Soil Structure Interaction Effect on Seismic Response of R.C. Frames with Isolated Footing

Dr. S. A. Halkude[1], Mr. M. G. Kalyanshetti[2], Mr. S. H. Kalyani[3]

(Civil Engg. Dept. Walchand Institute of Technology, Solapur, Solapur University, India)

Abstract

The seismic response of a structure is greatly influenced by Soil Structure Interaction (SSI). In this study the effect of soil flexibility on the performance of building frame is investigated. Two SSI modes are considered for the analysis; one is replacing soil by spring of equivalent stiffness (Discrete Support) and second by considering the whole soil mass (Elastic Continuum). Symmetric space frames resting on isolated footing of configurations 2 bay 2 storey (2X2X2), 2 bay 5 storey (2X2X5) and 2 bay 8 storey (2X2X8) are considered with fixed base and flexible base. The spring model is developed by using stiffness equation along all 6 DOF and elastic continuum model is developed by Finite Element Method using SAP-2000. For SSI study three types of soil are considered i.e. Hard, Medium Hard and Soft Soil. The dynamic analysis is carried out using Response Spectrum, given in IS1893-2002. The influence of soil structure interaction on various structural parameters i.e. natural time period, base shear, roof displacement, beam moment and column moment are presented. The study reveals that the SSI significantly affects on the response of the structure. Finite Element Method has proved to be the effective method for consideration of elastic continuum below foundation.

Keywords: *Soil Structure Interaction, Finite Element Method, Isolated Footing, Response Spectrum Analysis, Elastic Continuum, Winkler Method.*

1. Introduction

In the era of rapid urbanization, due to paucity of land one is compelled to construct the structures on available relatively soft soil which otherwise were deemed to be unsuitable in the past. However due to advancements in various ground improvement techniques it is possible to build the structure. However this will call upon the attention of designers to understand the dynamic behavior of such kind of structures considering SSI. Present study attempts to learn the effect of soil flexibility on various response parameters of building frames. The effect of soil flexibility is suggested to be accounted through the consideration of springs of specified stiffness to represent the soil. Many researchers have proposed different methods to evaluate the effect of soil-structure interaction from time to time. Winkler's idealization [10] (1867) represents the soil medium as a system of identical but mutually independent, closely spaced, discrete, linearly elastic springs. George Gazetas [1] (1991) has presented complete set of algebraic formulas and dimensionless charts for readily computing the dynamic stiffness (K) and damping coefficient (c) of foundation harmonically oscillating in a homogenous half space. Shekharchandra Datta [2] (2002) presented possible alternative models for the purpose of soil structure interaction analysis. Bhattacharya et al [3] (2004) concluded that the effect of SSI may cause considerable increase in base shear of low-rise building frames particularly those with isolated footing.

The use of finite element method has attained a sudden spurt to study the complex interactive behavior of structure. It is possible to model many complex conditions with high degree of realism including nonlinear stress-strain behavior, non-homogenous material condition, and change in geometry and so on. B.R. Jayalaxmi et al [4] (2009) studied earthquake response of multistoried RC frame with soil structure interaction effects by modeling structure –foundation-soil system using Finite Element Method. Seismic response of buildings considering SSI exhibit variation based on frequency content of motion and stiffness of soil. Garg and Hora [5] (2012) analyzed the performance of frame-footing-soil system by considering plane frame, infill frame, homogenous soil and layered soil mass. They concluded that shear force and bending moment in superstructure get significantly altered due to differential settlement of soil mass.

Objective of the study: The objective of the present study is to determine the SSI effect on various dynamic properties of R.C. frame such as Natural Time Period, Base shear, Beam Moment, Column moment, etc. Effect of various soil and structural parameters are also studied to identify their effect on seismic performance of building frames. The above study is carried out by two SSI methods i.e. discrete support (using spring) and Elastic Continuum (using FEM). An attempt is also made to understand the effectiveness and utility of these models.

2. Study Methodology

Foundations are considered to be resting on three types of soil namely, Hard Soil, Medium Hard Soil and Soft Soil. These soils have been designated as E-65000 (Hard Soil), E-35000 (Medium Hard Soil) and E-15000 (Soft Soil). The Elastic constant of these soil are considered as per Bowel's [5]. These are shown in Table 1.

Table 1. Soil Elastic Constants

Soil Type	**Designation**	**Modulus of Elasticity (kN/m^2)**	**Poisson's Ratio (μ)**	**Unit Weight (γ) (kN/m^3)**
Hard Soil	E-65000	65000	0.3	18
Medium Hard Soil	E-35000	35000	0.4	16
Soft Soil	E-15000	15000	0.4	16

Symmetric building space frames of 2 bays 2 storey; 2 bay 5 storey and 2 bay 8 storey are considered. The details of building frames, foundation and soil mass considered for the study are given in Table 2.

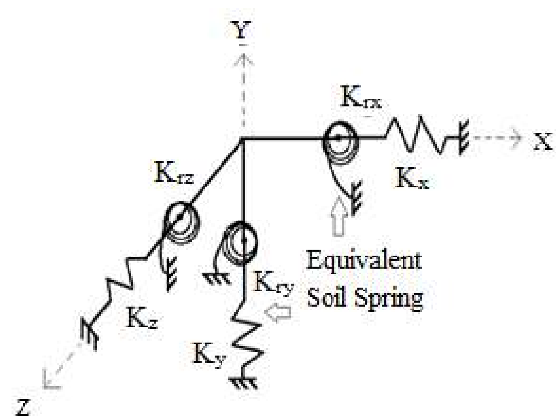
Table 2. Geometric and material properties of frame, footing and soil mass

Component	**Description**	**Data**
Frames	Number of storeys	2,5,8
	Number of bays in X direction	2
	Number of bays in Y direction	2
	Storey Height	3.2m
	Bay width in X direction	5m
	Bay width in Y direction	5m

Component	**Description**	**Data**
Frames	Size of Beam	0.3 m x 0.4 m
	Size of Column	0.3 m x 0.45 m
	Thickness of slab	0.125 m
Foundation	Isolated square footing	2 m x 2 m - 1m depth
	Elastic Modulus of concrete	2.5 x 10^7 kN/m^2
	Poisson's ratio of concrete	0.2
Soil	Block of Soil Mass	32m x 32m - 16m depth
	Modulus Elasticity of soil	65000, 35000, 15000 kN/m^2
	Poisson's ratio of Soil	0.3, 0.4

2.1 Idealization of discrete support

Effect of soil flexibility is incorporated by considering equivalent springs with 6 DOF as shown in Figure1. The stiffness along these 6 degrees of freedom is determined as per Gazetas [1] and is shown in Table3.



K_x, K_y, K_z = Stiffness of equivalent soil springs along the translational DOF along X,Y and Z axis.

K_{rx}, K_{ry}, K_{rz} = Stiffness of equivalent rotational soil springs along the rotational DOF along X,Y and Z axis.

Figure 1. Equivalent soil spring stiffness along 6 degrees of freedom

Table 3. Spring Stiffness Equations

Degrees of freedom	Stiffness of equivalent soil spring
Vertical	$[2GL/(1-v)](0.73+1.54\chi^{0.75})$ with $\chi = A_b/4L^2$
Horizontal (lateral direction)	$[2GL/(2-v)](2+2.50\chi^{0.85})$ with $\chi = A_b/4L^2$
Horizontal (longitudinal direction)	$[2GL/(2-v)](2+2.50\chi^{0.85})-[0.2/(0.75-v)]GL[1-(B/L)]$ with $\chi = A_b/4L^2$
Rocking (about longitudinal)	$[G/(1-v)]I_{bx}^{0.75}(L/B)^{0.25}[2.4+0.5(B/L)]$
Rocking (about lateral)	$[G/(1-v)]I_{by}^{0.75}(L/B)^{0.15}$
Torsion	$3.5G\, I_{bz}^{0.75}(B/L)^{0.4}(I_{bz}/B^4)^{0.2}$

A_b= Area of the foundation considered; B and L= Half-width and half-length of a rectangular foundation, respectively; I_{bx}, I_{by}, and I_{bz} = Moment of inertia of the foundation area with respect to longitudinal, lateral and vertical axes, respectively.

The values of stiffness for three types of soil are calculated as per the equations given in table 3 and are presented in Table 4.

Table 4. Spring Stiffness for Different Soil Type

Stiffness of equivalent soil spring (kN/m)			
Soil Type	E-65000	E-35000	E-15000
Horizontal (longitudinal direction)	132352.9	70312.5	30133.9
Horizontal (lateral direction)	132352.9	70312.5	30133.9
Vertical	162142.9	94583.3	40535.7
Rotation about the longitudinal axis	128512.1	74965.4	32128.0
Rotation about the lateral axis	132943.6	77550.4	33235.9
Rotation about vertical axis	59528.0	29764.0	12756.0

2.2 Idealization of Elastic Continuum

Soil Structure Interaction is also carried out by Finite Element Method (FEM) by considering elastic continuum below foundation. The finite soil mass is considered based on convergence study, with boundary far beyond a region where structural loading has no effect. This is assumed to be at a lateral offset of width of the building on all four sides and depth equal to 1.5 times the width of building. Considering this, soil bock of 32m x 32m in plan and having 16m depth is used for the study. The superstructure-foundation-soil system in three-dimensional form is modeled by FEM.

3. FEM Formulation

3.1 Soil Mass

The soil mass below the foundation is discretized as 8 noded solid elements with 3 DOF at each node. This will help to create the continuity and compatibility in stress and strain in all 3 directions. This will assist in more precise evaluation of stress and strain in soil mass. The soil mass is assumed to be linear, elastic and isotropic with input parameters namely, unit weight of soil (γ), poison's ratio (μ), modulus of elasticity (E) and shear modulus of soil (G).

3.2 Frame Elements

The beams and columns are modeled as frame element with 2 nodes. The element has 6 DOF at each node. Translation in X, Y, Z direction and rotation about X, Y, Z axis. It is a uniaxial element with tension, compression and bending capabilities. The element is defined by two nodes with the input of the cross-sectional area, and the material properties.

3.3 Foundation

The foundation material is discretized as 8-noded brick element. The foundation material is assumed to be elastic and isotropic. The element is defined by eight nodes, thickness, and the material properties

Three dimensional finite element modeling of the whole structure-foundation-soil system is generated using software SAP2000.Two typical models viz. Spring model and FEM model are as shown in the Figure2 and Figure3 respectively.

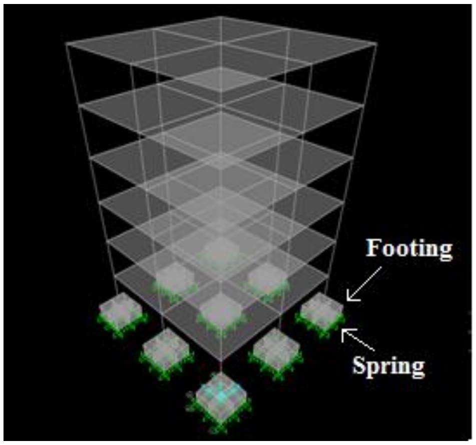


Figure 2. Spring Model (Discrete Support)

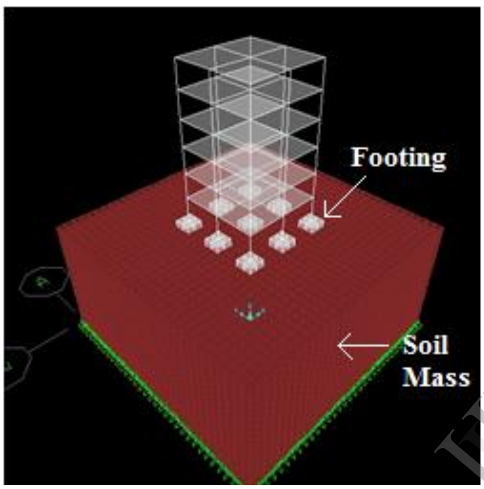


Figure 3. FEM Model (Elastic continuum)

4. Parametric Study

Three symmetric space frames viz. 2X2X2, 2X2X5 and 2X2X8 with isolated footings along with two SSI models viz. Spring Model and FEM Model are considered. The effect of different soil and structural parameters on seismic performance of building is studied considering and without considering SSI. Various parameters are given in Table 5.

Table 5. Formulation of Parametric Variation

Frames	2x2x2, 2x2x5, 2x2x8
Base Conditions	Fixed Base, Flexible Base (E-65000, E-35000, E-15000)
SSI Models	Spring Model, FEM Model

The dynamic analysis is carried out by Response Spectrum Method [8]. Response Spectrum given in IS: 1893-2000 is used for the analysis. The analysis of both the model is carried out by *SAP 2000*. Effects of SSI on different parameters are studied i.e. Natural Time Period, Roof Displacement, Base Shear, Beam bending moment, Column bending moment. These are discussed one by one below.

4.1 Natural Time Period

The variation in Natural Time Period of structure of fixed base and flexible base for both the models are presented in Figure 4, 5 and 6 for 2x2x2, 2x2x5 and 2x2x8 building frames respectively. The combined representation for all the frames for all support conditions are shown in Figure 7.

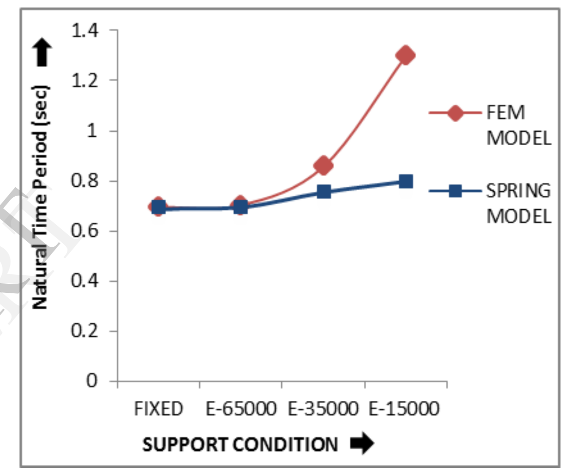


Figure 4. Variation of Natural Time Period for 2X2X2 structure for different support conditions

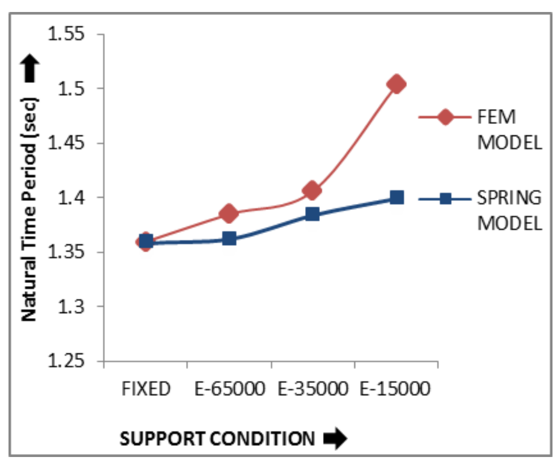


Figure 5. Variation of Natural Time Period for 2X2X5 structure for different support conditions

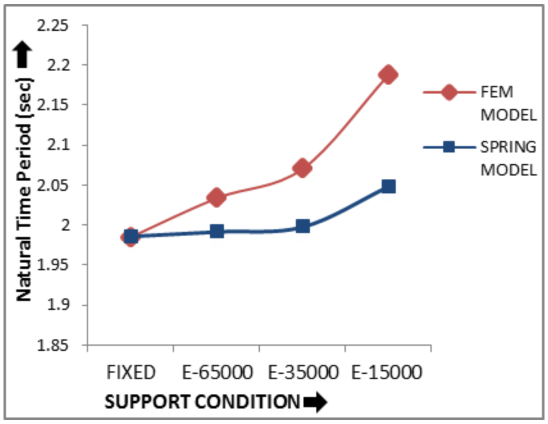


Figure 6. Variation of Natural Time Period for 2X2X8 structure for different support conditions

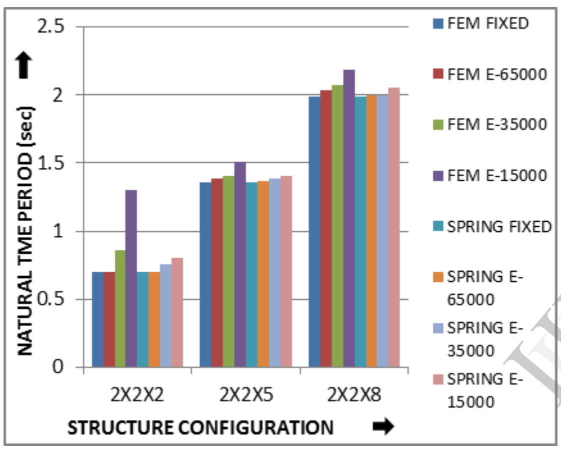


Figure 7. Variation of Natural Time Period for different Building Frames using Spring Model and FEM Model

From Figure 4 to 7 it is observed that with the increase in soil flexibility the Natural Time Period increases nonlinearly. The rate of increase of natural time period becomes steeper with softer soil. FEM model shows higher time period than the spring model. This difference is less for low rise building and goes on increasing with height of building. In case of hard soil the difference is less but for softer soils difference is large which is in the range of 45-55%. FEM model incorporates the flexibility more precisely due to realistic idealization (Elastic continuum) hence the higher time period is observed for softer soil. From above all discussion it can be stated that spring models under estimates the time period for softer soil. Thus for hard soil spring model is suitable and for softer soil FEM model is suitable.

4.2 Roof Displacement

The variations for Roof Displacement are presented in Figure 8, 9, and 10 and collectively for all support conditions and building frames presented in Figure11.

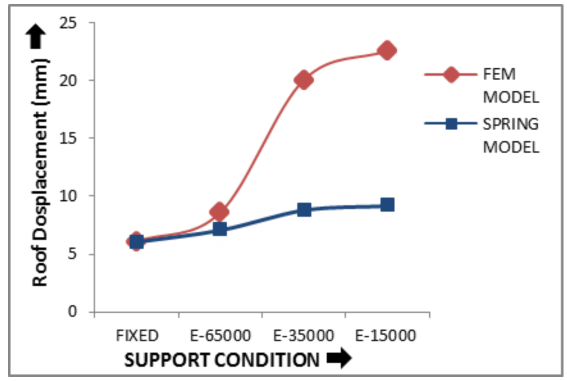


Figure 8. Variation of Roof Displacement for 2X2X2 structure for different support conditions

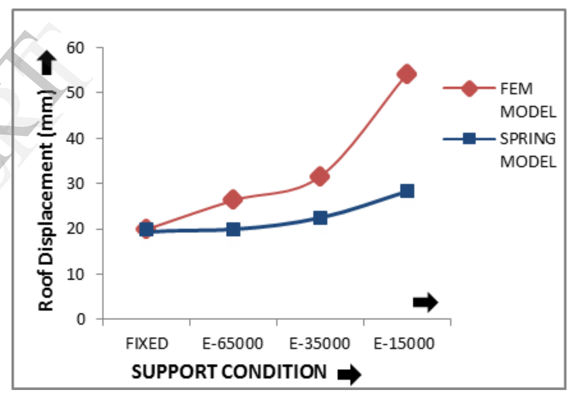


Figure 9. Variation of Roof Displacement for 2X2X5 structure for different support conditions

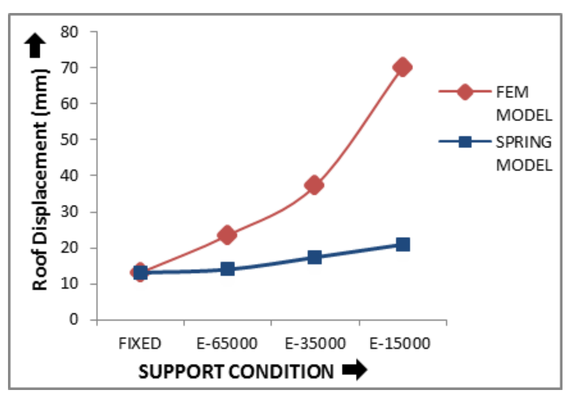


Figure 10. Variation of Roof Displacement for 2X2X8 structure for different support conditions

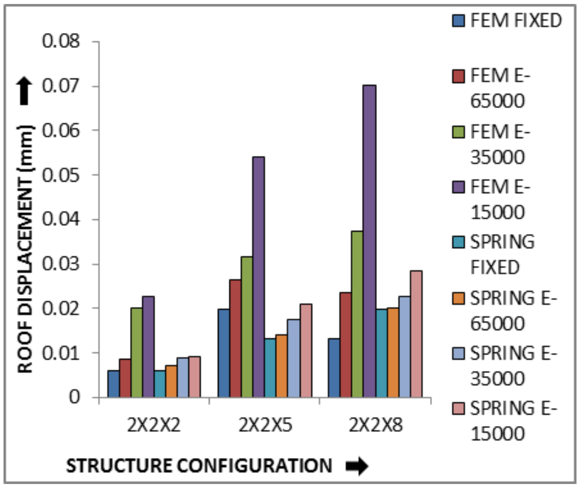


Figure 11. Variation of Roof Displacement for different Building Frames using Spring Model and FEM Model

From Figure 8 to 11, it is observed that the Roof Displacement increases with soil flexibility. In spring model there is 50 to 70% of increment in Roof displacement from fixed base to flexible base (soft soil) whereas in FEM model this is in the range of 200 to 250 %. The spring model doesn't reflect the flexibility with high precision due its idealization of only 6 DOF. However FEM model correctly reflects the flexibility as the complete elastic continuum is used therefore roof displacement increases with higher rate with increase in softness of soil.

4.3 Base Shear

The variations for Base Shear are presented in Figure12, 13, and 14 and are collectively shown for all support conditions and building frames in Figure15.

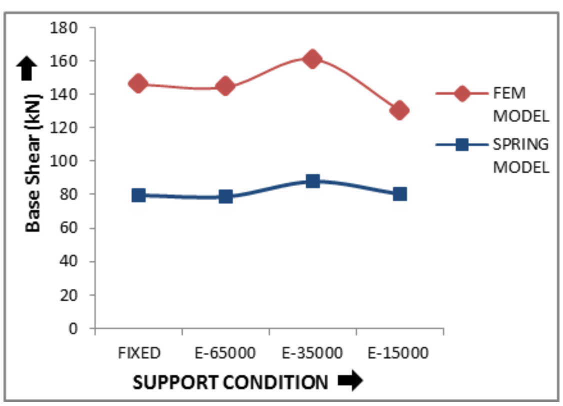


Figure 12. Variation of Base Shear for 2X2X2 structure for different support conditions

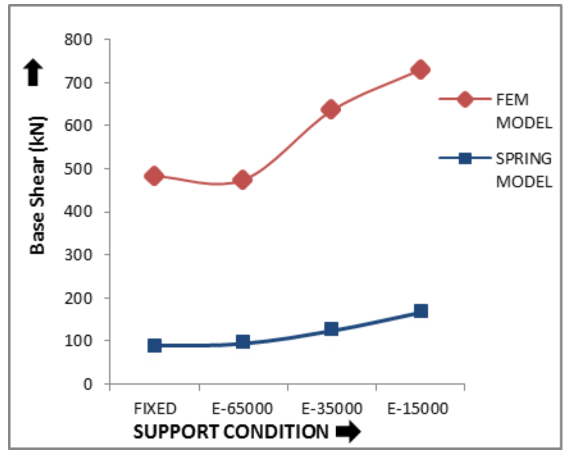


Figure 13. Variation of Base Shear for 2X2X5 structure for different support conditions

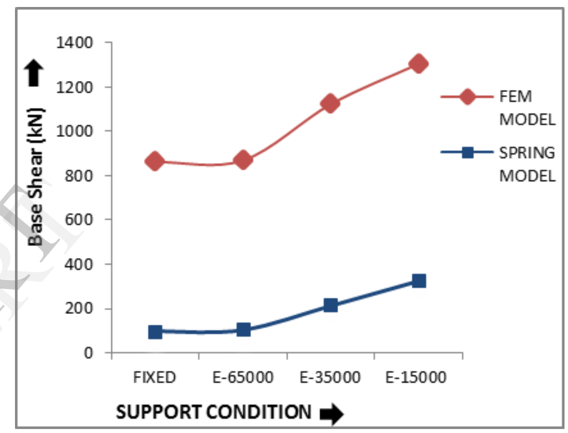


Figure 14. Variation of Base Shear for 2X2X8 structure for different support conditions

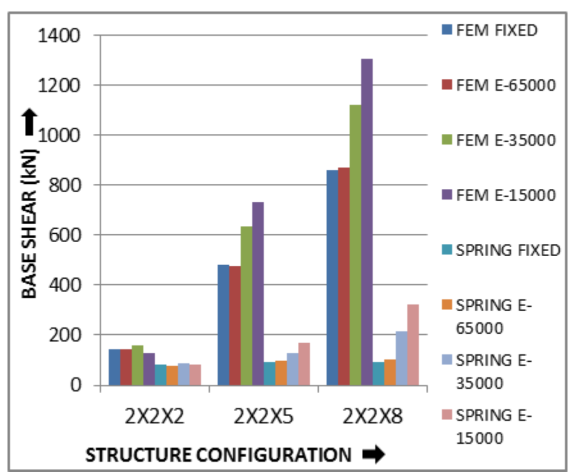


Figure 15. Variation of Base Shear for different Building Frames using Spring Model and FEM Model

From Figure 12 to 15, it is observed that Base Shear increases with increase in base flexibility. For small height of building the variation in base shear with increase in soil flexibility is marginal but it increases with increase in height of building. The increment in Base Shear from fixed base to flexible base (soft soil) is in the range of 20- 40% for spring model and 50 - 70% for FEM model. Base shear in FEM model is 3-5 times than Spring Model.

4.4 Beam Moment

The variations for Beam Moment are presented in Figure16, 17, and 18 and collectively for all support conditions and building frames in Figure19.

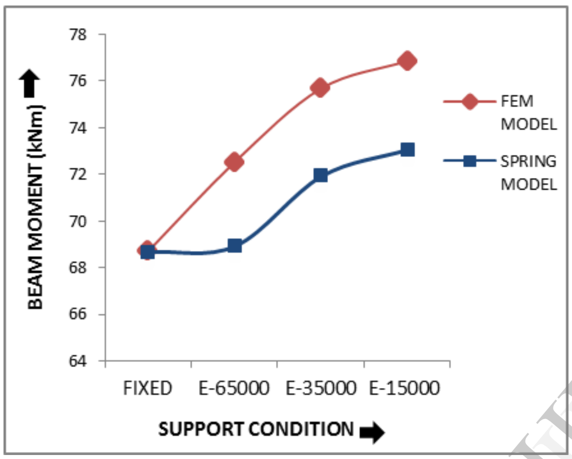


Figure 16. Variation of Beam Moment for 2X2X2 structure for different support conditions

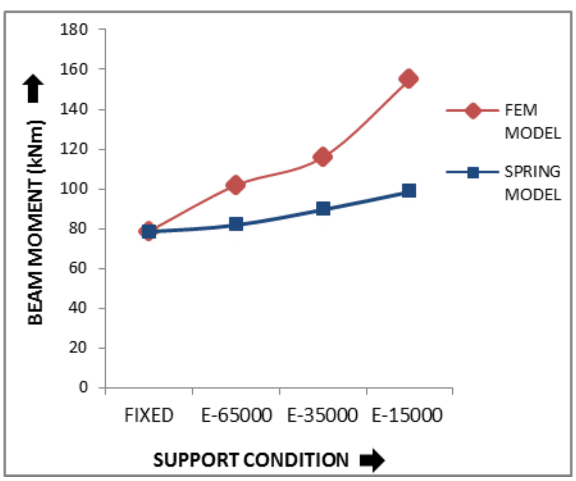


Figure 17. Variation of Beam Moment for 2X2X5 structure for different support conditions

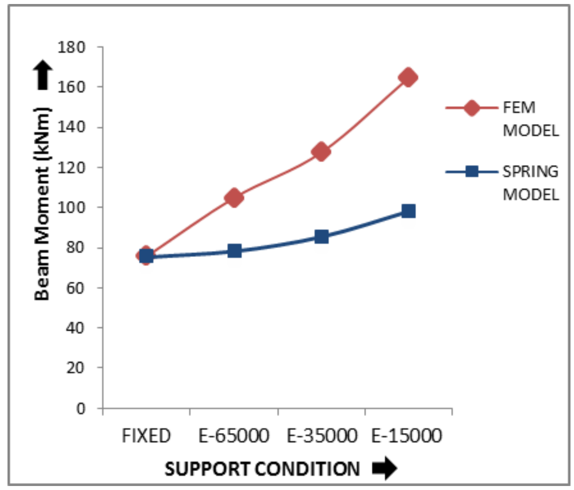


Figure 18. Variation of Beam Moment for 2X2X8 structure for different support conditions

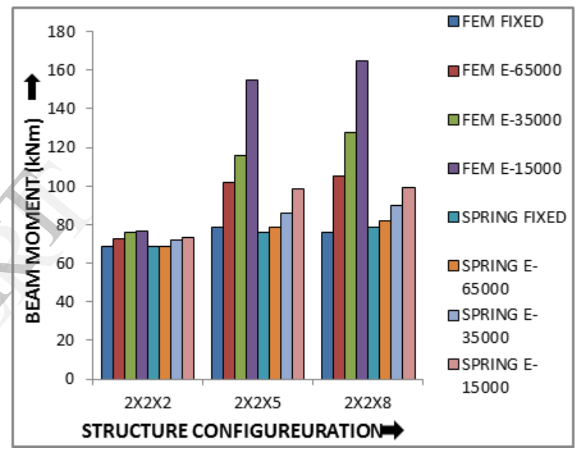


Figure 19. Variation of Beam Moment for different Building Frames using Spring Model and FEM Model

As the soil flexibility increases, Beam Moment increases. There is @ 20% of increment in Beam Moment from fixed base to flexible base (soft soil) for low rise building whereas this increment is in the range of 70-80% in high rise buildings. Beam Moment in FEM Model is about 40-60% more than spring model. Therefore spring model underestimates the bending moment especially for soft soil. The increase in the BM is due to differential settlement of supports due to support flexibility.

4.5 Column Moment

The variations for column moment are presented in Figure 20, 21, and 22 and collectively for all support conditions and building frames in Figure 23.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 1, January - 2014

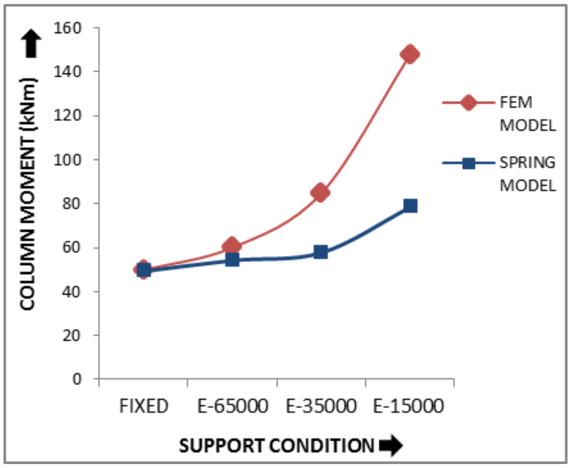


Figure 20. Variation of Column Moment for 2X2X2 structure for different support conditions

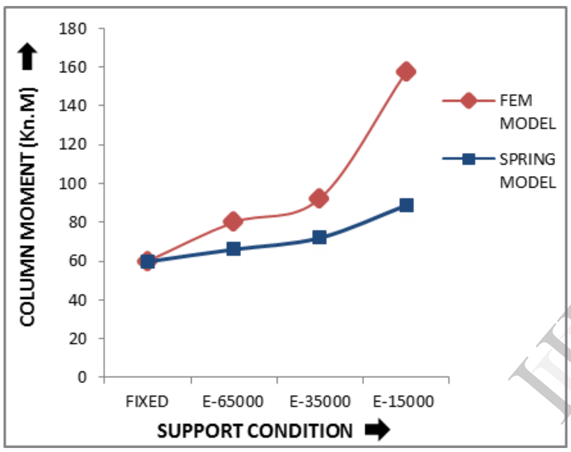


Figure 21. Variation of Column Moment for 2X2X5 structure for different support conditions

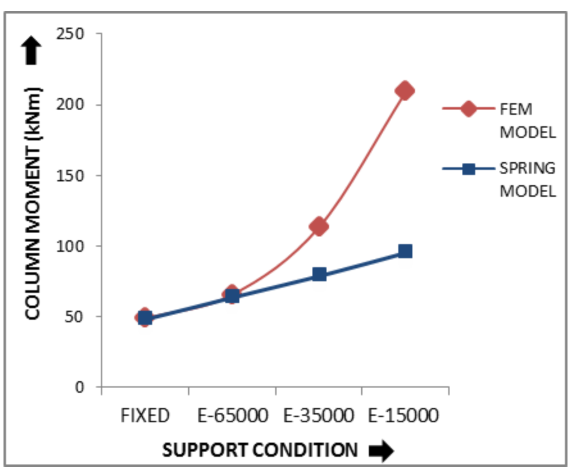


Figure 22. Variation of Column Moment for 2X2X8 structure for different support conditions

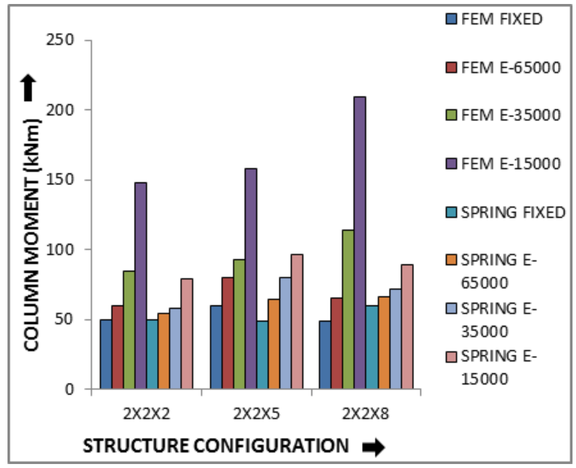


Figure 23. Variation of Column Moment for different Building Frames using Spring Model and FEM Model

From Figure 20 – 23, it is observed that the soil flexibility increases the column moment. From fixed base to flexible base (soft soil) there is about 60-70% of increment in spring model whereas 200 to 250% in FEM model. Column moment in FEM Model is 60-80% higher than Spring Model.

5. Conclusion

1) The natural period of structure increases due to SSI effect. For soft soil the effect is more prominent. Natural time period is a primary parameter which regulates the seismic lateral response of the building frames. Thus evaluation of this parameter without considering SSI may cause serious error in seismic design.
2) Natural period, Roof displacement, Base shear, Beam moment and Column moment are observed to be increasing with increase in soil flexibility. The variations are less for low storey building and goes on increasing with increase in storey height.
3) Idealization of supporting soil by spring is an approximate approach. This doesn't reflect the flexibility with high precision. Thus it yields the less accurate results. However the realistic idealization of supporting soil is possible by FEM. It is possible to incorporate variation in the soil properties, layered soil and boundary conditions etc. This will produce the precise data than spring model. The study also reveals that there is difference in the results of both. The spring model underestimates the values.

4) Difference in spring model and FEM model is less up to medium hard soil. For soft soils this difference is high. Therefore one can employ Spring models for hard soil and FEM models for soft soil
5) Finite Element Method has proved to be a very useful method for studying the effect of SSI. However to reduce the complexity for practical purpose, at least Winkler hypothesis should be employed to consider SSI instead of fixed base.

6. References

[1] George Gazetas, (1991) Member, ASCE, "Formulas and charts for impedances of surface and embedded foundations."

[2] Sekhar Chandra Dutta, Rana Roy, "A critical review on idealization and modeling for interaction among soil-foundation structure system", Computers and Structures 80 (2002), pp.1579_1594

[3] Koushik Bhattacharya, Shekhar Chandra Datta, "Assessing lateral period of building frames incorporating soil flexibility", Journal of sound and vibration, 269 (2004), pp.795-821

[4] B.R. Jayalekshmi, (2007) "Earthquake response of multistoreyedR.C. frames with soil structure interaction effects."

[5] VivekGarg, M.S. Hora, "A review on interaction behaviour of structure-foundation-soilsystem.",International Journal of Engineering Research and Applications,Vol. 2, Issue 6, November-December 2012, pp.639-644

[6] Bowles, J.E.(1998)."Foundation Analysis and design",McGraw Hills, New York.

[7] B.R.Jayalekshmi, Chandrashekhar.A, KattaVenkataramana, R.Shivashankar, Dynamic FE Analysis of multistoreyed frames including soil foundation structure interaction effects, NITK Research Bulletin Vol.16. No.1, June 2007, pp 14 to 18

[8] IS 1893 (Part I): 2002 Criteria for Earthquake Resistant Design of Structures-Generalprovisions and Buildings , Bureau of Indian Standards, New Delhi.

[9] Shiji P.V, Suresh S., Glory Joseph, "Effect of Soil Structure Interaction in Seismic Loads of Framed Structures"; International Journal of Scientific & Engineering Research Volume 4, Issue 5, May-2013 ISSN 2229-5518.

[10] Brown CB, Laurent JM, Tilton JR. Beam-plate system on winkler foundation. JEng Mech Div ASCE 1977;103(4): 589-600.

[11] Hetenyi M. A general solution for the bending of beams on elastic foundations of arbitrary continuity. Journal of Appl Phys 1950; 21:55-8.

Authors Biography

First Author

Dr. S. A. Halkude,

M.Tech. (IIT, Bombay in Civil Engineering), Ph.D. (IIT Bombay). Dean, faculty of Engineering & Technology, Solapur University, Solapur (Maharashtra, India). Recipient of IGS-Dr. B.B. Rai-S. N. Gupta Bi-ennial Prize for the best paper on "Earth and Earth Retaining Structures". Also recipient of Eminent Educationist Award by National & International Compendium, New Delhi (India). Fellow member of The Institution of Engineers (India), Life Member of Indian Society for Technical Education, New Delhi and Life Member of Indian Society for Rock Mechanics and Tunnelling Technology, New Delhi

Second Author

Mr. M. G. Kalyanshetti

B.E. (Civil), M.E. (Civil - Structures). Research Scholar and Assistant Professor, Walchand Institute of technology, Solapur . Pursuing doctoral study at Solapur University. Member of Institution of Engineers (India), Indian Society for Structural Engineer (ISSE).

Third Author

Mr. S. H. Kalyani

B.E. (Civil Engineering), M.E. (Civil - Structures),