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Dynamic Soil Structure Interaction in Buildings

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***Abstract*—**Since the evolution of computational tools and simulation software, there has been considerable increase in research on Soil Structure Interaction (SSI) to decrease the computational time and increase accuracy in the results. To aid the designer with a proper understanding of the response of structure in different soil types, the presented paper compares the deformation, shear stress, acceleration and other parameters of multi-storey building for a specific input ground motion using Response-spectrum Analysis (RSA) method. The response of all the models of different heights have been compared in different soil types. Finite Element Simulation software, ANSYS, has been used for all the computational purposes. Overall, higher response is observed with SSI, while it increases with decreasing stiffness of soil.

***Keywords*—**Soil-structure interaction, response-spectrum analysis, finite element method, multi-storey buildings.

I. Introduction

SOIL Structure Interaction (SSI) refers to deviations in the response of structure and soil under the influence of each other. Although papers by Okabe [1] and Mononabe [2] on the effect of soil on retaining walls under seismic loads were published in 1920s, the renaissance of soil structure interaction can be dated back to as early as 1936 when Reissner [3] published his work on the response of stationary, axially symmetric rigid disk on vertically oscillating elastic half-space with smooth, frictionless contact. Since then, the field saw the excellent works of many researchers' get closer to the reality. These efforts got a major boost with the highly cited papers of Luco & Westmann [4], and Veletsos & Wei [5], where they formulated the stiffness expression for circular foundation with more accuracy extended over wider range of frequencies. Until this period most of the studies were performed with surface footing and the results of these studies had ambiguities in case of embedded footing. Widely recognized paper by Kausel et al. [6] explained the soil structure interaction effect as the combined effect of Kinematic Interaction and Inertial Interaction. Since them, SSI has emerged to be a mature field now widely spread into many subfields.

Works done in the recent decade [7]-[10] have shown the importance of structure-soil-structure interaction on dynamic response of key structures such as silos, storage tanks, and offshore structures. However, in current practice the effects of supporting soil are neglected, primarily because of complexities associated in the modelling of soil and assumptions of conservative design on the simplification of the model. Apparently, this perception stems from oversimplifications in the nature of seismic forces adopted in most of the present codes [11]. Even the present Indian code IS 1893:2002 Part-I, which addresses the need of dynamic analysis in buildings, does not provide detailed provisions for including SSI. Mainly two methods have been devised for soil-foundation interaction analysis, namely the direct analysis and substructure method [12]-[18]. Direct analysis includes soil and structure in the same model and analyses it as a whole; whereas the substructure method treats each component separately and then combines them to get the result [19].

This paper presents an extensive study of impact of SSI on short height buildings up to 11 storeys, and with varying soil type using direct analysis approach. Several models ranging from two storeys to 11 storey have been modelled in ANSYS on three different soil types. The response of the structure has been compared under various conditions for seismic excitation of El Centro ground motion data.

II. Problem Formulation

The analysis of the SSI system is carried out by applying base excitations to the surrounding soil. These excitations are carried to the foundation and then transferred to the 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 interaction of force-displacement relationship in the 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 the soil-structure system, and $[S^{\infty}(t)]$ is the displacement unit impulse response matrix in time domain.

A. Model Specification

In present study, two foundation conditions are used; one with fixed base condition and the other with flexible base, considering the soil medium surrounding the partially embedded columns. Linear elastic models of G+2 and G+5 to G+10 buildings are modelled in both conditions. The details of

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the models are given in Tables I and II below. Fig. 1 shows the meshed rendered views of both the G+10 models.

TABLE I
SOIL SPECIFICATIONS FOR CONSIDERING SSI

Structural Element	Dimension
Soil Depth (mm)	12000
Plan of soil considered	30m x 25m

B. Material Properties

Properties of concrete and the various types of soils used are shown in Tables III and IV. Fig. 2 shows the stress-strain behavior of foundation soil.

TABLE II
SPECIFICATIONS OF BUILDING MODEL FOR CONSIDERATION OF BOTH FIXED BAS CONDITION AND SSI

Structural Element	Dimension
Column (mm^2)	400mm x 400mm
Slab Thickness (mm)	120
Floor to floor height (mm)	3200
Plan (m^2)	6m x 5m
No. of bays in one direction	1
Clear span of each bay (m)	6
Number of bays in z-direction	1
Clear span of each bay (m)	5
Depth of column below ground level (mm)	1000

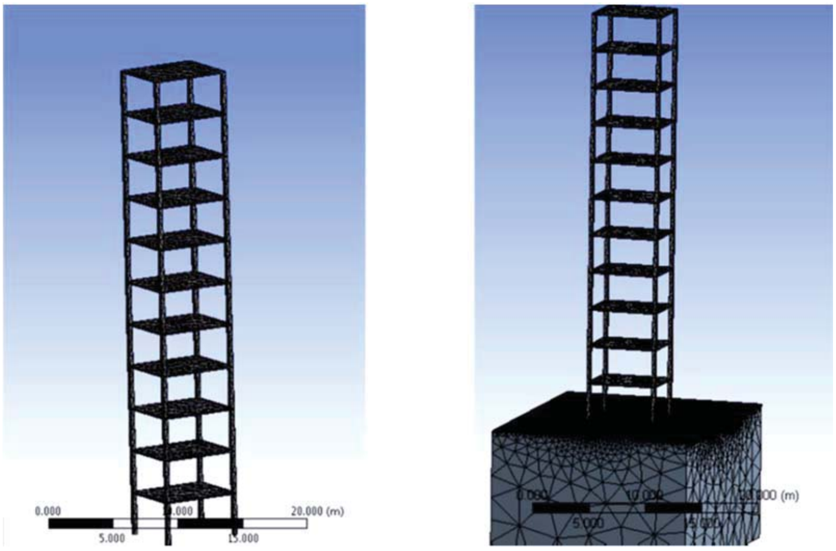

Fig. 1 Fixed base model and model with soil-structure interaction after generating mesh in ANSYS

TABLE III
PROPERTIES OF CONCRETE USED IN THE BUILDING

Properties	Concrete
Density (kg/m^3)	2,300
Young's Modulus (Mpa)	30,000
Poisson's Ratio	0.18
Bulk Modulus (Mpa)	15,625
Shear Modulus (Mpa)	12,711.86
Coefficient of Thermal Expansion	1.4E-05

TABLE IV
PROPERTIES OF DIFFERENT SOIL USED IN THE ANALYSIS

Properties	Soil		
	Hard	Medium	Soft
Density (kg/m^3)	2,100	2,050	1,700
Young's Modulus (Mpa)	948.06	381.1	107.1
Poisson's Ratio	0.27	0.40	0.40
Bulk Modulus (Mpa)	687	635.16	178.5
Shear Modulus (Mpa)	375.25	136.1	38.25
Cohesion	40	40	40

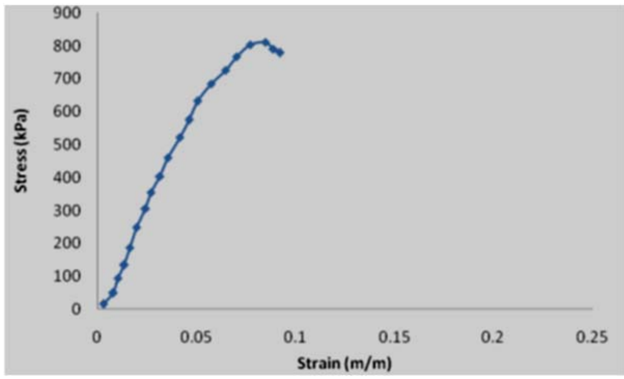

Fig. 2 Stress-Strain curve of foundation soil

C. Earthquake Input Data

The time-acceleration data is converted into frequency-magnitude values using Fast-Fourier Transformation (FFT) in Matlab. Scaled earthquake records of the El Centro earthquake were employed to represent a seismic zone IV hazard. The graphical representation of the time domain and frequency domain data selected are shown in Figs. 3 and 4.

D.Finite Element Model and Meshing

For better convergence of the results, mesh has been refined for soil, building at the interface separately. Mesh size is controlled for three elements as shown in Fig. 5; body mesh for building (A), face mesh for top surface of soil (B) and edge mesh for building-soil contact (C). Fig. 6 shows the converging value of maximum deflection with the increase in the fineness of the mesh for fixed base model. Figs. 7 and 8 show the converging values of maximum deflection in structure and soil, respectively, with increasing fineness of the mesh.

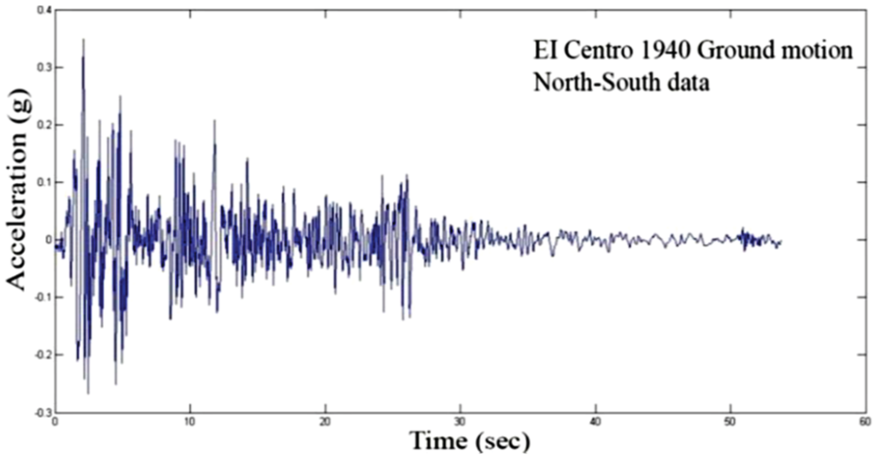

Fig. 3 Time domain data of El Centro earthquake

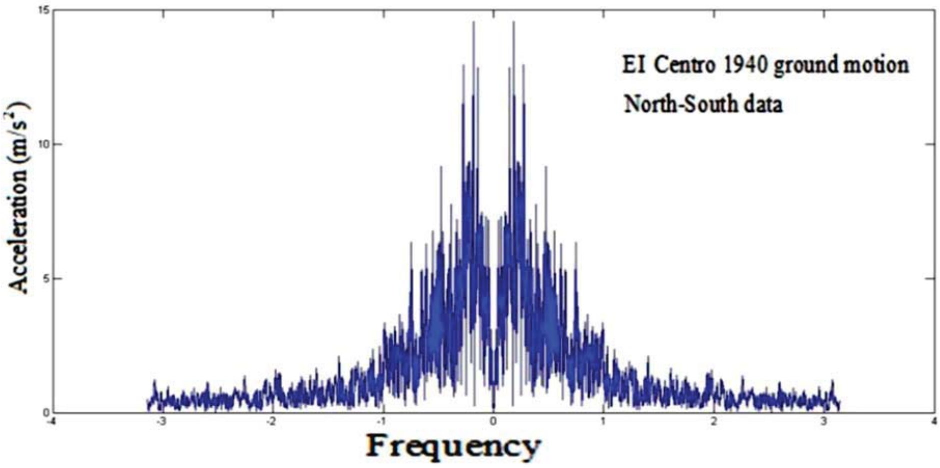

Fig. 4 Frequency domain data of El Centro earthquake

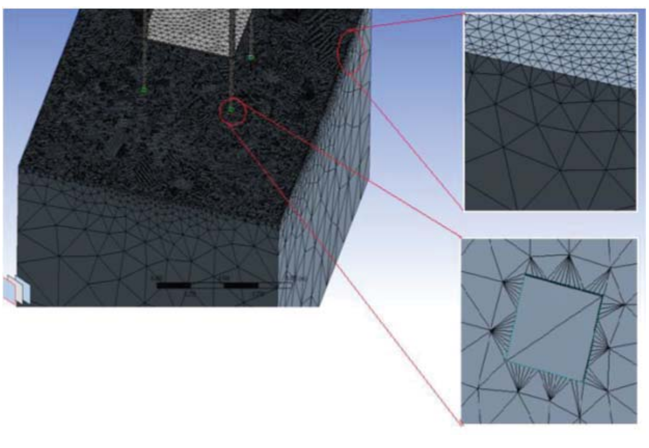

Fig. 5 Mesh size control, (A) Body mesh for building, (B) Edge mesh for soil-building contact and (C) surface mesh for top soil surface

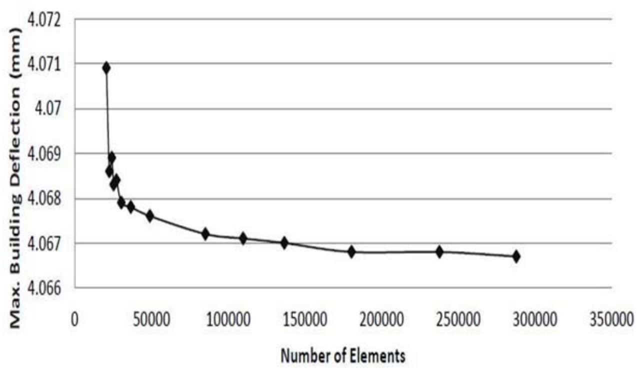

Fig. 6 Mesh convergence for fixed base condition

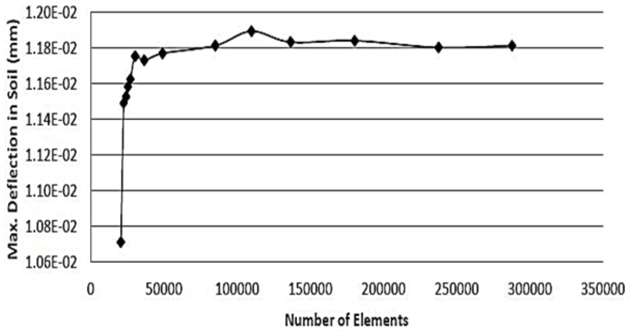

Fig. 7 Mesh convergence for soil in model with SSI consideration

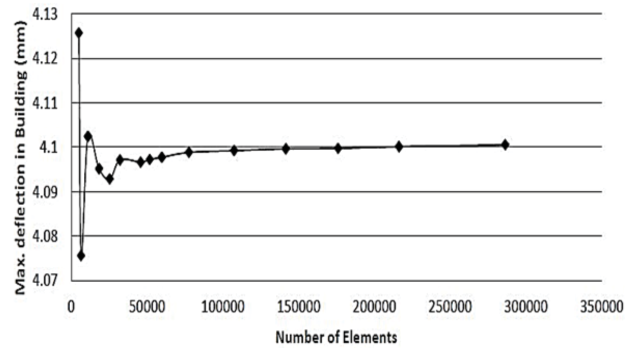

Fig. 8 Mesh convergence for building in model with SSI

E. Modal Analysis

Modal analysis is performed in ANSYS in order to obtain the natural frequencies corresponding to various mode numbers. Results from the modal analysis are then used to perform Response Spectrum Analysis (RSA) for the same structures. Table V contains a summary of the results for all the buildings for fixed based and SSI conditions in varying soil types.

TABLE V
FUNDAMENTAL FREQUENCY FOR DIFFERENT MODELS

Number of Storeys	Fundamental Frequency			
	Fixed Base	Hard Soil	Medium Soil	Soft Soil
G+2	1.44244	1.66066	1.626714	1.53972
G+3	1.58641	1.19554	1.17957	1.13025
G+4	1.34125	0.955922	0.942969	0.904345
G+5	0.907065	0.966546	0.954483	0.914717
G+6	0.799731	0.980697	0.962542	0.903053
G+7	0.781705	0.756147	0.743029	0.698337
G+8	0.792899	0.537081	0.531191	0.511201
G+9	0.670517	0.487481	0.47956	0.459507
G+10	0.330617	0.408806	0.404932	0.39093

III. RESULTS AND DISCUSSIONS

Table VI summarizes the results obtained for the building system from RSA of fixed based models. The results for responses in hard, medium and soft soils are presented Tables VII, VIII and IX, respectively. The corresponding plots for building deformation, stress and strain are shown in Figs. 9 and 10, separately, for comparison in values obtained for the different fixity conditions.

Maximum deformations obtained from RSA for the fixed base model show a growing trend, with critical values of deformation for G+5 and G+6 storey models. From Fig. 9 it is seen that this trend criticality reverses in the case of SSI models. It can be concluded that inclusion of the soil system in the model, as well as a decrease in the rigidity of base leads to higher values of deformation. Further, the difference in the deformation values increases greatly with the increase in the height of the building. The soft soil model has approximately thre3e times more deformation than the fixed base model for the G+10 storey building.

TABLE VI
BUILDING RESPONSES OF FIXED BASE MODEL

No. of Storeys	Max. Deformation (m)	Max. Velocity (m/s)	Max. Acceleration (m/s2)	Max. Shear Stress x 10^7 (Pa)	Max. Elastic Shear Strain (m/m)
G+2	0.06446	0.58607	5.5757	0.44919	0.000353
G+3	0.05345	0.53525	5.6862	0.628806	0.000296
G+4	0.07559	0.64027	5.6976	0.87565	0.000357
G+5	0.20463	1.0439	5.7548	0.8919	0.000702
G+6	0.23831	1.0713	5.2542	1.1467	0.000639
G+7	0.20773	1.0636	5.8858	1.3341	0.000562
G+8	0.19213	0.96546	5.2844	1.6373	0.000596
G+9	0.30443	1.2929	5.9791	1.7769	0.000629
G+10	0.38862	1.4279	5.6868	1.9564	0.000728

TABLE VII
BUILDING RESPONSES OF SSI MODEL IN HARD SOIL

No. of Storeys	Max. Deformation (m)	Max. Velocity (m/s)	Max. Acceleration (m/s2)	Max. Shear Stress x 107 (Pa)	Max. Elastic Shear Strain (m/m)
G+2	0.053296	0.61008	13.465	0.4412	0.000347
G+3	0.097403	0.75115	10.338	0.61637	0.000485
G+4	0.14995	0.91413	7.6577	0.86559	0.000681
G+5	0.14307	0.89129	10.214	1.5873	0.001249
G+6	0.15109	0.94934	8.3518	1.486	0.001225
G+7	0.19105	1.0385	14.483	1.4974	0.001339
G+8	0.4746	1.6571	21.044	1.2123	0.000954
G+9	0.58027	1.796	8.1812	1.3759	0.001082
G+10	0.80704	2.0891	6.3441	2.4312	0.001913

TABLE VIII
BUILDING RESPONSES OF SSI MODEL IN MEDIUM SOIL

No. of Storeys	Max. Deformation (m)	Max. Velocity (m/s)	Max. Acceleration (m/s2)	Max. Shear Stress x 107 (Pa)	Max. Elastic Shear Strain (m/m)
G+2	0.062713	0.66821	9.0075	0.4913	0.000386
G+3	0.10547	0.85646	11.604	0.6597	0.000519
G+4	0.15883	0.96665	8.0347	0.90658	0.000713
G+5	0.154444	0.97783	10.617	1.7183	0.001352
G+6	0.16455	1.0409	10.214	1.6014	0.00126
G+7	0.20825	1.4565	28.579	1.6275	0.00128
G+8	0.49316	1.6796	9.5369	1.224	0.000963
G+9	0.6081	1.9147	16.565	1.4372	0.001131
G+10	0.82851	2.2351	22.956	2.5331	0.001993

From Fig. 10, it is observed that shear stress also shows gradual increase in value with an increase in structure height. The fixed base model follows an almost linear pattern of increase, while the SSI models show a slight fluctuation for the values of the G+8 and G+9 models. Overall, the pattern indicates that shear stress increases with a decrease in soil rigidity and a similar pattern is followed by elastic shear strain. Hence, a building is more susceptible to failure if designed according to the fixed base model. Also, the chance of failure increases as height of structure increases.

TABLE IX
BUILDING RESPONSES OF SSI MODEL IN SOFT SOIL

No. of Storeys	Max. Deformation (m)	Max. Velocity (m/s)	Max. Acceleration (m/s2)	Max. Shear Stress x 107 (Pa)	Max. Elastic Shear Strain (m/m)
G+2	0.10684	1.0902	12.28	0.8479	0.000667
G+3	0.1303	8.6451	0.9645	0.78521	0.000618
G+4	0.19496	20.486	1.0923	1.0717	0.000843
G+5	0.19557	1.1751	10.906	1.9886	0.001564
G+6	0.21691	16.313	1.4543	1.8012	0.001408
G+7	0.2675	23.141	1.6655	2.2513	0.001769
G+8	0.56196	10.091	1.8746	1.3165	0.001035
G+9	0.6975	22.532	2.4483	1.7617	0.001356
G+10	0.90737	8.6801	2.2784	2.5189	0.001982

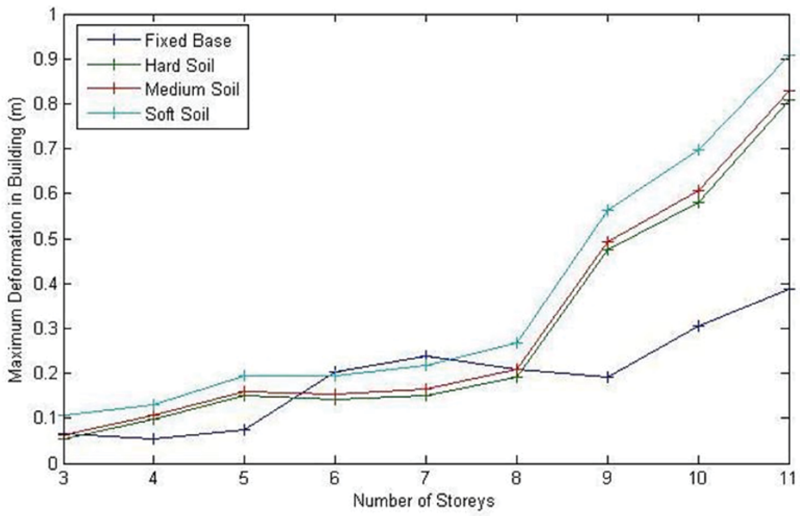

Fig. 9 Variation of maximum deformation of building with increase in height for fixed base and SSI models of three types of soil

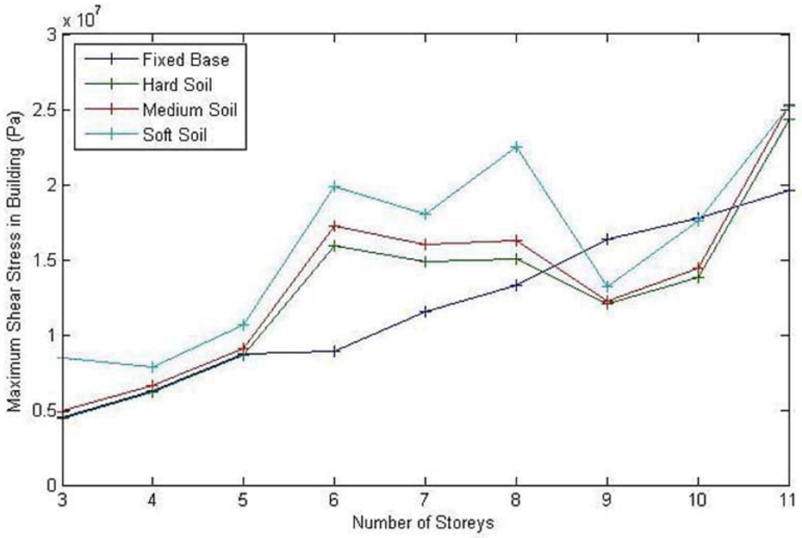

Fig. 10 Variation of Max. Shear Stress in building with increase in height for fixed base and SSI models of three types of soil

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