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Response of Buildings with Soil-Structure Interaction with Varying Soil Types

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***Abstract*—**Over the years, it has been extensively established that the practice of assuming a structure being fixed at base, leads to gross errors in evaluation of its overall response due to dynamic loadings and overestimations in design. The extent of these errors depends on a number of variables; soil type being one of the major factor. This paper studies the effect of Soil Structure Interaction (SSI) on multi-storey buildings with varying under-laying soil types after proper validation of the effect of SSI. Analysis for soft, stiff and very stiff base soils has been carried out, using a powerful Finite Element Method (FEM) software package ANSYS v14.5. Results lead to some very important conclusions regarding time period, deflection and acceleration responses.

***Keywords*—**Dynamic response, multi-storey building, Soil-Structure Interaction.

I. Introduction

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. Aided by the revolution in computer technology, tackling such problems has become possible lately. Works done in the recent decade [1]-[4] have shown the importance of structure-soil-structure interaction on dynamic response of key structures such as silos, storage tanks, offshore structures. SSI calls for [5] improvement in codal provisions for seismic design and communications between geotechnical and structural engineers.

Variation in dynamic response between fixed base and SSI model can be mainly attributed to (i) foundation stiffness and damping, (ii) foundation deformations and (iii) change in foundation input motion from free-field motion on account of kinematic and inertial interactions. An attempt has been made here to check for the extent of variations rooted to the first factor i.e. foundation stiffness.

Investigations done by [6] show that sandy soils amplify seismic waves on the soil-structure interface because of the soil-structure interaction effect. NEHRP [7] has given an extensive report to develop consensus guidance for implementing soil-structure interaction in response history analyses, and have identified areas of further research.

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Eurocode 8, part 5, identifies impact of relative stiffness of soil and structure on the dynamic response. It states that the important cases in which effect of SSI needs to be considered are structures with massive or deep-seated foundations, such as silos, offshore caissons and bridge piers, and; slender tall structures, such as chimneys and towers; and structures supported on very soft soils. Thus understanding the effect of soil properties on response of structures during earthquake becomes imperative for seismic analysis.

In the following sections of this paper, first the need for undertaking this work has been established by verification of effect of SSI on modal frequencies of multi-storey buildings. Section II gives details of the SSI model adopted for analysis in ANSYS 14.5. Section III consists of results and detailed discussions on the observations acquired from the modeled structure. In the end, the main concluding notes and ideas for furthering this research have been provided.

II. Problem Formulation

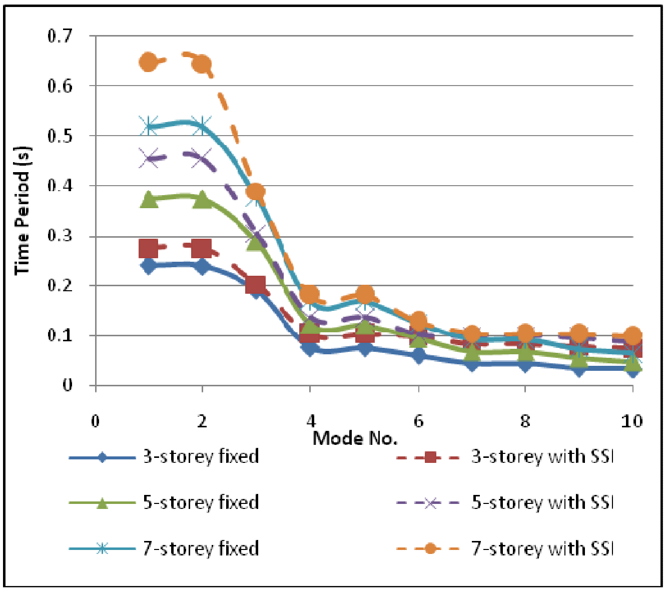

Fig. 1 Variation of Time Period with Mode No. for different height of the buildings

The analysis of SSI system is carried out by applying base excitations to the surrounding soil. These excitations are carried to the foundation and then transferred to structure.

The basic equation for time-dependent movement of a 3D volume under the influence of a dynamic load is:

$$M\ddot{u} + C\dot{u} + Ku = F(t) \tag{1}$$

Here, M is the mass matrix, u is the displacement vector, C is the damping matrix, K is the stiffness matrix and F is the load vector. The displacement, u, the velocity, $\dot{u}$, and the acceleration, $\ddot{u}$, can vary with time. The last two terms in (1) (Ku, F) correspond to static deformation.

The interaction force-displacement relationship in time domain is expressed as,

$$\{R(t)\} = \int_0^t [S^\infty(t-\tau)]\{u(\tau)\}d\tau \tag{2}$$

Here, $\{R(t)\}$ refers to the interaction forces of the unbounded soil acting on the nodes at the interface in soil-structure system and $[S^\infty(t)]$ is the displacement unit impulse response matrix in time domain.

To substantiate the effect of these interaction forces on overall response of building, Modal Analysis has been carried out. Fig. 1 shows the graph for time periods in first 10 modes for buildings of various heights with and without the consideration of underlying soil effects. It should be noted that the first 3 modes of vibration are the most important modes for study as they are the cause for majority of damages. From Fig.1 it can be 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 here using Time History Analysis method.

A. Input Data

Acceleration data (Fig. 1) of a 6.9 Richter scale earthquake (El Centro, California, U.S.A. 1940) has been applied as earthquake ground excitation in z- direction.

Standard earth gravity = 9.8m/s^2

Floor load = 3.0 kN/m^2

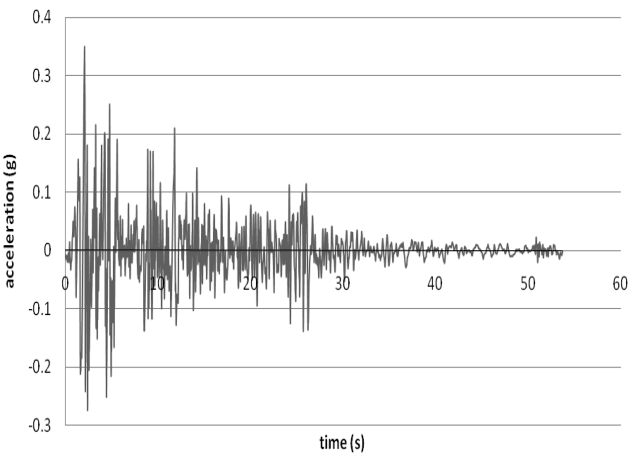

Fig. 2 El Centro Earthquake acceleration record

B. Material Properties

Properties of concrete and the various types of soils used are shown in Tables I and II. Very stiff, stiff and soft soils, corresponding to type 1, type 2 and type 3 respectively, have been used.

TABLE I
PROPERTIES OF CONCRETE USED IN ANALYSIS

Concrete Properties	
Density, kg/m^3	2300
Young's modulus, MPa	30000
Poisson's ratio	0.18
Tensile Ultimate strength, MPa	5
Compressive Ultimate Strength, MPa	41

TABLE II
PROPERTIES OF DIFFERENT SOILS USED IN THE ANALYSIS

Soil Properties	Type 1	Type 2	Type 3
Density, kg/m^3	2100	2050	1700
Young's modulus, MPa	1745	381.1	107.1
Poisson's ratio	0.27	0.40	0.40
Bulk Modulus, MPa	687	136.12	38.25
Shear wave velocity, m/s	586	272	150
Cohesion (c), kPa	40	40	40

C. Model Description

Two models are used, one with fixed base condition and other with flexible base considering soil medium surrounding partially embedded columns. The details of the models are given in Tables III and IV.

TABLE III
SPECIFICATIONS OF BUILDING MODEL FOR CONSIDERATION OF BOTH FIXED BASE CONDITION AND SSI

Structural element	Dimensions
Column	500mm x 500mm
Beam	500mm x 500mm
Slab thickness	200mm
Floor to floor height	3750mm
Plan	8.5m x 8.5m
No. of bays in x-direction	2
Clear span of each bay	3.5m
No. of bays in z-direction	2
Clear span of each bay	3.5m
No. of storey	5
Depth of columns below ground level	2000mm

TABLE IV
ADDITIONAL SOIL SPECIFICATIONS FOR CONSIDERING SSI

Structural Element	Dimension
Soil Depth	6000mm
Plan of the soil considered	18.5m x 18.5m

In ANSYS, SOLID45 is used to represent both the bedrock and the gravel bed, with linear-plastic properties used in the element. SOLID65 element was used to represent the lightly reinforced concrete. The beam-column frame and foundation are modeled using the Finite Element Method (FEM). The calculations are carried out using ANSYS.

III. RESULTS AND DISCUSSION

All the results are calculated for central point, on roof of the five storey building models, in the direction of the applied earthquake excitation. Detailed study has been presented for the deflection and acceleration response of structure. From the texts on "Dynamics of Structures" [8], [9], we know that the deflection, velocity and acceleration responses associatively determine design forces. Hence, changes in these responses indicate underestimation or overestimation in design forces.

A. Deflection

Figs. 3-5 show the variation in deflection response, towards the time dependent base excitation, on account of change in base fixity condition. A smaller value of deflection would mean that the structure is more serviceable in given conditions. Significant changes, of varying degrees, in behavior of structure can be noticed in all the cases.

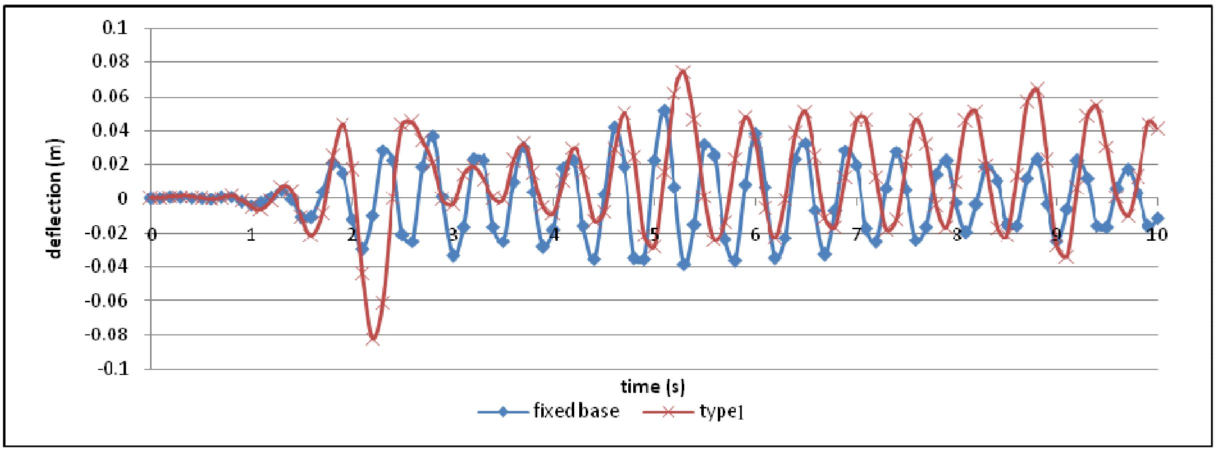

Fig. 3 Displacement variation between fixed base and considering SSI with type 1 soil

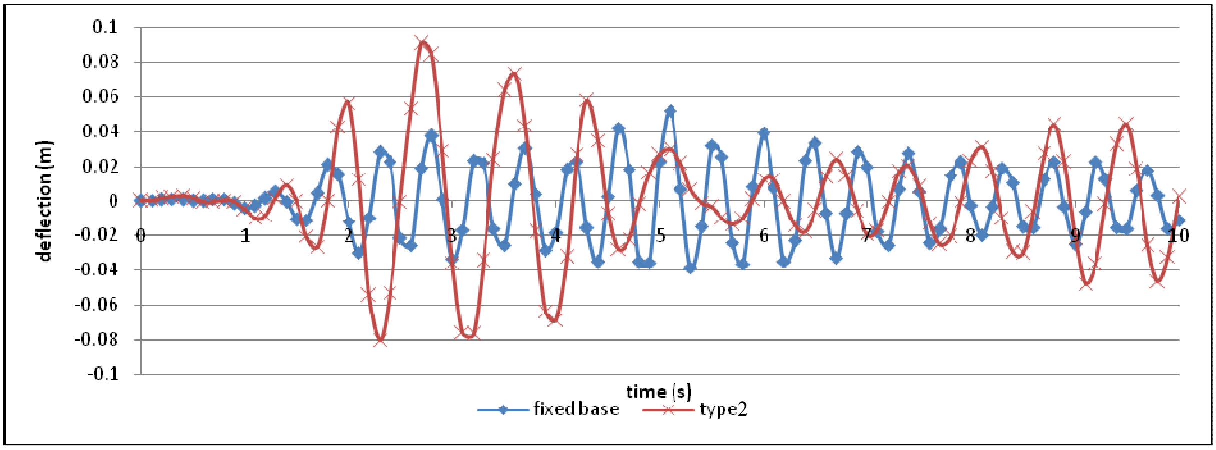

Fig. 4 Displacement variation between fixed base and considering SSI with type 2 soil

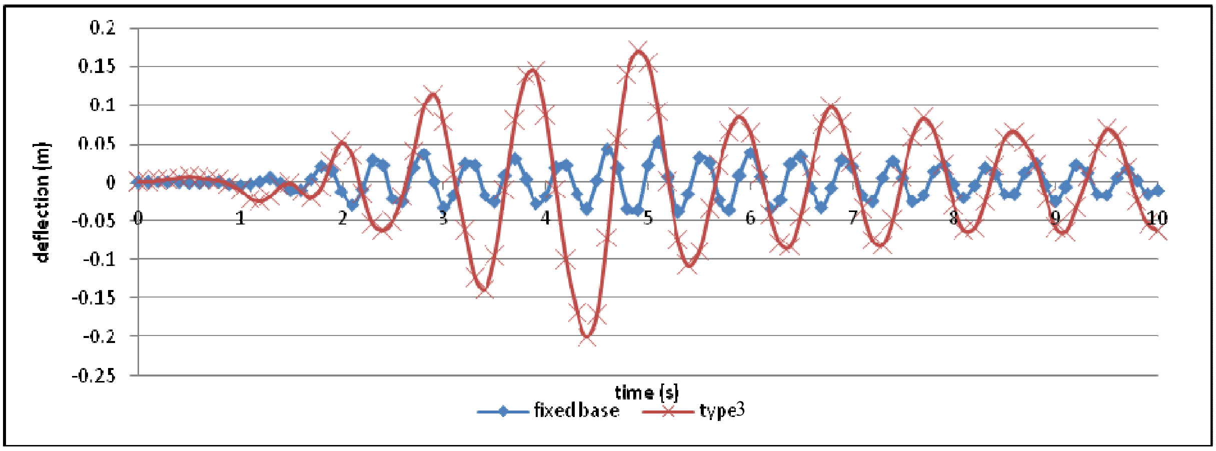

Fig. 5 Displacement variation between fixed base and considering SSI with type 3 soil

TABLE V
SUMMARY OF THE MAXIMUM DEFLECTION OF ROOF FOR DIFFERENT SOILS

Deflection (cm)	Fixed base	Type 1	Type 2	Type 3
In +ve z-direction	5.18	7.44	9.01	16.9
% change		43.6%	73.9%	226.2%
In -ve z-direction	3.84	8.22	8.02	20.0
% change		114.0%	108.8%	420.8%

It can be seen from Table V that as stiffness of the soil increases, the difference in deflection in the buildings considering SSI decreases when compared with fixed-base buildings. As we move from hard to soft soil, the deflection gets increased upto four times. It can be seen that the change in deflection is negligible for hard and medium soils.

B. Acceleration

Figs. 6-8 show the variation in acceleration response, towards the time dependent base excitation, on account of change in base fixity condition.

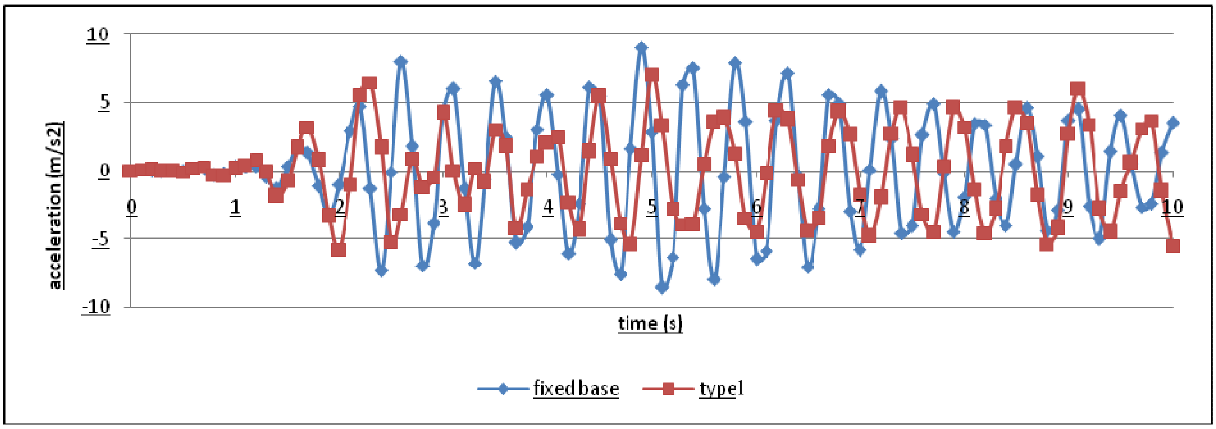

Fig. 6 Acceleration variation between fixed base and considering SSI with type 1 soil

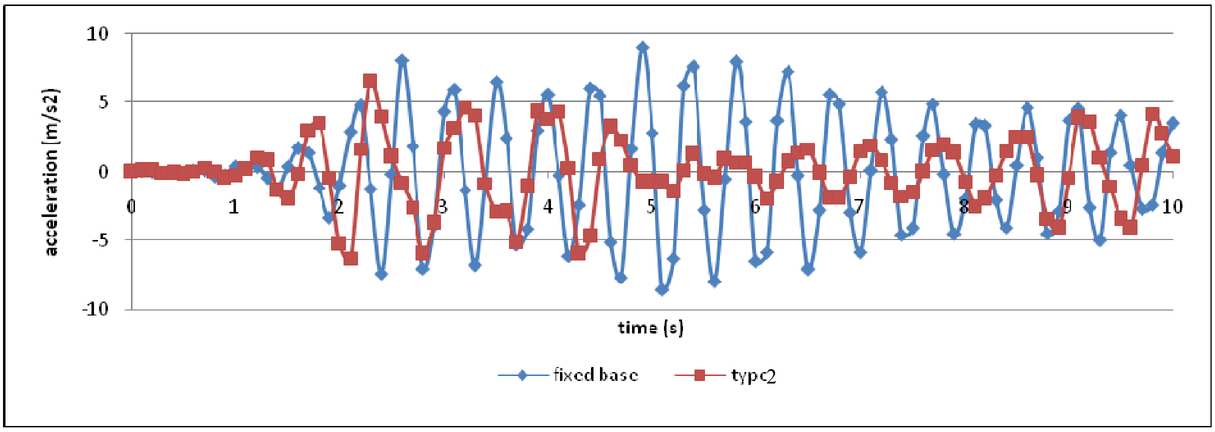

Fig. 7 Acceleration variation between fixed base and considering SSI with type2 soil

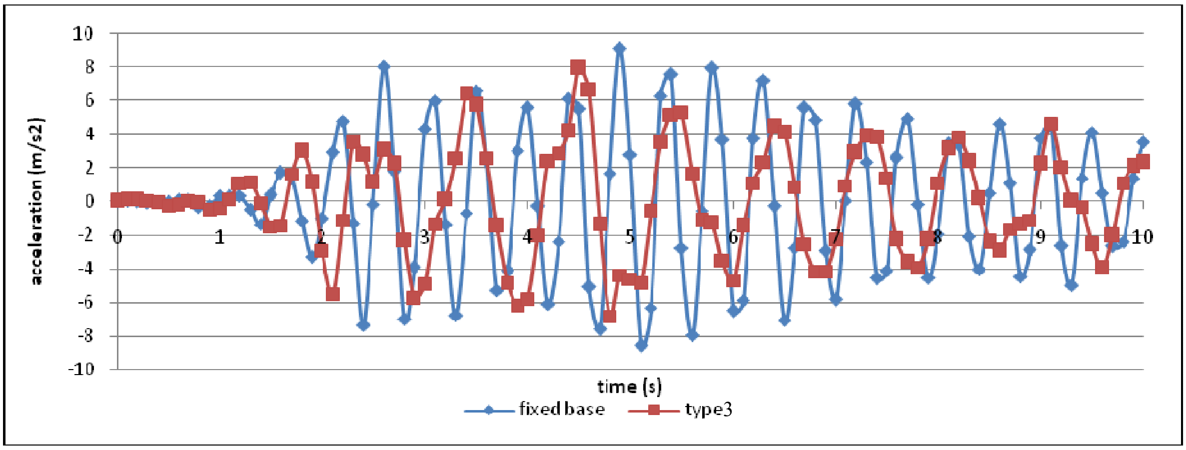

Fig. 8 Acceleration variation between fixed base and considering SSI with type3 soil

TABLE VI
SUMMARY OF THE MAXIMUM ACCELERATION OF THE TOP ROOF FOR DIFFERENT SOILS

Acceleration (m/s^2)	Fixed base	Type 1	Type 2	Type 3
In +ve z-direction	9.04	6.98	6.64	7.94
% change		-22.7%	-26.5%	-12.2%
In -ve z-direction	8.57	5.79	6.28	6.82
% change		-32.4%	-26.7%	-20.4%

From Table VI, it can be said that acceleration response pattern changes drastically as stiffness of base soil decreases. This is important because spectral acceleration in first mode is used for base shear computation. It is seen that for low values of time period, the base shear values decrease with decrease in base fixity whereas for higher values of time period it increase with decrease in base fixity.

C. Time Period

It is clear from Fig. 9 that the variation of fundamental time period of buildings with type1 soil, i.e. stiffer soil is similar to that for the fixed-base condition with a small amount of difference. The difference in time periods for different soils decreases as we move from soft to stiff soils.

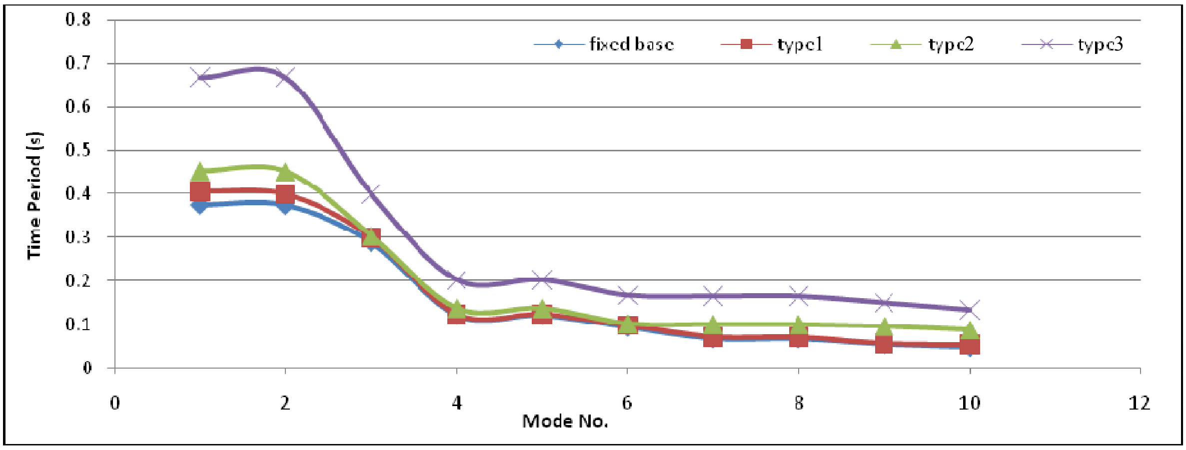

Fig. 9 Variation of Time Period with Mode No. for different soil conditions

IV. CONCLUSION

On the basis of preceding results and discussion, following main conclusions can be made:

1) 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.
2) The spectral acceleration response pattern changes drastically as stiffness of base soil decreases.
3) 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.

Rather than getting into the classical method and working with tedious differential equations, the development in FEM and computer technology has made it possible, these days, to work with elements in the three dimensional space very easy. This revolution in the field of Structural Engineering should be exploited to the fullest to better our knowledge of structural behavior so that safer practices of constructions are adopted. In the field of SSI, there is a need to determine its effect on cluster of buildings, to understand the city-site conditions. Large scale experimental works are required to validate the numerical results. There is also a need to develop more studies with varying soil properties under real site conditions to fully understand the effects of SSI. A code based guidance system must be developed for the professional design community that includes the SSI effects.

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