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Effects of Soil Structure Interaction on RC Frame Building

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Abstract - *The soil-structure interaction can be defined as the process in which the response from the soil affects the motion of the structure and the motion of the given structure affects the response from the soil. The study of soil-structure interaction (SSI) is related to the field of earthquake engineering. This is a form of seismic excitation. A committee of engineering research deals with the study of soil-structure interaction only which brings an appreciable effect on the basement motion when we are comparing it with the free motion. Many researchers examined various structures by taking different cases of varying soil types, varying foundation types, inclusion of shear walls, infill walls. Rigorous software analysis was also provided to validate the result. It was concluded that the soil structure interaction plays a vital role in the design consideration for high rise buildings, nuclear structures, and the structures build on soft soil. Study shows that soil structure interaction is beneficial over fixed base condition as it increases the resonance. It also helps in increasing the damping of the structure. In this paper a G+7 RC frame building was modeled using SAP 2000 using different base i.e. fixed base and flexible soil base using elastic continuum boundary condition for studying the effects of soil structure interaction. Three different soil types soft, medium and hard were taken into consideration. Base reaction and maximum lateral story displacement were compared.*

***Key Words*: Soil Structure Interaction, Kinematic Interaction, Inertial Interaction, Finite Element Model, Elastic Continuum Boundary**.

1. INTRODUCTION

After several major destructive earthquakes, 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. Investigations were done experimentally, analytically, numerically and also through various 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. The behavior of soil becomes much complex and several factors needs to be considered. This phenomenon of motion in soil inducing motion in structure and motion of structure inducing motion in soil is termed as Soil Structure Interaction (SSI).

It was found that in many cases suitable and efficient way to strengthen the structure and enhance the ductility capacity is through the rehabilitation of beam-column joints. Innovative and reliable retrofit solutions have been introduced and implemented into existing buildings. It is known that flexibility of foundation usually is accompanied with lengthening of the fundamental period of soil-structure system and an increase in the damping. Using typical code spectra, this may lead always to a reduction in the spectral acceleration and consequently, lower seismic demands for the superstructure. As recent findings have revealed, this may not be the case for some soil sites and under some specific earthquakes with particular properties.

1.1 AIM

To study the effects of soil structure interaction on RC frame building.

1.2 OBJECTIVES

a) To study the Soil Structure Interaction Phenomena.
b) To model and analyze RC frame building with fixed and flexible base in SAP 2000.
c) To perform response spectrum analysis on RC frame building.
d) To compare the effects of SSI on base reaction and lateral story displacement of RC frame building by varying soil types.

2. LITERATURE SURVEY

The Soil Structure Interaction is one of the most flourishing areas of research in structural engineering at present. It can be defined as the coupling between a structure and its supporting medium (bedrock or soil bed) during an earthquake. Soil Structure Interaction majorly covers a vast area of Civil Engineering field. As it affects the structure and the soil conditions, thus it becomes the important parameter to be focused for the researchers. The literature survey given below explores some of the fields and the Soil Structure Effects in them.

2.1 LITERATURE REVIEW

Shreya Thusoo et. Al. (2015), studied the effects of Soil Structure Interaction on a building by varying the soil types beneath. They carried out modal analysis for buildings of various heights with and without the consideration of underlying soil effects. They evidently concluded that SSI lengthens the time period of structure and hence modifies its dynamic behavior and consequently the design forces. Since seismic events are a time dependent phenomenon, therefore, evaluation of responses with respect to frequency and intensity of earthquake has been done by using Time History Analysis method. Investigations done shows that sandy soils amplify seismic waves on the soil-structure interface because of the soil-structure interaction effect. The analysis of SSI system was carried out by applying base excitations to the surrounding soil. These excitations are carried to the foundation and then transferred to structure. They also analyzed it using ANSYS software for validation. In this paper they concluded that the deflection in cases, where the soil is hard or medium, is significantly less as compared to the buildings on soft soils. For moderately stiff soil, as the size of the building increases, deflection response also increases significantly. The spectral acceleration response pattern changes drastically as stiffness of base soil decreases. The difference in response pattern of the building for both conditions gets can be easily observed and compared from the analysis results. Time period of all the responses increases while considering Soil-Structure Interaction effects. The difference in time period of the building for both conditions gets increased as the stiffness of the soil increases from soft to hard.

H. Matinmanesh et. Al. (2011), Observed and stated that the seismic waves propagation through near-surface soil layers can produce ground motions much larger and with different characteristics on the soil surface in comparison with those recorded at the rock base. In this paper finite element method has been used for seismic analysis of soil-structure interaction. Two different sandy soils (dense and loose sand) has been considered 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 results thus illustrated considerable amplification on the soil-foundation interface for both soils and buildings in each earthquake. The paper concludes that all soil types amplify bedrock motions in the soil-structure interface but with different degrees. The amount of amplification is affected by many factors including the soil type and properties, earthquake frequency content and the properties of the overlying building. 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.

Kanhaiya Abhay Zanwar et. Al. (2016), explained that the flexibility of soil causes lengthening of natural period due to overall decrease in stiffness of the structural system. Such lengthening alters the seismic response of the building frame to some extent. It is therefore, necessary that the dynamic inter-relationship between soil and structure to be taken into account in the seismic analysis of structures. To evaluate the response due to provision of spring support system, the stiffness of soil was computed as per FEMA 356 guidelines. Stiffness of soil was calculated and incorporated as spring in the software. Foundation on medium stiff soil is considered for the study. The elastic properties for this soil were taken from Joseph E. Bowles. The structural system is modeled using ETABS V.13 software. The paper concluded that the natural periods increase when the soil-structure interaction effect is considered as compared to the assumption of fixed support. The storey displacements increase when the soil-structure interaction effect is considered as compared to the assumption of fixed support. The increase in the displacements is more for the very flexible soil medium.

R. M. Jenifer Priyanka et. Al. (2012), studied the seismic behaviour of RCC buildings with fixed and flexible foundation on different soil conditions. Multi storeyed building with fixed and flexible base subjected to seismic forces were analyzed under different soil condition like hard, medium and soft. The buildings were analyzed using response spectrum method using STAAD Pro software. The values of Base Shear, Axial Force and Lateral Displacement were compared between two frames. Lateral Displacement, Base Shear, Axial Force and Moment in the column increases when the type of soil changes from hard to medium and medium to soft for all the building frames. It was concluded that the soil structure interaction must be suitably considered while designing foundation for seismic forces. The paper also concludes that lateral deflection, Storey drift, Base shear and Moment values increase when the type of soil changes from hard to medium and medium to soft for fixed and flexible base buildings. Lateral deflection, Storey drift, Base shear and Moment values of fixed base building was found to be lower as compared to flexible base building. Hence suitable foundation system considering the effect of soil stiffness has to be adopted while designing building frames for seismic forces.

Sharma N et. Al. (2018), studied the effect of soil structure interaction (SSI) on the fundamental period of reinforced concrete building frame with shear wall supported on pile foundation. The superstructure-foundation-soil continuum model is modeled and analyzed in Open SEES, a finite element software. The boundary condition does not allow for application of conventional Eigen value analysis. For this, FFT analysis of time history response of the superstructure had been used to obtain the natural periods of the frames with shear walls, based on variations in the structural configuration, foundation and soil properties. The various parameters influencing the natural period, of the frames with shear wall, under the influence of seismic SSI were also identified. It was observed that the natural frequency of the frame supported on loose sand has lower frequency than that supported on dense sand. As the supporting soil gets stiffer, the natural frequency of the structure supported by soil-pile foundation also is reduced. The effect of SSI on the natural period of the building frame with shear wall is quantified by determining the ratio T_{SSI}/T_F. T_{SSI} is the fundamental period of the building frame with shear wall under the influence of SSI. T_F is the fundamental period of the same frame with fixed base condition. Larger the value of the ratio, greater is the increase in the natural period of the frame under the influence of SSI. It is also observed that for both short and tall building frames, the increase in natural period is highest for the soft soil. As the soil gets stiffer, the effect of SSI also reduces as indicated by lower values of T_{SSI}/T_F.

Rahul Sawant et. Al. (2016), studied the interaction between the super-structure and sub-structure, it is investigated by modeling the soil as simple as possible to capture the overall response of the system. The nonlinear response of a single-degree-of freedom system which can be representative of a broad range of newly designed structures is investigated while allowing for flexibility of the soil-foundation system and SSI effects. The non-linear frame model is high rise residential building of G+42 storeys located at Mumbai and time history of ELCENTRO is used to study the response of the model in ETABS. The simple soil model with pile-raft foundation is then employed in MIDAS GTX NX to this nonlinear frame models to quantify the effect of SSI on the overall response of actual structures. It concluded that the designer should first decide that whether the SSI effect should be included in the design or not by checking the overall site condition, soil properties etc. Wave nature of SSI effects requires special attention when FEM is used. Element size for the soil and time setup must be compared with frequency ranges of interest. SSI effects are frequency-dependent. Most of effects are valid in a certain frequency range. Out of this range they may lead to the opposite changes and show different results.

P. V. Manekar et. Al. (2017) analyzed the performance of RC frame buildings with and with-out infill walls. In structural construction, RC framed structures are frequently used due to ease of construction and rapid progress of work. Both stiffness and strength of the frame is enhanced by the use of infill panels and it behaves like compression strut between column and beam and compression forces are transferred from one node to another. Equivalent diagonal strut concept analysis is used in-order to assess their response in seismic resistance of reinforced concrete buildings. Comparing the results, which are obtained from the computerized modal analysis (with and without infill structures). Parameters included are base shear, lateral floor displacement, story drift, and beam and column reactions by buildings for the comparison of results.

2.2 SUMMARY OF LITERATURE

1. The SSI effect is generally ignored from design consideration till date.
2. Different structures with various properties were chosen for analysis.
3. The structures were analyzed over different soil conditions i.e. hard, medium and soft soil.
4. Time History Analysis of the superstructure has been used to obtain the natural periods.
5. The analysis of SSI system was carried out by applying base excitations to the surrounding soil.
6. Various software were used for the analysis which included ETABS, ABAQUS, ANSYS, STAAD Pro.

3. SOIL STRUCTURE INTERACTION

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. When the external forces such as earthquake act on this system, neither the structure displacements nor the ground displacements are independent of each other. A seismic soil-structure interaction analysis evaluates the collective response of the structure, the foundation, and the geologic media underlying and surrounding the foundation, to a specified free-field ground motion. The term free-field refers to motions that are not affected by structural vibrations or the scattering of waves at, and around, the foundation. SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. Accordingly, SSI accounts for the difference between the actual response of the structure and the response of the theoretical, rigid base condition.

3.1 Dynamics of Soil-Structure Interaction

When analyzing the seismic response of structures it is common in practice to assume the base of the structure to be fixed, which is a gross assumption since in most situations the foundation soil is flexible. This assumption is realistic only when the structure is founded on solid rock or when the relative stiffness of the foundation soil compared to the superstructure is high. In all other cases, compliance of the soil can induce two distinct effects on the response of the structure, first, modification of the free field motion at the base of the structure, and second, the introduction of deformation from dynamic response of the structure into the supporting soil. The former is referred to as kinematic interaction, while the latter is known as inertial interaction and the whole process is commonly referred to as soil-structure interaction.

The main concept of site response analysis is that the free field motion is dependent on the properties of the soil profile including stiffness of soil layers. The stiffness of the deposit can change the frequency content and amplitude of the ground motion. Likewise, on the path to the structure, wave properties might be changed due to the stiffness of the foundation. In fact, kinematic interaction is the inability of the foundation to conform to the deformations of the free field ground. On the other hand, the inertial forces and moments induced by structure to the foundation can change the ground motion too. These two effects are discussed in more detail in the following sections.

3.2 Kinematic Interaction

When the earthquake ground motion in the free-field is varying over the area corresponding to that of the rigid foundation, then it can be constrained and modified by the rigid foundation. This deviation from free field motion is called kinematic interaction between the soil and foundation. Moreover, stiffness of the foundation can cause variation of ground motion with depth and scattering of waves at the corners of the foundation. If the foundation dimensions are small compared to the wave length of interested frequency range, kinematic interaction has negligible effects on the response. But if the foundation dimensions are in the same order of the wave length, a base slab averaging effect will result. The output from an analysis accounting for the kinematic interaction is an effective input motion, which is denoted as foundation input motion. kinematic interaction is important for structures supported on large and stiff foundations.

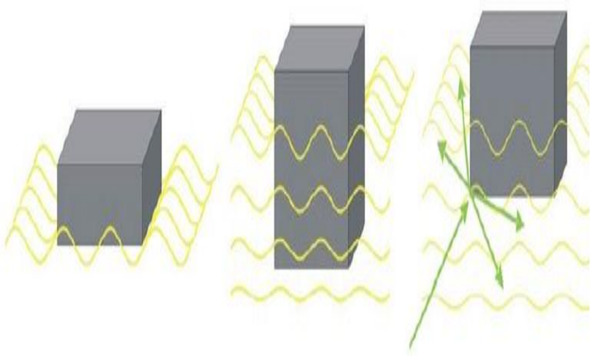

Fig - 1: Kinematic Effect of SSI due to Earthquake wave motion.

3.3 Inertial Interaction

The second effect considering the existence of soft soil under the foundation of the structure is denoted as inertial interaction. Inertial forces induced by foundation motion during the earthquake can cause the compliant soil to deform which in turn affects the super-structure inertial forces. This deformation propagates away from the structure in six degrees of freedom of the foundation motion. In other words, the dynamic response of the superstructure decreases. This removal of energy from the system is referred to as radiation damping in literature. Wolf used a viscous damper to take into account the radiation damping. The coefficient of the viscous damper is proportional to the wave velocity in the soil and the foundation area. This increase in effective damping is significant for a soil site approaching a homogeneous elastic half space.

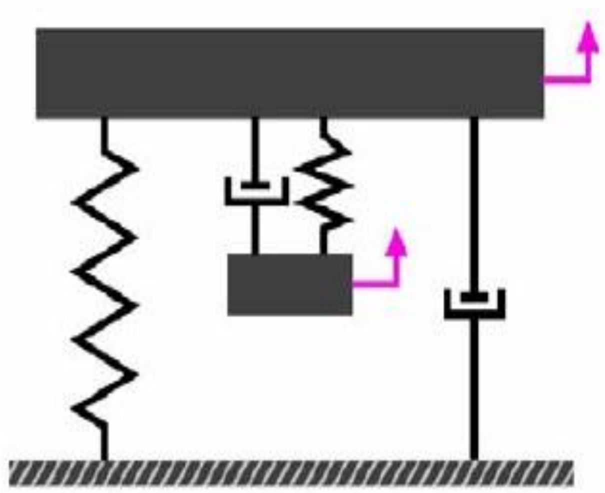

Fig - 2 : Inertial effect using a viscous damper

4. MODELING

4.1 Analytical Calculations

A RC frame building is studied for calculating the base reaction with fixed base condition situated in zone IV and on medium soil. The following data is used for analytical calculation to calculate the total base reaction V_b of the structure using M20 grade of concrete and Fe415 grade of steel with reference of IS 1893 : 2016

Table - 1: Geometric properties of model

Sr. no.	Properties	Dimensions
1	No. of stories	7
2	Plan size	18.00 x 18.00 m²
3	Number of bays in X direction	3

4	Number of bays in Y direction	3
5	Size of columns	0.30 x 0.30 m^2
6	Size of beams	0.25 x 0.40 m^2
7	Thickness of slab	0.12 m
8	Floor to floor height	3.00 m
9	Live Load	3.00 kN/m^2
10	Wall Load	9.00 kN/m^2

The base reaction is given by

$V_b = A_h \times W_i$……………………………………………………(Cl. 7.5.3)
Here,
W_i = Total seismic weight of the structure.

$A_h = \frac{Z\,I\,Sa}{2\,R\,g}$ ……………………………………………………(Cl. 6.4.2)
Here,
Z = Zone factor = 0.24 ………………………………………(Table 2)
I = Importance factor = 1 ……………………………………(Table 6)
R = Response reduction factor = 5 ……………………(Table 7)
For given data,
$Ta = \frac{0.09}{\sqrt{d}} = \frac{0.09}{\sqrt{18}} = 0.02$ ………………………………………(Cl. 7.6.2)

Hence,
$\frac{Sa}{g} = 1.32$ …………………………………………………………(Cl. 6.4.5)

Therefore we get $A_h = 0.03$

Now,
W_i = Total seismic weight of the structure.
We calculate seismic weight of single story which is as follows :

1. Self weight of beams = 0.25 x 0.40 x 6.00 x 25.00 x 24.00 = 360.00 kN
2. Self weight of columns = 0.30 x 0.30 x 3.00 x 25.00 x 16.00 = 108.00 kN
3. Self weight of slabs = 0.12 x 6.00 x 6.00 x 25.00 x 9.00 = 972.00 kN
4. Wall load = 18.00 x 0.25 x 9.00 x 8.00 = 324.00 kN
5. Live Load = 0.25 x 3.00 x 18.00 x 18.00 = 243.00 kN

Total seismic weight of each floor = 2007.00 kN
Total seismic weight of the whole structure :
W_i = 2007.00 x 7.00 = 14049.00 kN
Now,
Total base shear :
$V_b = A_h \times W_i$ = 0.03 x 14049.00
V_b = 445.00 kN

4.2 Software Analysis

To study the effect of soil structure interaction on RC frame building with foundation to be resting on three different soils namely soft, medium and hard which were modeled using SAP 2000 software. Elastic Continuum soil boundary of 30 m in length, 30m in width and 6m in depth below the base and was modeled in Finite Element Method and Response Spectrum Analysis was carried out.

Table - 2 : Details of soil properties

Sr. No.	Soil Type	Density of Soil (ρ) kN/m^3	Modulus of Elasticity (E) MPa	Poission's Ratio (μ)
1	Soft	16	15000	0.4
2	Medium	16	35000	0.4
3	Hard	18	65000	0.3

Table - 3 : Details of seismic properties

Sr. No.	Properties	Data
1	Type of structure	SMRF
2	Seismic zone	IV
3	Importance factor	1
4	Response reduction factor	5
5	Damping ratio	0.50 %

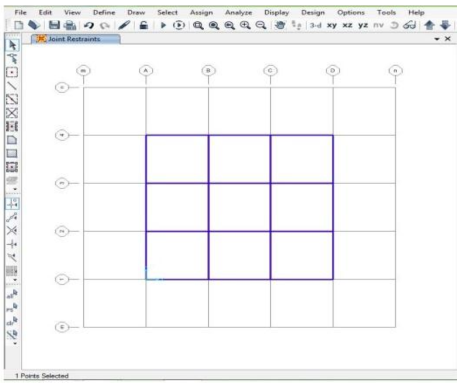

Fig - 3 : Plan in SAP 2000

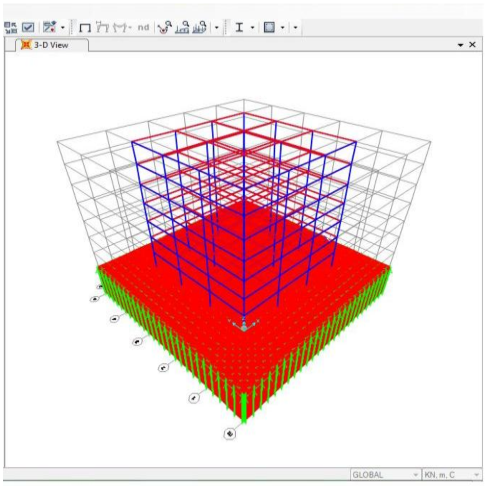

Fig - 4 : Elastic continuum model

5. RESULTS

The RC frame building with seven storey was modeled and analyzed in SAP 2000 using response spectrum analysis. The building was first analyzed with fixed base condition and than with flexible base resting on elastic continuum soil boundary with three different soil types namely soft, medium and hard. Analytical calculation was also carried out to find base reaction of RC frame building with fixed base condition. Thus the results obtained after the analysis are as follows :

5.1 Effects on base reaction with and without SSI considering different base condition

After performing response spectrum analysis the values of base reaction were as shown in below graph 1. It can be observed that the maximum base reaction occurs when the soil structure interaction effects are taken into consideration.

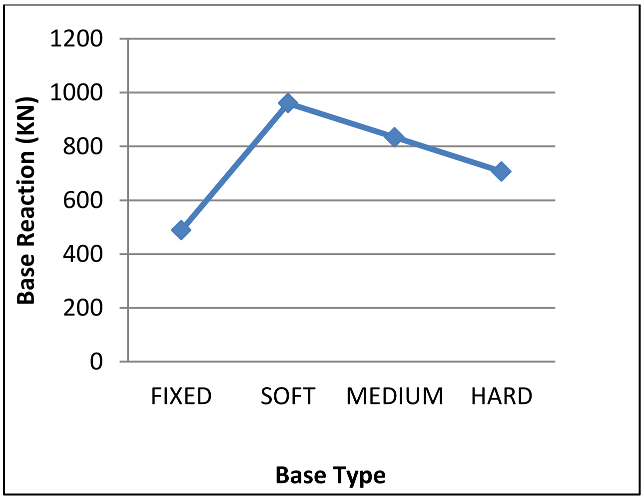

Chart - 1: Base reaction with different base

The base reaction thus calculated analytically was 445kN for the RC frame building with fixed base condition, whereas the software analysis gave base shear as 487.92 kN. It can be also observed from the graph 1 that base reaction is more for soft soil than medium than that of hard soil.

5.2 Variation in Lateral Story Displacement by varying base soil properties :

Along with the base reaction the lateral storey displacement for the RC frame building on fixed base and flexible base with soft, medium and hard soil considering the soil structure interaction effect was also noted.

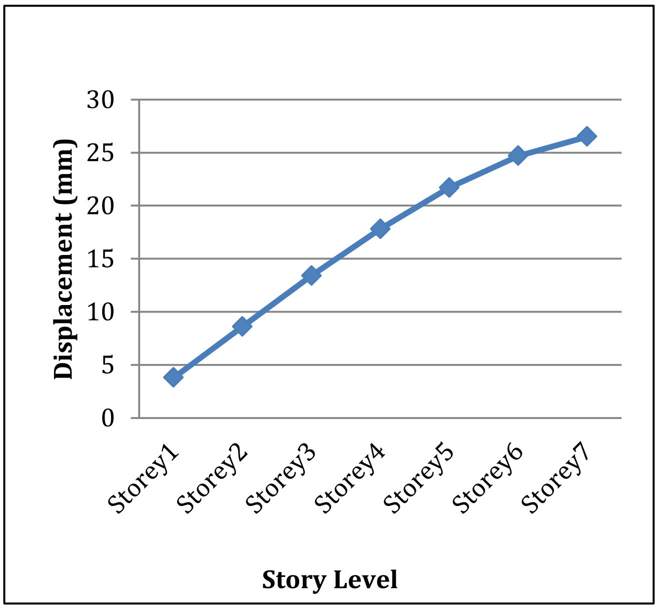

Chart - 1: Max. Story Displacement for Fixed Base

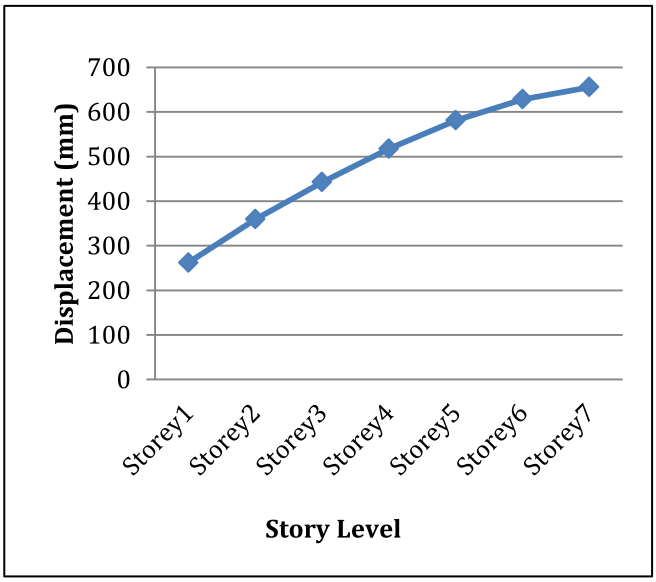

Chart - 2 : Max. Story Displacement for SSI in Soft Soil

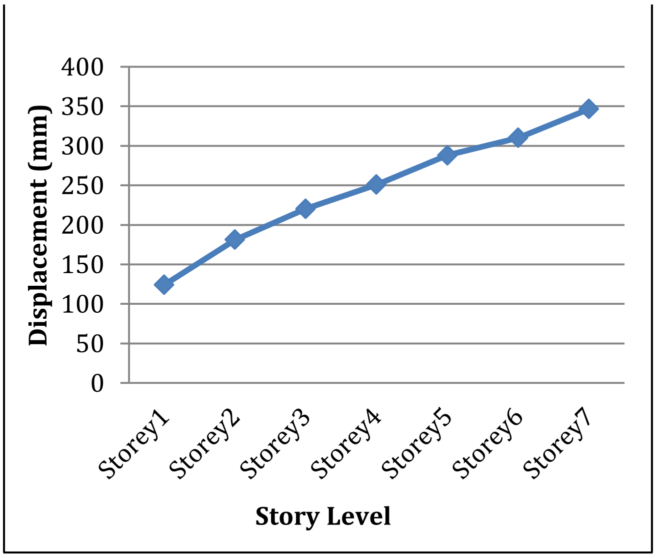

Chart - 3 : Max. Story Displacement for SSI in Medium Soil

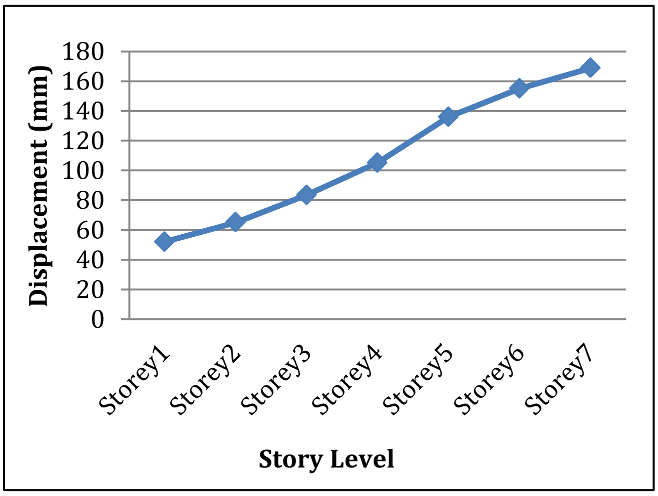

Chart - 5 : Max. Story Displacement for SSI in Hard Soil

From chart 2, 3, 4, 5 we can observe that the lateral story shows maximum displacement when soil structure interaction is considered. It shows maximum displacement in soft soil than that of in medium and hard soil. It also shows higher displacements in flexible base as compared to that of the modeled with fixed base.

6. CONCLUSIONS

1. The software response spectrum analysis shows results approximately 10% more of the actual base reaction calculated analytically for the fixed base condition.
2. The base reaction is maximum when SSI effect is considered. Base reaction for SSI effect is more for soft >>medium>>hard>>fixed base.
3. Both the base reaction and lateral story displacement increases with the increase in the flexibility of the soil.
4. Thus one should estimate the importance of SSI and decide whether it should be considered at all.
5. It is recommended that the effect of soil structure interaction to be taken into consideration for the seismic analysis and design of any structure in the region were soft and medium soil are present.

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