Influence of Soil Structure Interaction on Seismic Performance of Steel Structure Interaction with Different Types of Foundations and Soil

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Abstract

Soil Structure Interaction is the reaction of soil that influence the motion of the structure. During serve seismic events, the dynamic response of the structure is affected not only by the behavior of the superstructure but also by the nature and behavior of the soil present in and around the substructure. The steel structure design process usually assumes the base of the foundation to be completely restrained in a fixed base condition. In the present project the influence of soil structure interaction on the seismic performance of a steel space frame on different soil has been investigated. The multi-story steel building (G+7) with column to column spacing distance 5m and six number of columns having both X and Y direction of the structure, is designed to withstand self-weight and seismic loads. The study also examined the impact of earthquake loading on the steel structure with soil structure interaction using Response Spectrum Method and Time History Method for seismic zone III, with forces determined using IS 1893 (Part-3):2015. The study measured the displacement of steel structure with influences of soil under seismic forces. Comparison of seismic performance like maximum storey displacement, maximum storey drift and base shear along with soil structure interaction under different types of soil are presented in this project. This paper discusses the influences of the soil structure interaction on steel structure with various configuration and different types of foundations and soil.

Keywords: Multi-story steel structure, Soil Structure Interaction, Displacement of Seismic forces.

1. Introduction

1.1 Soil Structure Interaction

The soil structure interaction refers to effects of the flexible of supporting soil-foundation system on the response of structure. Soil-structure may not be considered in the seismic analysis of structure supported on rock or rock-like material at shallow depth. The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as Soil Structure Interaction. Soil structure interaction consists of the interaction between soil and a structure built upon it. The response of the soil influences the motion of the structure and the motion of the structure influence the response of the soil. It is primarily an exchange of mutual stress, whereby the movement of the ground structure system is influenced by both the types of ground and the type of structure. This is especially applicable to areas of seismic activity. Various combinations of soil and structure can either amplify or diminish movement and subsequent damage. Soil structure interaction has mainly by requirement of the nuclear power, off-shore industries, high rise building to improve the seismic safety. Seismic design codes allow designers to reduce the design base shear of buildings by considering SSI as a beneficial effect. Modern seismic design codes emphasize considering the entire structural system, including superstructure, foundation, and ground, to account for SSI effects.

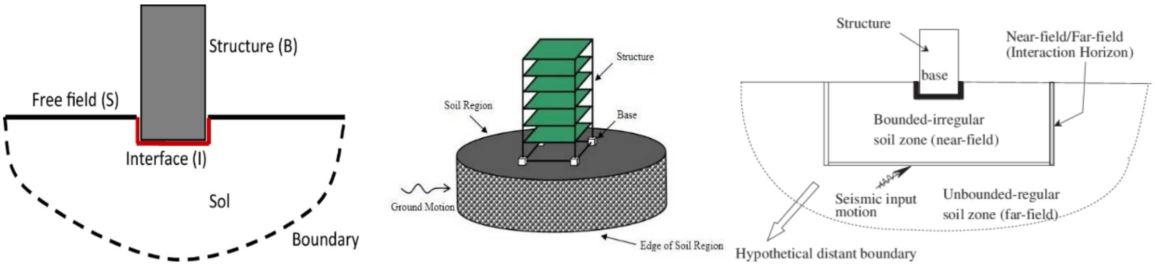


Fig: 1.1 Soil Structure Interaction

1.2 Foundation

The lowest division of the building in direct contact with the soil, based on which a structure rests or stands is called the foundation. It is the basis of groundwork so the load is transferred from the constructed building to the soil. The soil in which the foundation is to be built must have the capacity to bear the weight of the structure. So, we can say that foundation is one of the most vital components when considering to construct something at any place. A foundation bed is a ground on which it is to be built. Without the foundation bed of the building being strong or compatible with the soil, it is very likely to collapse especially during natural calamities such as an earthquake. The foundation can be classified into two, namely shallow foundation and deep foundation. A shallow foundation transfers the load to a stratum present in a shallow depth. The deep foundation transfers the load to a deeper depth below the ground surface. A tall building like a skyscraper or a building constructed on very weak soil requires deep foundation. If the constructed building has the plan to extend vertically in future, then a deep foundation must be suggested. The following types of foundations are:

- Mat Foundation
- Isolated Foundation
- Combined Foundation

1.3 Soil

In civil engineering, soil is defined as an unconsolidated material composed of solid particles, produced by the disintegration of rocks. Soil is a mixture of rock or mineral particles, water, and air. The void space between the particles may contain air, water or both. Soil is used by engineers to create the bases of structures and bridges, embankments, highways, dams, culverts, tunnels and even retaining walls. The following types of soil are:

- Hard Soil
- Medium Soil
- Soft Soil

1.4 Response Spectrum Method

Response Spectrum Method (RSM) is a linear-dynamic statistical analysis method. It measures the contribution from each natural mode of vibration to indicate the likely maximum seismic response of an essentially elastic structure. Response Spectrum Method provides insight into dynamic behaviour by measuring pseudo-spectral acceleration, velocity, or displacement as a function of structural period for a given time history and level of damping. Response Spectrum Method is useful for design decision-making because it relates structural type-selection to dynamic performance. Structures of shorter period experience greater acceleration, whereas those of longer period experience greater displacement. Structural performance objectives should be taken into account during preliminary design and response-spectrum analysis. In SAP 2000, the seismic analysis is done using the Response Spectrum Analysis method. This analysis helps determine dynamic response properties like base shear, story deflection, story drift, and story shear.

1.5 Time History Method

Time History Analysis is a numerical simulation method used to predict the dynamic response of structures to real-time varying loads. Unlike simplified static analysis, which assumes constant and instantaneous load application, Time History Analysis considers the evolving nature of forces over time. This method allows for the assessment of dynamic structural responses under varying loading conditions, accommodating both linear and nonlinear scenarios in accordance with prescribed time functions. It provides a method of assessing displacements, stress, and reactions developed in a piping system over time. In Time History Analysis, the structural response is computed at a number of subsequent time instants. In other words, time histories of the structural response to a given input are obtained as a result. This technique empowers engineers to precisely evaluate how a structure reacts when subjected to actual dynamic events like earthquakes, windstorms, or industrial vibrations. It’s important to note that the most demanding part of this process is creating the time history curve needed for the analysis. Obtaining varying ground acceleration data is necessary, and this data is readily available in countries with sufficient seismic experience. However, in countries lacking earthquake expertise, they must rely on curves developed by other nations.

1.6 Objective

- To model, analyze and design the steel structure under influence of seismic forces by SAP 2000.
- To analyze and design the steel structure with soil structures interaction based on different types of foundations and soil.
- To compare the performance of the steel structure with soil structures interaction under seismic forces.

1.7 Methodology

- A literature review regarding the project will be done.
- The design of the soil structure interaction on steel structure will be executed using the SAP 2000 software.
- The analysis of the soil structure interaction on steel structure will be done on SAP 2000 software to record the observation.

2. Literature Review

Gaurav S Kewatkar and P. S. Lande (2023) explored the SSI greatly affects the seismic behavior of structures, leading to a significant rise in the natural time period, particularly for soft soil. The period is longest for soft soil and shorter for a fixed base. As soil flexibility and story height increase, so does the base shear, but it’s lower for a flexible base than a fixed one. With SSI, a G+10 building’s displacement can rise in soft and medium soil, but fall in other conditions. Story drifts rise in higher stories due to medium and soft soil, with the most drift in middle stories. Roof displacement also rises with SSI, especially for soft soil. Winkler’s spring method indicates that the building’s period grows with spring stiffness. Story drift can reduce by up to 20-30% on hard and medium soil with SSI as a soft story. SSI, especially as a soft story at the building's base, expressively impacts the seismic response of a high-rise building on various soil types. The modulus of subgrade reaction is best estimated through geotechnical studies and inverse analysis. Finally, parametric analysis shows that high-rise structures on soft soil are more affected by SSI than low-rise ones.

Umesh R and Divyashree M (2018) studied elastic modulus of the sub-grade to be linear results in more displacement compared to when it's considered constant in the soil. The study also indicates that solely relying on concrete doesn't address all issues associated with foundation disorders. Therefore, understanding and controlling soil parameters is crucial to reduce these disorders.

Resmi.R and S. Thenmozhi (2018) reported incorporating soil into structural analysis yields results, stresses, and deformations that closely mirror the structure's actual behavior, compared to those from a fixed-base structure analysis. Traditional design methods that overlook Soil Structure Interaction (SSI) are insufficient for ensuring structural safety. Therefore, Design Engineers should primarily consider the impacts of SSI in soft soils.

P. E. Kavitha, K. S. Beena and K. P. Narayanan (2016) experimented this paper thoroughly examines the analysis of Soil-Structure Interaction (SSI) in Laterally Loaded Piles (LLPs). The behavior of a soil-structure system is largely influenced by factors like soil and pile properties, loading type, and analysis methods. Five key soil parameters are identified for their crucial role in soil behavior. Standard methods such as ASTM and BIS are suggested for accurately measuring these properties. The soil's vertical profile and ground surface gradient are vital in predicting soil-pile behavior. Pile stiffness and characteristics significantly contribute to the pile's lateral load-carrying capacity and the structural behavior of LLPs. Seismic loads can be studied using a sinusoidal loading condition. During dynamic analysis, variations in the system's natural frequency with changes in soil properties are important. The analysis method for studying LLP can be analytical, experimental, or numerical, each with its own advantages and disadvantages.

Vijaykumar P. Bhusare and Saifan B. Makandar (2019) exposed various studies reveals that while there's a wealth of research on steel and concrete chimneys, steel chimneys are less studied. These studies offer experimental and theoretical perspectives on the behavior of tall chimneys under wind and seismic forces, with a majority focusing on their earthquake response. However, research is limited on the comparative analysis of self-supporting steel chimneys with and without soil structure interaction, and on vibration analysis for steel chimneys. During an inspection of a self-supporting steel chimney, the existence of a manhole increases the von-mises stress resultant and top displacement. This is attributed to the manhole reducing the chimney's actual stiffness, as indicated in modal analysis results. Hence, it's crucial to include the manhole opening in the analysis.

P. H. Dalal, M. Patil, T. N. Dave and K. K. R Iyer (2020) focused on this research explores the use of municipal solid waste of finer fraction (MSW-FF) as a fill material. When applied as a structural fill layer on soft clay or medium stiff silty clay soils, MSW-FF significantly enhances the safe bearing capacity. However, its impact on improving the allowable pressure based on payment criteria (APSC) is less pronounced. The study finds that the use of MSW-FF as a structural fill layer under the foundation leads to a notable increase in load carrying capacity for square foundations with lesser improvement seen in raft foundations. The enhancement in the modulus of subgrade reaction is lower for raft foundations and higher for square foundations. The soil structure interaction study concludes that the modulus of subgrade reaction significantly affects foundation base pressure and settlement, but has a negligible impact on bending moment and shear stress in the foundation.

Chetan J Talakeri and Nagashree B (2020) discussed with impact of Soil Structure Interaction (SSI) on Reinforced Concrete Multi-story buildings. It considers three models (G+8, G+10, and G+12) in all seismic zones (Zone-II to V) as per IS 1893:2016, supported on three soil types (Hard, Medium, and Soft).The study reveals an increase in top story displacement in all flexible base building models with SSI compared to fixed base models. The SSI effect is also more significant for a structure located in a higher seismic zone. An increase in time period was observed in all flexible base models, mainly due to the lower stiffness of the whole structure due to the presence of soil springs. The study concludes that the height of the structure, foundation soil type, and seismic zone are crucial for the seismic analysis of high-rise structures, emphasizing the importance of considering SSI for seismic analysis.

Yigit Isbiliroglu, Ricardo Taborda and Jacobo Bielak (2015) compared research that the ground motion in and around building clusters, as well as the base motion of the structures themselves, changes due to the combined impact of local site conditions and individual Soil Structure Interaction (SSI) and collective Structure Cluster Interaction (SCI). The alterations in peak ground velocities fluctuate between reductions of approximately 30% and increases of about 10% compared to the free-field ground motion. The peak horizontal velocities of the buildings' base motion can reduce by as much as 40% for soft soils.

Azra Hanna Razvi J.B., Yashaswini R.K., Arun A.C., Vinay Kumar R. and Goutham D.R. (2018) suggested that the ground motion in and around building clusters, as well as the base motion of the structures themselves, changes due to the combined impact of local site conditions and individual Soil Structure Interaction (SSI) and collective Structure Cluster Interaction (SCI). The alterations in peak ground velocities fluctuate between reductions of approximately 30% and increases of about 10% compared to the free-field ground motion. The peak horizontal velocities of the buildings' base motion can reduce by as much as 40% for soft soils.

Korrapati Pratyusha, Doredla Nagaraju and K Dinesh Kumar (2019) performed displacements, shear forces, and bending moments are calculated using both conventional design methods and numerical analysis methods, such as the finite element method, in columns. This is done both with and without soil structure interaction (SSI). The estimated subgrade modulus response (Ks) is expected to be 12000 KN/m3.The results show that the analysis of a structure with SSI indicates more displacement than a structure without SSI. Similarly, structures with SSI show less shear forces compared to those without SSI. The bending moments in a structure with SSI are more or less the same as those in a structure without SSI.

Faisal Mehraj Wania, Jayaprakash Vemuria, Chenna Rajaramb and Dushyanth V. Babu R (2022) investigated seismic evaluations of reinforced concrete structures often focus solely on the superstructure, overlooking the flexibility of foundations. However, soil-structure interaction (SSI) significantly impacts the dynamic characteristics of structural response. This paper presents results from a nonlinear time history analysis of a G+10 reinforced concrete building, considering SSI effects, modeled using Winkler's approach.

Dhiraj Raj and Bharathi M (2013) presented for a relatively rigid structure (with bracing), the fundamental time period of the building considering Soil Structure Interaction (SSI) effect (TSSI) is about twice that of the fundamental time period with a fixed base (T) for Type-III soil. For the same type of structure, the increase in TSSI is around 1.5 times that of T for Type-II soil. In both cases, i.e., fixed and considering SSI effect, among all positions and orientations of bracings, buildings with inverted mid bracing exhibit the least story drift in Zones IV and V.

Alireza Azarbakhta and Mohsen Ghafory Ashtiany (2014) discussed designing or rehabilitating foundations for structures with stiff lateral resistance systems usually involves a linear static procedure with a fixed base assumption, which often leads to a relatively conservative design. However, when soil-structure interaction is taken into account, the seismic demand reduces, resulting in a more economical foundation design. A simple method is proposed to modify the foundation design in the linear static procedure with the fixed base assumption, in accordance through the FEMA 356 guideline. This suggested approach is based on the philosophy of the alternative method for managing overturning, which is included in the guideline. It's shown that the foundation design, derived from the proposed procedure, is cost-effective without the need to explicitly take into account base flexibility.

Halkude S.A.A, Kalyanshetti M.G.B and Barelikar S.M.B (2014) carried out the natural time period, a key parameter that governs the seismic lateral response of structural frames, increases due to Soil Structure Interaction (SSI) effects. This effect is more noticeable in soft soil. Evaluating this parameter without considering SSI could lead to serious failures in seismic design. An increase in soil flexibility leads to an increase in base shear, which is more pronounced in soft soil. Base Shear shows a significant increase with an increase in soil softness and story height.

Abinayaa Uthayakumar, Naveed Anwar and Fawad Ahmed Najam (2018) discussed this research assessed the impact of incorporating Soil-Structure Interaction (SSI) on the seismic behavior of a 40-story existing building with a Reinforced Concrete (RC) core wall. The findings from the response history analysis of five comprehensive computer models were compared. These models included one without any SSI effects, two with SSI and two using a direct approach. The study found that the inclusion of SSI effects using simplified (substructure) methods moderately influenced the story displacements and story drifts of the buildings under study. However, the impact on story shears, story moments, and roof accelerations was not significant under various input ground motions. Notably, a noticeable difference in anticipated responses was observed between the substructure and direct modeling methods, with the latter resulting in higher shear and moment demands. Therefore, it is suggested that the dynamic behavior of a structure can be more accurately analyzed by considering SSI effects and 3D modeling of the surrounding soil, rather than idealizing the base of the structure with rigidly fixed support conditions.

Rahul Raghunath Kharadel and M. V. Nagendra (2020) demonstrated in both scenarios, the variation of story drift follows a parabolic pattern, with the middle story exhibiting the highest drift. When considering Soil-Structure Interaction (SSI), there is an amplification of story drift at the middle level. Additionally, the lateral displacement variation is greatest at the top stories in both cases, indicating maximum displacement. Furthermore, the inclusion of SSI leads to an increase in the displacement value. Interestingly, the base shear for the soil-structure case remains nearly the same as compared to the fixed base case, as there is no additional seismic weight added to the building.

Putu Tantri Kumala Sari and Indrasurya B. Mochtar (2008) proposed approach involves assumptions and techniques for conducting a three-dimensional (3-D) analysis of soil-structure interaction in buildings with shallow foundations on soft ground. Computational results from various building models demonstrate that this 3-D analysis is particularly suitable for designing structures on soft soils. Unlike conventional methods, which overlook the impact of significant consolidation settlement, the 3-D approach accounts for these effects. Consequently, it ensures that buildings can withstand substantial consolidation settlement without suffering damage or structural failure.

3. Procedure

The design of the microwave tower structure involved the following steps:

- Modelling of the Steel structure in SAP 2000
- Necessary Data Assumption
- Assign Properties
- Calculations of Seismic load
- Design as per IS Codal Provision
- Analysis Steel Structure in SAP 2000
- Check Displacement
- Modelling of Steel Structure with Soil Structure Interaction in SAP2000
- Assign Properties
- Assign Seismic Parameters
- Analysis Steel Structure in SAP 2000
- Check Displacement

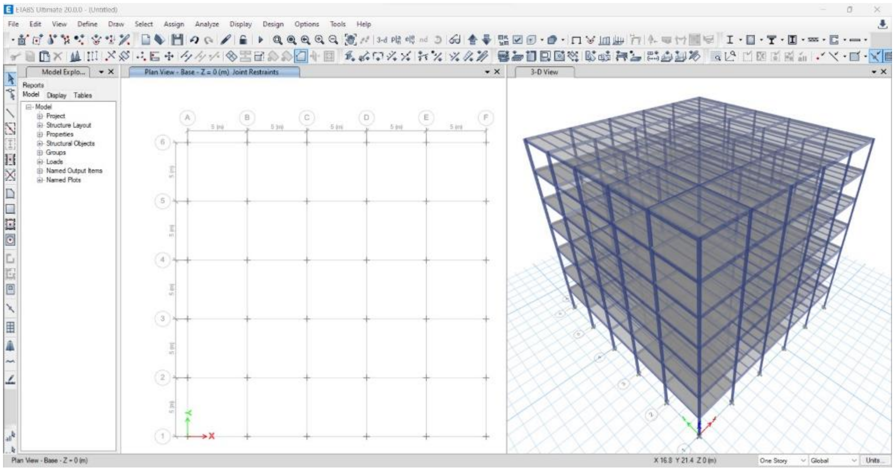


Fig: 3.1 Modelling of Steel Structure without Soil Structure Interaction

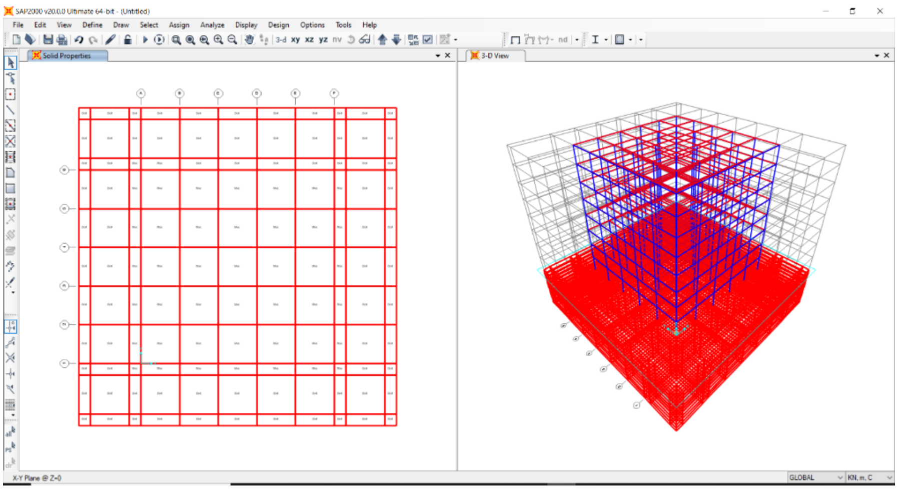


Fig: 3.2 Modelling of Mat Foundation with Soil Structure Interaction

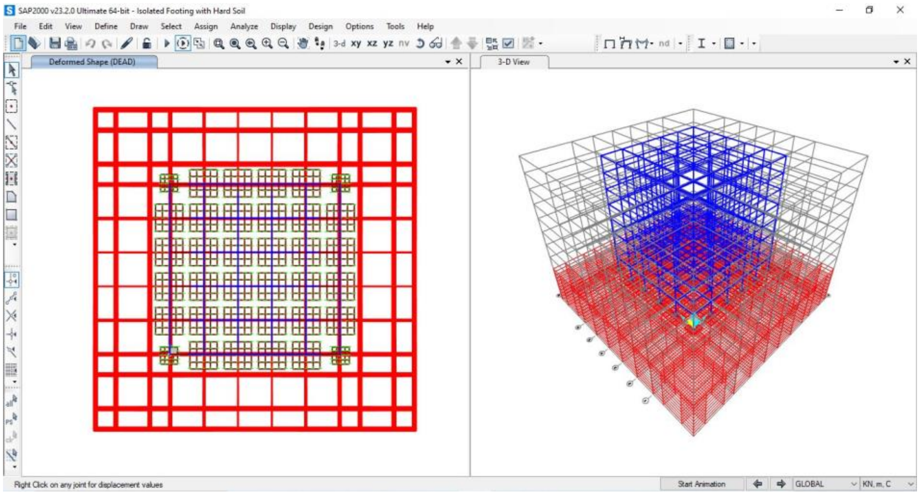


Fig: 3.3 Modelling of Isolated Foundation with Soil Structure Interaction

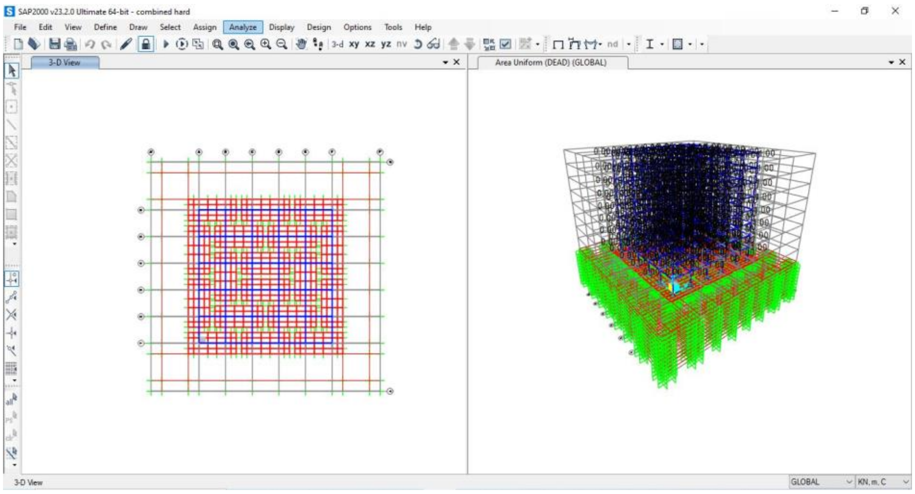


Fig: 3.4 Modelling of Combined Foundation with Soil Structure Interaction

3.5 Loading

Dead load, live load have been applied on the tower as per IS 800:2007. The wind pressure at any height above mean ground level shall be obtained by using IS 875 (Part 3):2015. The design wind pressure can be obtained.

3.6 Steel Structure Parameter

Table: 3.1 Steel Structure Parameter

Height of the Story	7
Spacing of Column to Column	5m
Height of each Steel Story	3.5m
Thickness of Slab	150mm

3.7 Seismic Load Parameter

Table: 3.2 As per IS Codal Provision of Seismic Load Parameter IS 1893 (Part 3):2016

Height of the tower	50m
Seismic Zone Factor, Z	Zone III
Seismic Intensity	0.16 (Moderate)

Importance Factor, I	1.5
Response Reduction Factor	5

4. Results And Discussion

4.1 Analytical Results

Table: 4.1 Dimension of Steel Structure

Cross Section of Beam	ISMB 300
Cross Section of Column	ISMB 300
Cross Section of Secondary Beam	ISMB 125

Table: 4.2 Displacement of the Steel Structure without Soil Structure Interaction

Loads	Maximum Storey Displacement (mm)	Maximum Storey Drift	Auto Lateral Load Story
Dead Load	0.013674	0.000005	-
Live Load	0.006925	0.000002	-
Super Dead	0.010681	0.000003	-
Seismic force (X- direction)	53.794	0.002797	275.190323
Seismic force (Y- direction)	269.006	0.013695	149.8263

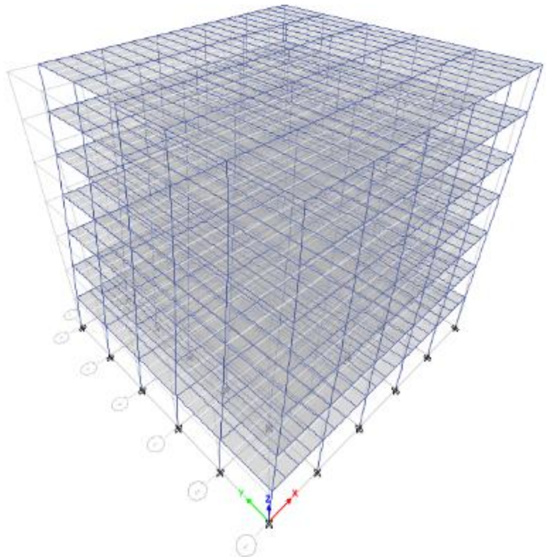


Fig: 4.1 Displacement of Steel Structure without Soil Structure Interaction

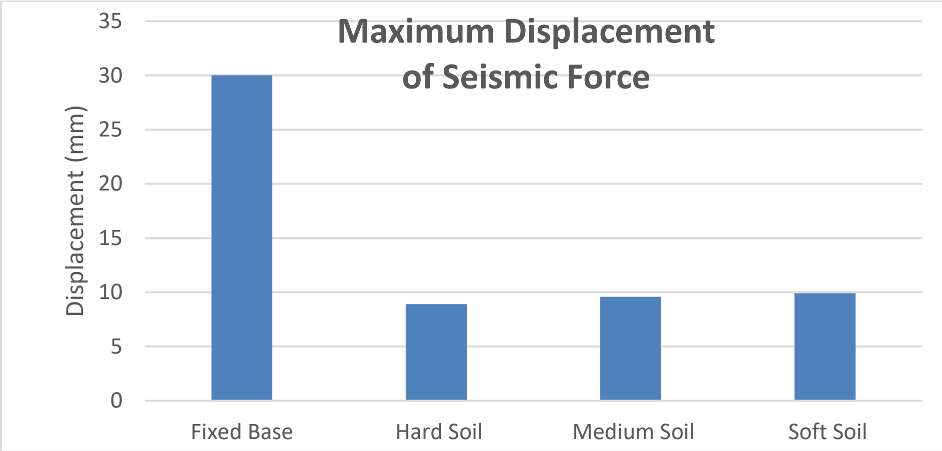
Table: 4.3 Compare the Performance of Steel Structure with Soil Structure Interaction under Seismic Force

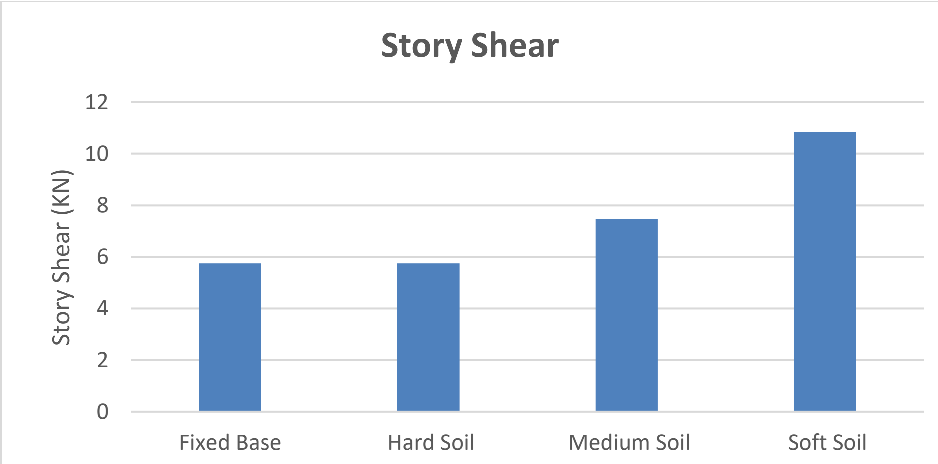
Foundation with Soil	Maximum Displacement of Seismic Force (mm)	Storey Shear (KN)	Maximum Storey Drift
Fixed Base	30	5.747	0.001771
Mat Foundation with Hard Soil	8.675	5.747	0.00093
Mat Foundation with Medium Soil	9.897	7.463	0.00196
Mat Foundation with Soft Soil	9.909	10.842	0.00201
Isolated Foundation with Hard Soil	7.242	6.165	0.001876
Isolated Foundation with Medium Soil	9.319	8.973	0.002586
Isolated Foundation with Soft Soil	10.195	9.248	0.00532
Combined Foundation with Hard Soil	30.431	9.793	0.002755
Combined Foundation with Medium Soil	31.585	10.742	0.005241
Combined Foundation with Soft Soil	32.792	11.134	0.007624

Table: 4.4 Compare the Performance of Steel Structure with Soil Structure Interaction under Response Spectrum Method

Foundation with Soil	Maximum Displacement of Response Spectrum Method (mm)	Storey Shear (KN)	Maximum Storey Drift (mm)
Fixed Base	14.48	0.61	0.000037
Mat Foundation with Hard Soil	7.040	0.61	0.000012
Mat Foundation with Medium Soil	8.448	1.866	0.000019
Mat Foundation with Soft Soil	9.752	2.799	0.000027
Isolated Foundation with Hard Soil	10.217	3.259	0.000049
Isolated Foundation with Medium Soil	11.322	4.038	0.000071
Isolated Foundation with Soft Soil	13.030	7.470	0.000088
Combined Foundation with Hard Soil	27.182	10.112	0.000056
Combined Foundation with Medium Soil	29.212	11.495	0.000086
Combined Foundation with Soft Soil	31.981	12.124	0.000092

Fig: 4.2 Compare the Performance of Mat Foundation with Different Types of Soil under Seismic Force





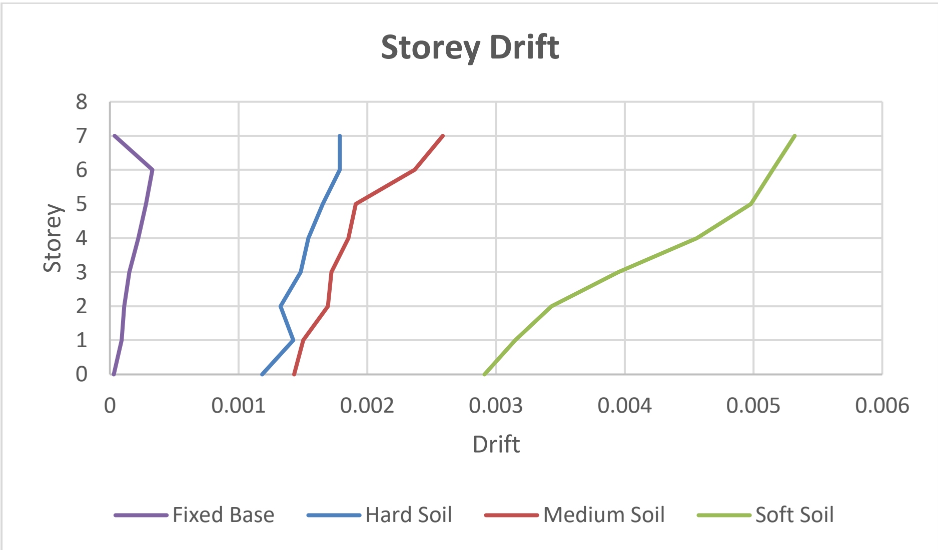


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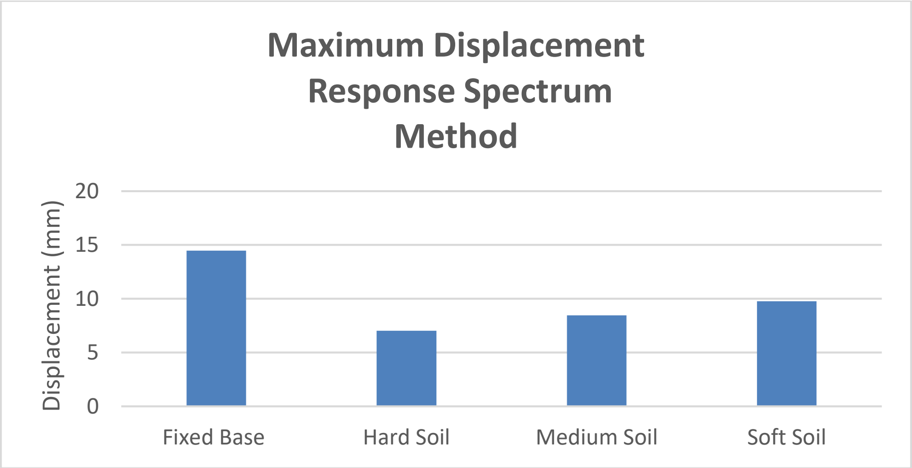
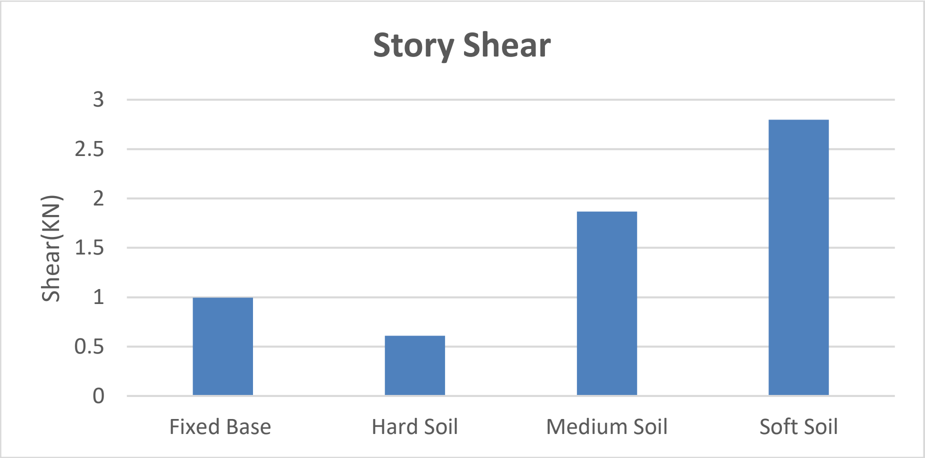
Fig: 4.3 Compare the Performance of Mat Foundation with Different Types of Soil under Response spectrum Method





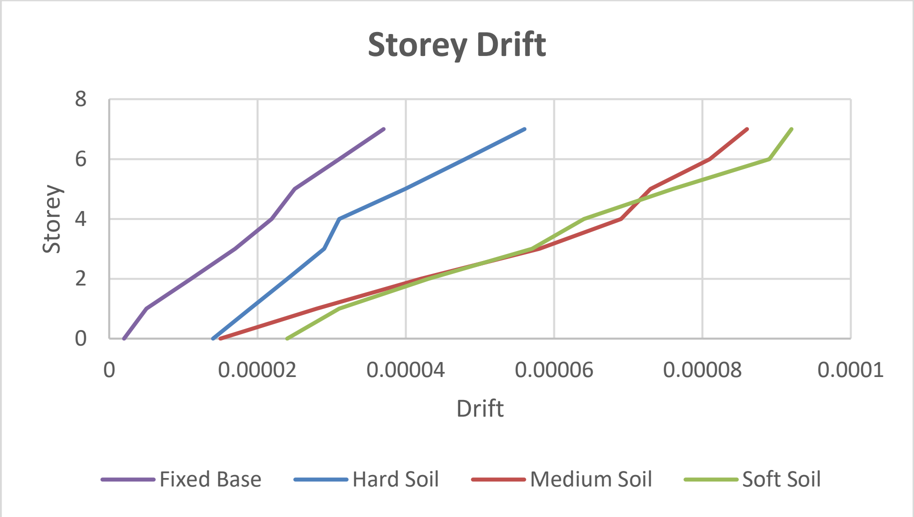
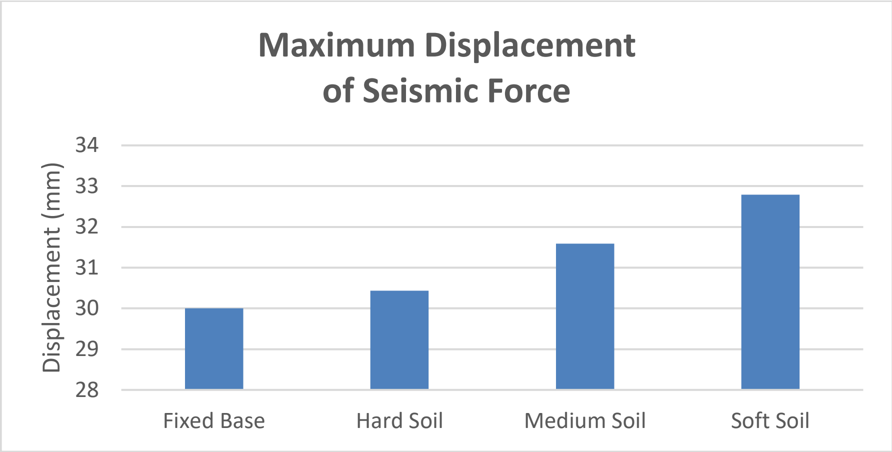
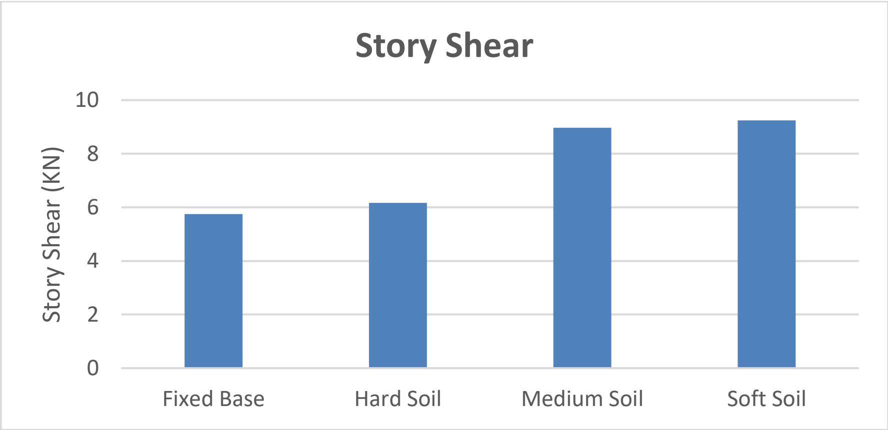


Fig: 4.4 Compare the Performance of Isolated Foundation with Different Types of Soil under Seismic Force





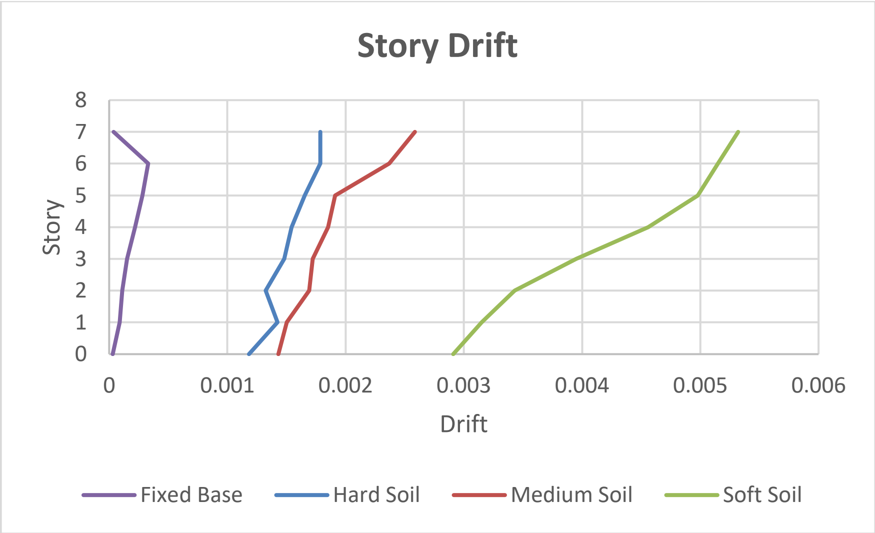
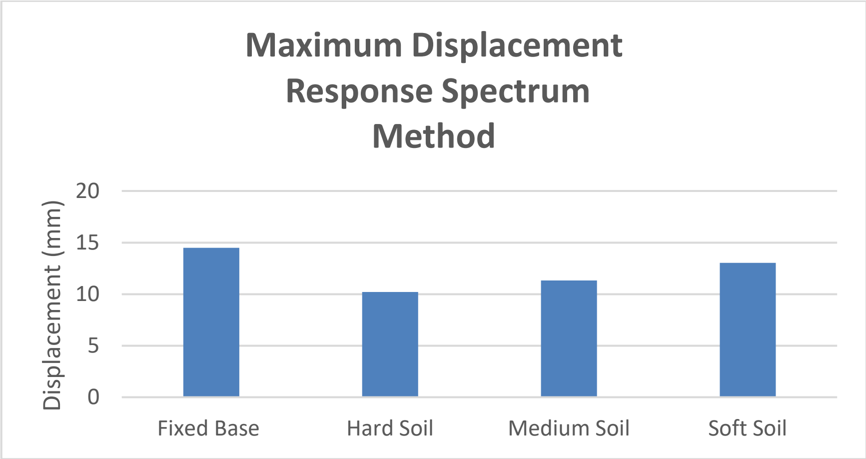
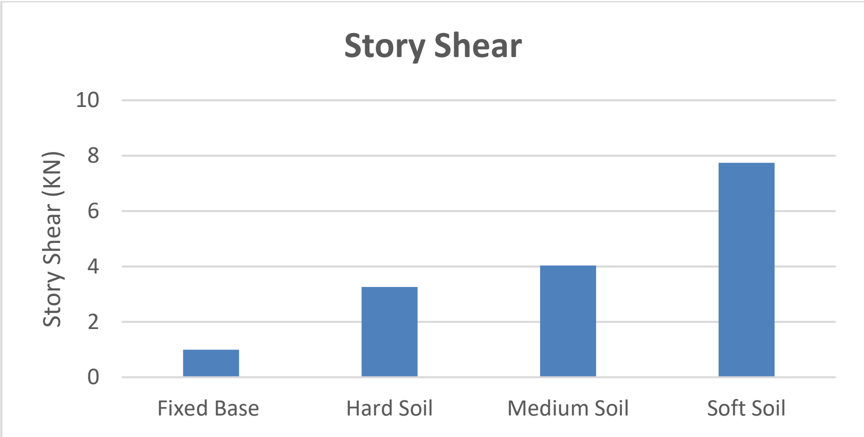


Fig: 4.5 Compare the Performance of Isolated Foundation with Different Types of Soil under Response spectrum Method





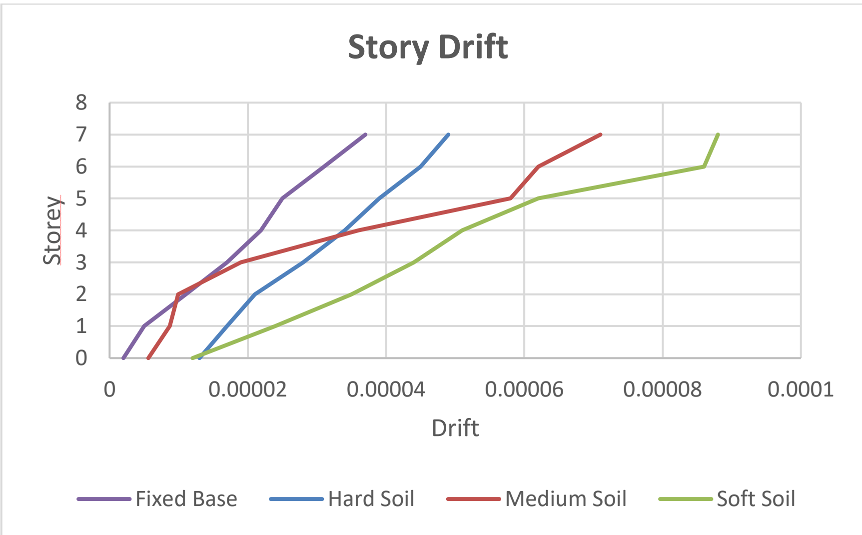
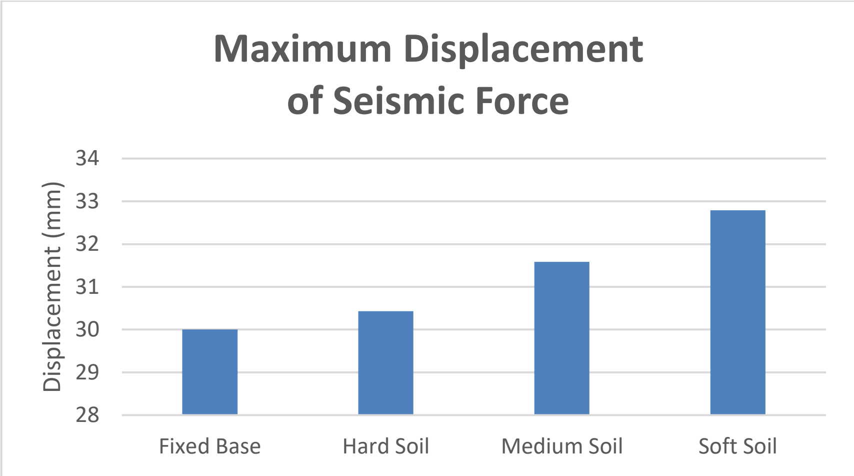
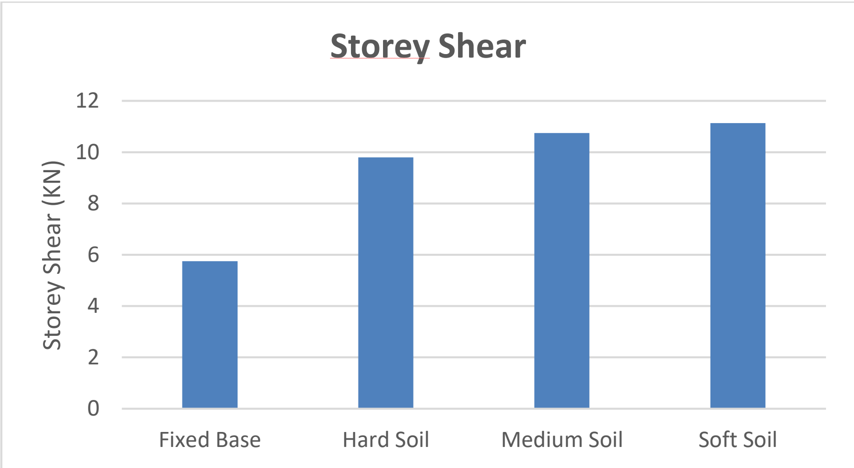


Fig: 4.6 Compare the Performance of Combined Foundation with Different Types of Soil under Seismic Force





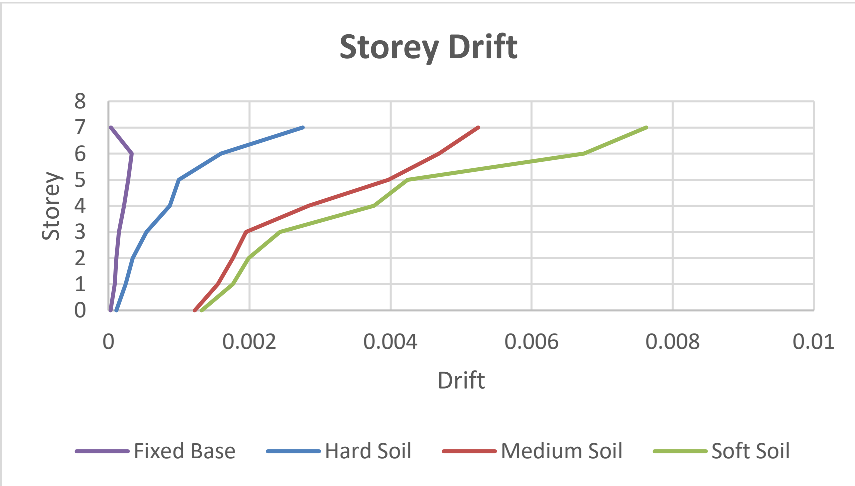
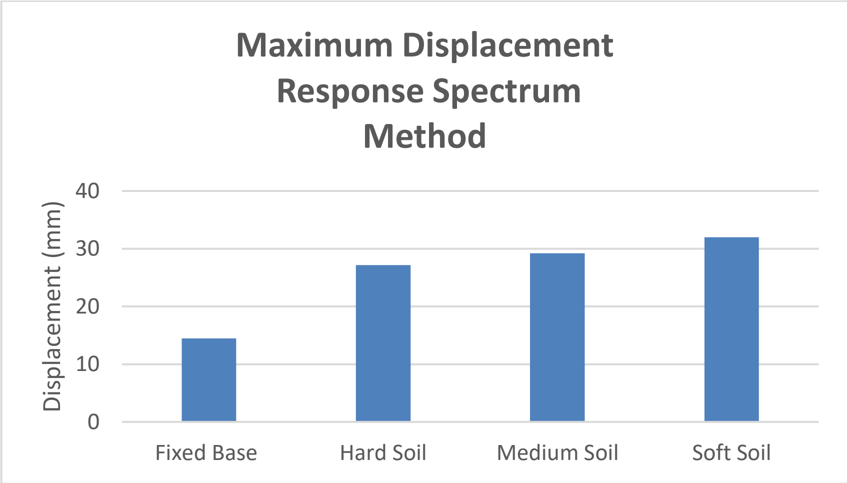
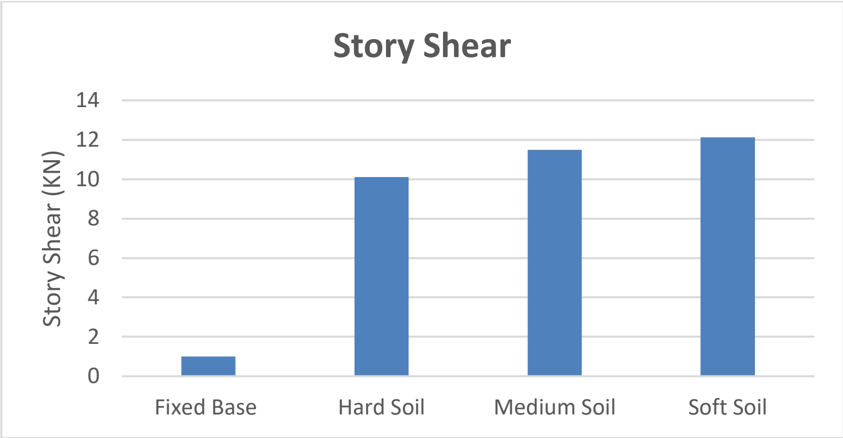


Fig: 4.7 Compare the Performance of Combined Foundation with Different Types of Soil under Response spectrum Method





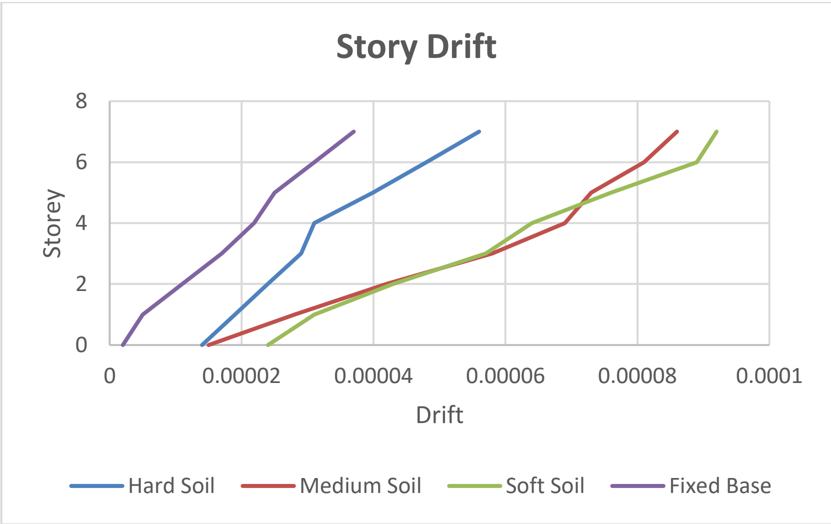


Fig: 4.8 Compare the performance of Time History Method with Different Types of Soil

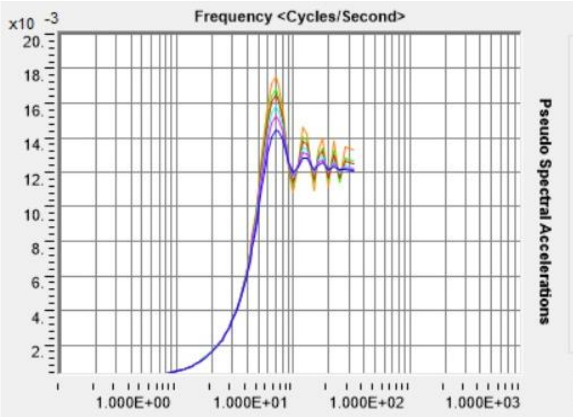


Fig: 4.9 Mat with Hard Soil

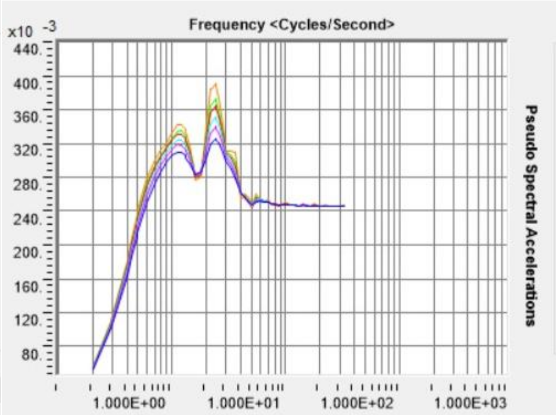


Fig: 4.10 Mat with Medium Soil

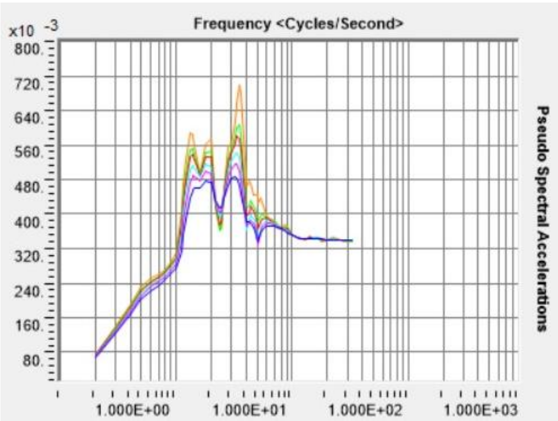


Fig: 4.11 Mat with Soft Soil

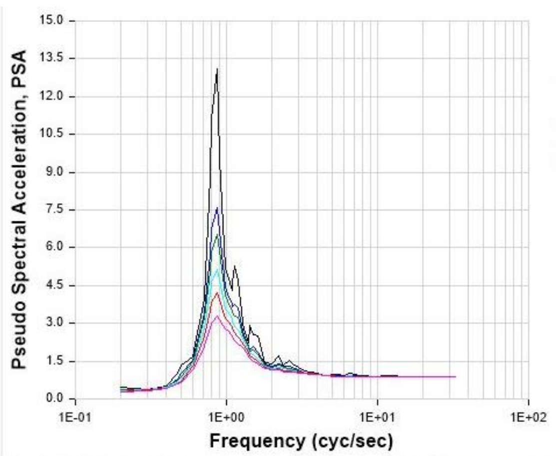


Fig: 4.12 Isolated with Hard Soil

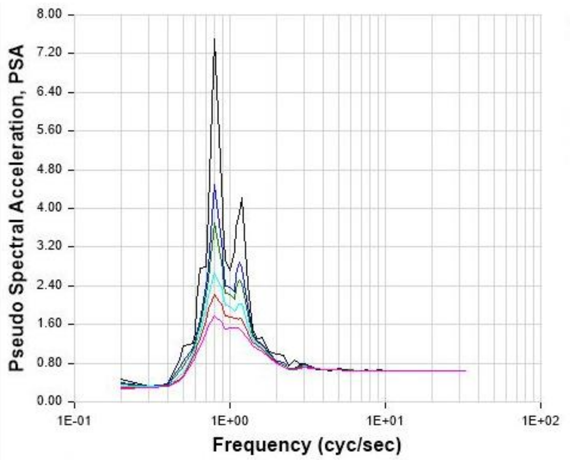


Fig: 4.13 Isolated with Medium Soil

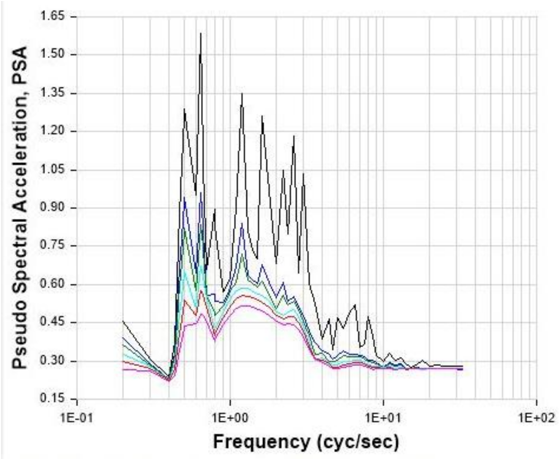


Fig: 4.14 Isolated with Soft Soil

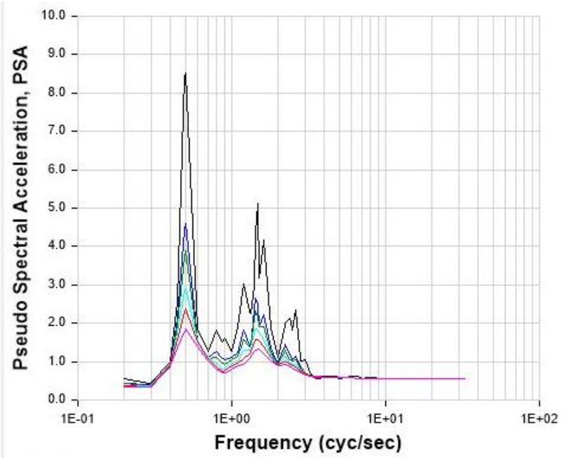


Fig: 4.15 Combined with Hard Soil

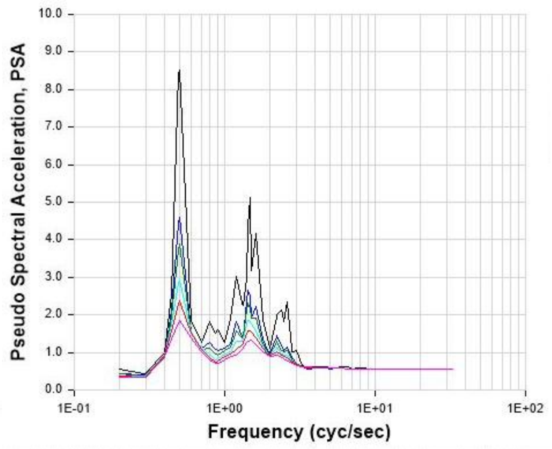


Fig: 4.16 Combined with Medium Soil

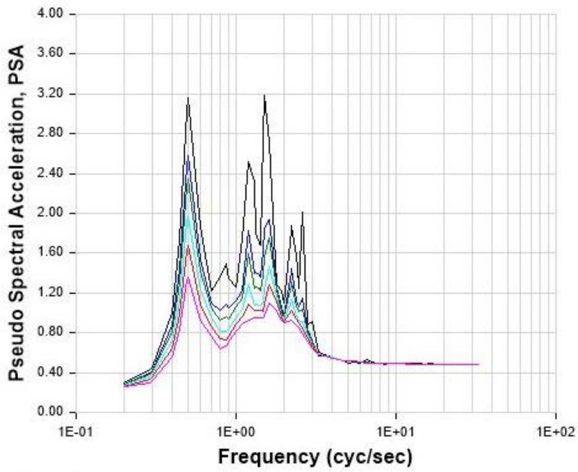


Fig: 4.17 Combined with Soft Soil

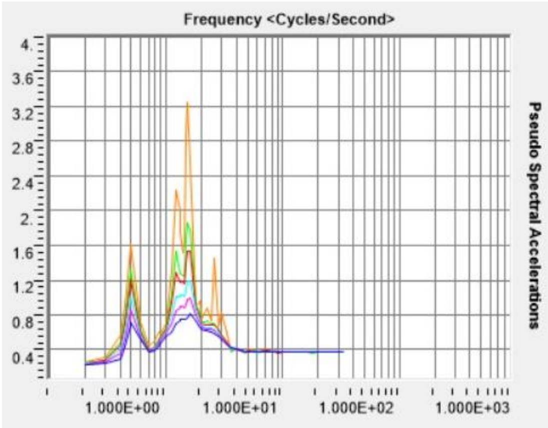


Fig: 4.18 Fixed Base Condition

Above tables 4.3 and 4.4 present data on steel structures with soil-structure interaction. These structures were designed using various foundation types, including mat, isolated, and combined foundations, and were constructed on different soil types (hard, medium, and soft). The performance of these steel structures was studied under seismic forces, utilizing both the response spectrum method and the time history method.

5. Conclusion

- Soil Structure Interaction on steel structure has been modelled and analyzed using SAP 2000 software.
- To enhance the performance of soil structure interaction on steel structure, various types of foundation including mat, isolated and combined foundation and were constructed on different types of soil (hard, medium and soft).
- Soil structure interaction on steel structure was designed for gravity loads and seismic forces. The performance of the steel structure like maximum storey displacement and maximum storey drifts were studied under seismic forces, Response Spectrum Method and Time History method of Analysis.
- From the analytical results, it is found that the mat foundation can be employed when considering displacement and seismic force of the soil structure interaction on steel structure.
- Base on the result, it is found that the value of maximum displacement of seismic force and response spectrum method, storey shear and maximum storey drift to be minimum in mat foundation.
- When comparing mat foundation to fixed base, the displacement of seismic force is reduced by 65-70%. Storey drift of the structure with soil structure interaction is reduce by 20-30% to compare fixed base.
- The lateral displacement due to seismic force is reduced and found to be within the permissible maximum value of lateral displacement and storey drift.

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