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Effects of Soil Structure Interaction (SSI) on the design of Reinforced Concrete Buildings

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Abstract — *Normally reinforced concrete buildings are analyzed and designed as fixed or hinged supports which are assigned to columns, ignoring foundation flexibility and its interaction with soil underneath and around it. To investigate the response of buildings under seismic loads the fixed base condition is considered to provide a conservative estimation that's why the SSI analysis is generally ignored. The fixed base assumption adopted by the structural engineers is not always cost effective and conservative, especially in the case of soft soils supporting rigid buildings. The design outputs such as fundamental time period, Inter-story drifts, story lateral displacements and beam & column design is compared for flexible and fix based supports. The fundamental time period, inter-story drift, lateral displacement are not that much substantial but the lateral displacement must be considered for pounding analysis of adjacent buildings. The local differences in flexure reinforcement of columns in fixed base and flexible base is significant.*

Keywords: *Reinforced Concrete Buildings, Fixed support, Hinge support, Foundation flexibility, Soil structure interaction*

I. INTRODUCTION

The numerical modeling i.e. the transformation of physical structure to its equivalent idealized form is one of the important steps in the design cycle. The major objective in the modeling process is that idealized structure should represent the behavior of the physical structure corresponding to all anticipated loads as closely as possible.The absence of implementation of SSI analysis are often mainly ascribed to the misconception of the conservative methodology of using fixed base supports for all kinds of soil conditions. Moreover, the poor understanding of this phenomenon, time-consuming application, and the lack of available technical information support the limited implementation of SSI analysis for building structures.

Soil Structure Interaction effects have been classified as effects of inertial interaction, effects of kinematic interaction, and effects of soil-foundation flexibility. The Inertia developed in a vibrating structure which gives rise to torsion, base shear & moment. These forces create rotations & displacements at the foundation-soil interface. These rotations & displacements are only likely to occur due to flexibility within the foundation-soil system, which considerably adds to overall flexibility of structure (and expands the period of building). Additionally, these displacements produce energy dissipation via radiation damping and hysteretic soil damping, which can considerably influence the total system damping. As these effects are established due to the inertia of structure, they're mentioned as effects of inertial interaction.The effects of Kinematic interaction results from the existence of stiff foundation components on or in soil, which makes vibrations at the footing to differ from vibration in the free-field. One reason for these differences is the base-slab averaging, due to which spatially variable ground motions inside the building envelope are averaged within the foundation footprint because of the stiffness and strength of the foundation system. Other reason for these differences is embedment effects, due to which foundation-level motions are reduced as an effect of ground motion reduction with depth underneath the free surface.Foundation Soil flexibility effects (Axial, shear Flexural deformations of foundation structural components take place because of displacement and forces applied by the soil medium & superstructure) shows the seismic demands for which foundation elements shall be designed and these might be crucial, particularly for foundations like piles and rafts which are flexible.

As this study is concerned with the study of effects of SSI on the design of RC buildings, that's why criteria for FE software selection was to select the software which is normally used in the design offices for the design of multistory RC buildings. A number of commercial software are available for analysis and design of multi-story buildings. Some of the widely used software are SAP 2000, ETABS, STAAD PRO and RISA TEKLA etc. All these software have the capability to design buildings in accordance with specified codes available in the software. However, Finite Element Analysis software ETABS has been selected for the study due to its user friendly interface. According to a recent survey 45% users rely on ETABS/SAP200 for analysis.

Design cycle of a new building starts with estimation of member sizes based on past experience and minimum codal requirements. Column shapes, usually rectangular or circular in shape, are dictated by the architect. The next step is modeling which is an idealization of actual physical structure. Beams and columns are modeled as line elements while slabs and shear walls are normally modeled as shell elements. A shallow foundation with relatively smaller dimensions is idealized as a hinge support while a relatively deep foundation with relatively larger dimensions e.g. continuous and raft footing is idealized as fixed support ignoring interaction of soil with building structure. Infill walls are not modeled ignoring its lateral stiffness contribution to the structure while the load of infill walls is applied on beams and slabs where they support it. Beam-column joints are modeled as rigid joints. Effect of cracking is accounted for by using a reduced moment of inertia. Linear analysis is carried out on this model and engineering judgment is used to interpret the analysis results. Serviceability limit states like slab deflections and maximum drift ratio are checked at this stage for specified load cases. After verification of analysis results, design is carried out in accordance with the specified code and structural members' proportions are checked. If members proportioning is satisfied and conforms to the codal requirements, the design is considered as completed otherwise the design cycle is repeated. After the design is completed, detailing of reinforcement i.e. drafting of structural members, keeping in view the practical constraints like bar size availability etc. is carried out and lap locations are provided in typical details.

Commercially available soft wares like ETABS, SAP2000 and SAFE are used currently for design of reinforced concrete buildings. Building is modeled in ETABS or SAP2000 and structural members like columns, beams and shear walls are designed with the aid of these software's. Raft footings and slabs are exported to SAFE for design, which is specialized software for the design of slabs and footings and has the capability of carrying out finite element-based and strip-based design of slabs and footings.

II. METHODOLOGY

Three dimensional hypothetical buildings frames are designed in accordance with UBC-97 static lateral force procedure for zone 2B. The design of these frames are carried out in commercially available finite element software ETABS with and without flexible base.

The flexible base models includes soil-foundation stiffness modelled as spring elements according to Pais and Kausal (1981) equations. The same frames with fixed supports assigned to columns, are designed in the same way. The design outputs such as fundamental time period, inter-storey drift, base shear and reinforcement in all cases of flexible base models are compared with fixed base frames.

The material properties, geometric properties & modeling techniques are given in following sections below;

2.1. Modeling

Beams and columns are modeled as line elements. (Linear elastic), Slab are modeled as shell elements. (Linear elastic), Beam-column joint are modeled as rigid joints.Soil foundation stiffness are incorporated as spring elements in the case of flexible base models. In case of fixed base models, foundation supports are modeled as fixed supports.

2.2. Material properties

Compressive strength of Concrete, fc'=3,000 psi, Concrete Elastic modulus=3,122ksi, Steel Reinforcing bars yield strength=60,000 ksi, Steel Elastic modulus=29,000 ksi, Soil-foundation stiffness = As per Figure 1Pais and Kausal (1981) equations. (NEHRP-NIST).

Degree of Freedom	Pais and Kausel (1988)	Gazetas (1991); Mylonakis et al. (2006)
Translation along z-axis	$K_{z,sur}=\frac{GB}{1-\nu}\left[3.1\left(\frac{L}{B}\right)^{0.75}+1.6\right]$	$K_{z,sur}=\frac{2GL}{1-\nu}\left[0.73+1.54\left(\frac{B}{L}\right)^{0.75}\right]$
Translation along y-axis	$K_{y,sur}=\frac{GB}{2-\nu}\left[6.8\left(\frac{L}{B}\right)^{0.65}+0.8\left(\frac{L}{B}\right)+1.6\right]$	$K_{y,sur}=\frac{2GL}{2-\nu}\left[2+2.5\left(\frac{B}{L}\right)^{0.85}\right]$
Translation along x-axis	$K_{x,sur}=\frac{GB}{2-\nu}\left[6.8\left(\frac{L}{B}\right)^{0.65}+2.4\right]$	$K_{x,sur}=K_{y,sur}-\frac{0.2}{0.75-\nu}GL\left(1-\frac{B}{L}\right)$
Torsion about z-axis	$K_{zz,sur}=GB^{3}\left[4.25\left(\frac{L}{B}\right)^{2.45}+4.06\right]$	$K_{zz,sur}=GJ_{t}^{0.75}\left[4+11\left(1-\frac{B}{L}\right)^{10}\right]$
Rocking about y-axis	$K_{yy,sur}=\frac{GB^{3}}{1-\nu}\left[3.73\left(\frac{L}{B}\right)^{2.4}+0.27\right]$	$K_{yy,sur}=\frac{G}{1-\nu}(I_{y})^{0.75}\left[3\left(\frac{L}{B}\right)^{0.15}\right]$
Rocking about x-axis	$K_{xx,sur}=\frac{GB^{3}}{1-\nu}\left[3.2\left(\frac{L}{B}\right)+0.8\right]$	$K_{xx,sur}=\frac{G}{1-\nu}(I_{x})^{0.75}\left(\frac{L}{B}\right)^{0.25}\left[2.4+0.5\left(\frac{B}{L}\right)\right]$

Figure 1. Static stiffness equations for rigid foundation on soil surface

2.3. Model Description

Table 1. Model Description

Number of grids	Grid spacing	Number of storeys	Storey height	Slab thickness	Beam dimension	Column dimensions
4	25	3,6,9,12,15	12 ft	As per design	As per design	As per design

Hence, 5 fixed base frame are modelled.In the same manner, flexible base frames are modelled having soil properties, making a total number of 5 flexible base frame models.Therefore, a total of 10 models are developed.

2.4. Evaluation of Static Stiffness for Foundation Spring

The equations proposed by Pais and Kausel (1988) as shown in **Error! Reference source not found.**are used to evaluate the static stiffness of the foundation springs. Evaluation of the Static Stiffness for Foundation Spring included the following:

- Determination of the shear wave velocity for each soil profile.
- Calculation of the combined footing stiffness in the vertical and horizontal directions, as well as the rotational component for stiffness.
- Distribution of springs along the foundation.
- The shear wave velocity for soil are taken as per UBC-97 as shown in Table 2. The respective shear wave velocity of soil profile is shown in Table 3.

Table 2. Soil Profile Types

SOIL PROFILE TYPE	SOIL PROFILE NAME/GENERIC DESCRIPTION	AVERAGE SOIL PROPERTIES FOR TOP 100 FEET (30 480 mm) OF SOIL PROFILE		
		Shear Wave Velocity, $\bar{v}_s$ feet/second (m/s)	Standard Penetration Test, $\bar{N}$ [or $\bar{N}_{CH}$ for cohesionless soil layers] (blows/foot)	Undrained Shear Strength, $\bar{s}_u$ psf (kPa)
S_A	Hard Rock	> 5,000 (1,500)	—	—
S_B	Rock	2,500 to 5,000 (760 to 1,500)		
S_C	Very Dense Soil and Soft Rock	1,200 to 2,500 (360 to 760)	> 50	> 2,000 (100)
S_D	Stiff Soil Profile	600 to 1,200 (180 to 360)	15 to 50	1,000 to 2,000 (50 to 100)
S_E[1]	Soft Soil Profile	< 600 (180)	< 15	< 1,000 (50)
S_F	Soil Requiring Site-specific Evaluation. See Section 1629.3.1.			

[1]Soil Profile Type S_E also includes any soil profile with more than 10 feet (3048 mm) of soft clay defined as a soil with a plasticity index, $PI > 20$, $w_{mc} \geq 40$ percent and $s_u < 500$ psf (24 kPa). The Plasticity Index, PI, and the moisture content, w_{mc}, shall be determined in accordance with approved national standards.

Table 3. Shear wave velocity

Soil Type	**Shear Wave Velocity, V_s (feet/second)**
Soft Soil	443

To incorporate the flexibility of soil in the numerical models, the static foundation stiffness for the springs are calculated (Table 4) using the shear wave velocity (Table 3), poison ratio, ν = 0.3 and raft dimensions having half Length, L & half Breadth, B equal to 40 feet 6 inches.

Table 4. Static Foundation Stiffness

Static Foundation Stiffness, K (kips/ft, kips-ft/rad)	
Degree of Freedom	Soil(Shear Modulus, G = 784599 lb/ft^2)
K_z (vertical)	213354
K_y (horizontal)	171965
K_x (horizontal)	171965
k_{yy} (rotational)	297834298
k_{xx} (rotational)	297834298

2.5. Analysis and Design

Analysis is carried out as per Static lateral force procedure as given in UBC-97 section 1630.2. Linear analysis is carried out for all frames. The output parameters used in design such as time period, maximum inter-storey drift, base shear, and flexure reinforcement in all of the cases of SSI models are compared with the corresponding fix base models.

III. RESULTS

3.1. Fundamental Time Period

The fundamental time periods of vibration for the model with a fixed base, T, is clearly stiffer than the fundamental time periods of vibration for models with flexible base.It is clear from the figure that the fundamental time period of vibration increases with the decrease in soil stiffness

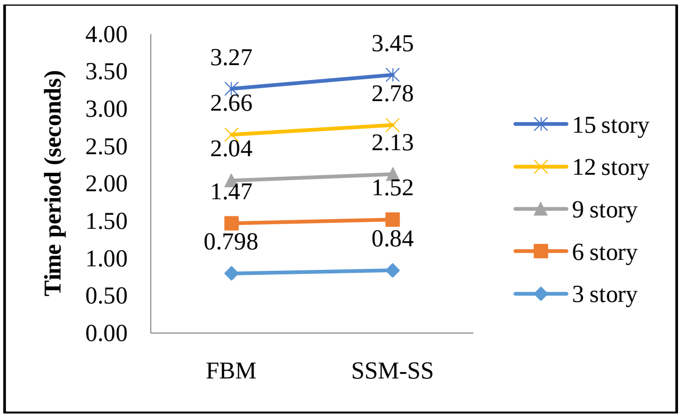

Figure 2. Fundamental Time Period variation with decreasing soil stiffness.

3.2. Maximum Inter-Story Drift Ratio

The inter-story drift ratio increases with the decrease in soil stiffness as shown in figure.

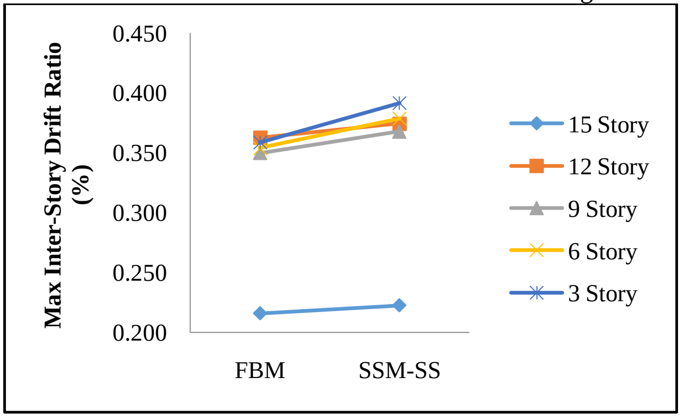

Figure 3. Max. Inter-Story Drift Ratio variation with decreasing soil stiffness

3.3. Total Lateral Displacement

The lateral displacement increases with the decrease in soil stiffnessas shown in figure.

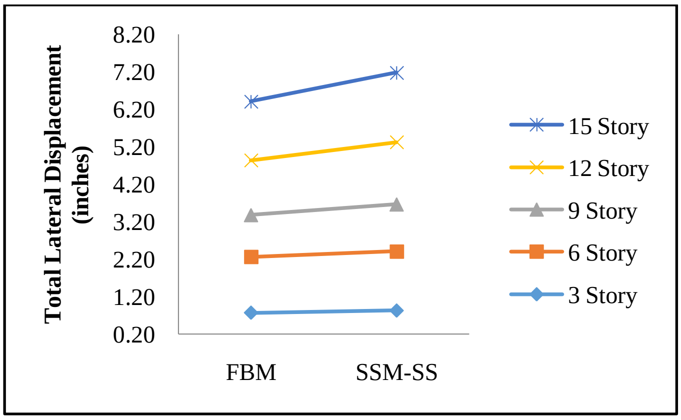

Figure 4. Total Lateral Displacement variation with decreasing soil stiffness

3.4. Column Flexure Reinforcement

Modelling soil flexibility increases the flexural reinforcement of columns. The increase in reinforcement is inversely proportional to the soil stiffness as clear from the figure.

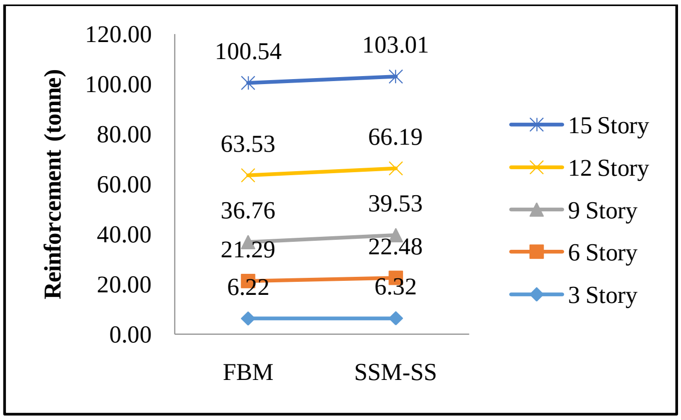

Figure 5. Column Flexure Reinforcement variation with decreasing soil stiffness

IV. CONCLUSIONS

Based on the results obtained from the analysis, the conclusions for this study are:

- The fundamental time period increases with the decrease in soil stiffness because modelling soil springs makes the RC Frames flexible which is quite obvious.
- The maximum inter-story drift ratio increases with the increase in soil flexibility and height of the building which means that SSI must be considered in the high rise building resting on soft soil.
- The reinforcement in columns of flexible model significantly increases for RC frames resting on soft soil. Consequently, ignoring Soil Flexibility in the modelling may lead to unsafe design of columns. Therefore soil flexibility must be considered in the design of buildings at modelling stage.

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