decreased due to a 3 layered soil foundation but the effect of the design modifications in the pile foundation is almost negligible.

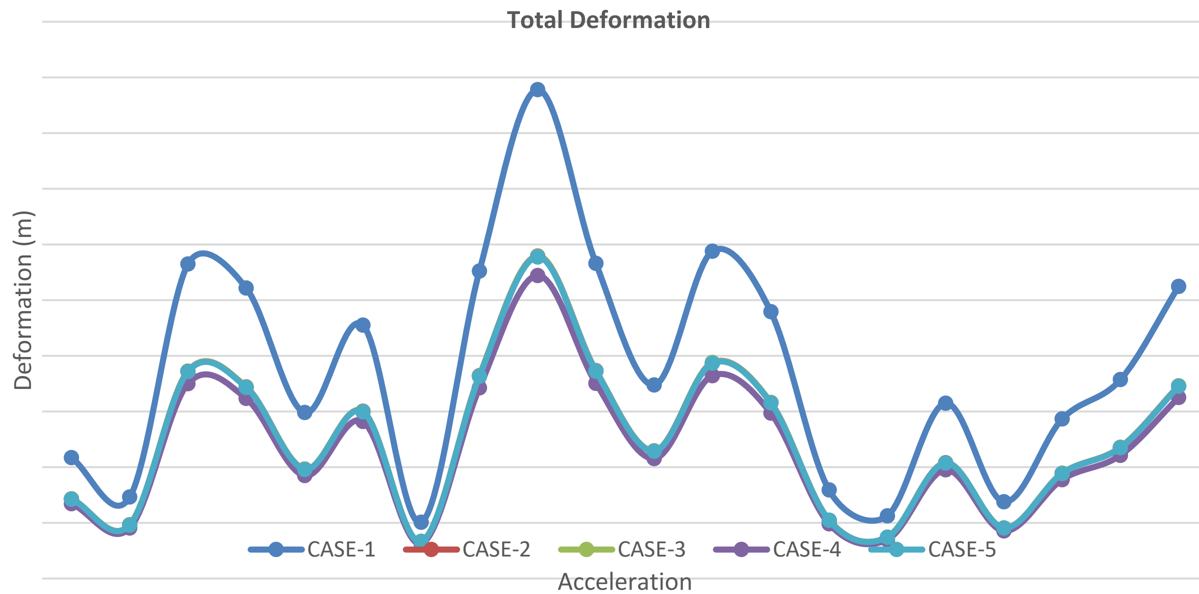



*Figure -10 Graph for total deformation due to the acceleration of the vibrations*

## 5. Equivalent Stress Due To Acceleration

The comparison of equivalent stresses of the building structure with different types of foundations at different accelerations during a seismic vibration, obtained for all the G+9 storeys in the all the cases have been shown below in the figure 11 below.

As observed, the equivalent stresses obtained at different accelerations due to vibration is maximum in the case 5, i.e., a 3 layered soil foundation structure with 3 bulb pile foundation while it is minimum for case 1, i.e., for the structure with a simple pile foundation, indicating that the equivalent stresses in the structure increases as the number of bulbs in the pile foundation design increases.

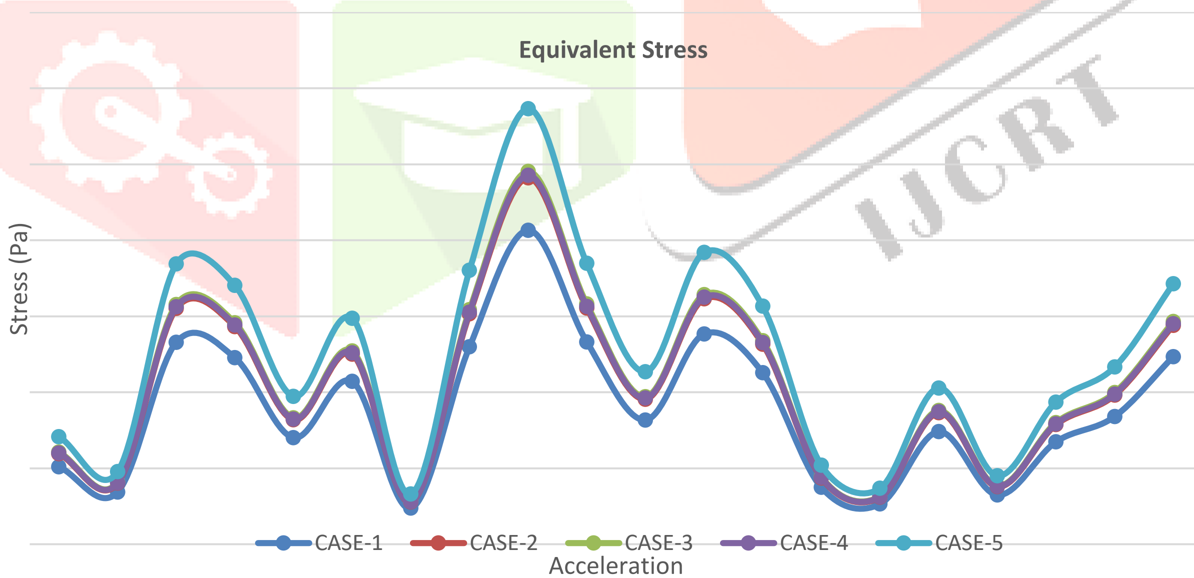



*Figure 11 Graph for equivalent stresses during the vibration due to different accelerations*

## CONCLUSION

In this thesis, a three layered soil system comprising of Silt sand, clay as well as stiff clay has been used with 6m, 18m and 21m of respective layer thickness, to build a G+9 multistory building. Different cases have then been analysed with modifications in the design of the pile foundations, i.e., a simple pile foundation as well as pile foundations with one, two and three bulbs. The equivalent stress as well as total deformation of the building structure is least in case 5, i.e., a 3 layered soil foundation structure with 3 bulbs on the pile foundation. The values of the equivalent stress and the total structural deformation for this case are $3.2262e^7$ Pa and 0.0781m, respectively. The frequency of the structure during a seismic vibration is increased due to a 3 layered soil foundation but the effect of the design modifications in the pile foundation is almost negligible. The deformations of the structure during a seismic vibration is decreased due to a 3 layered soil foundation but the effect of the design modifications in the pile foundation is almost negligible. The equivalent stresses due to a seismic vibration have been observed to be directly proportional to the number of bulbs in the pile foundation design as the maximum equivalent stresses have been measured in the case 5, , i.e., a 3 layered soil foundation structure with 3 bulbs on the pile foundation.

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