SOIL-PILE-STRUCTURE INTERACTION EFFECTS ON HIGH-RISE BUILDING UNDER SEISMIC SHAKING

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ABSTRACT

In this paper, study of the response (base shear, time period, storey drift, storey displacement) of a structure is done for the tall building including basement with fixed base and with pile foundation considering Soil Structure Interaction (SSI). Finite element based program ETABS2016 v16.1.0 is used for the analysis of the superstructure. Seismic analysis is done to get the dynamic response of superstructure for two types of model,one model is with fixed baseand second is Model with Winkler spring for Chhaya Center, Thamel, a high rise building with 14 story including double basements. Itisobserved with the consideration of Soil Structure Interaction (SSI). The soil is replaced by spring and assigned at joints. El Centro earthquake (1940) is used for time history analysis. The response obtained due to SSI effect is compared with fixed based model. Results of analysis presented include the comparison of natural periods, base shears, displacements and overturning moment. It is observed that the natural periods increase and the base shears decrease as the base become more flexible.

1. INTRODUCTION

Structures founded on rock are considered to be fixed base structure. Computation of their response is relatively simple. On the other hand, the same structure would respond differently if supported on soft deposit. First, the inability of the foundation to confirm to the deformations of the free field motion. Second, the dynamic response of the structure itself would induce deformation of the supporting soil. This process, in which the response of the soil influences the motion of the structure and the response of the structure influence the motion of the soil, is referred to as soil structure interaction.

1.1 Types of Analysis

1.1.1 Direct Analysis

Direct Analysis method is the one in which the soil and substructure are modeled together in a single step accounting for both inertial and kinematic interaction. Inertial interaction develops in structure due to own vibrations give rise to base shear and base moment, which in turn cause displacements of the foundation relative to free field. Kinematic interaction develops due to presence of stiff foundation elements on or in soil cause foundation motion to deviate from free field motions.

1.2.2 Substructure Approach

Sub-Structure Method is one in which the analysis is broken down into several steps that

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is the principal of superposition is used to isolate the two primary causes of soil-structure interaction, inability of foundation to match the free field deformation and the effect of dynamic response of structure foundation system on the movement of supporting soil.

1.1 Problem Statement

Conventional structural design methods neglect the SSI effects. Neglecting SSI is reasonable for light structures in relatively stiff soil such as low rise buildings and sample rigid retaining walls. The effect of SSI, however, becomes prominent for heavy structures resting on relatively soft soils for example nuclear power plants, high-rise buildings and elevated-highways on soft soil.

A controversial issue in the seismic analysis and design of high rise building lies in incorporating the effects of the seismic response of these structures. Building codes lack recommendations concerning this controversy; thus, the designers are basing their analysis on approximations, engineering judgment and experience. This has been an active area of research throughout the past decade: (Dutta and Roy, 2002), (Dutta et al., 2004), (Shakib, 2004), (Naim et al., 2008), (El Ganainy and El Naggar, 2009), (Raychowdury 2010), (Tabatabaeifar and Massumi, 2010). The soil-structure interaction (SSI) is a complicated phenomenon for structures coupled with the soil medium, which is generally semi-infinite in extent and non-linear in its material behavior. The problem of SSI in the seismic analysis of high-rise buildings with pile foundation have become increasingly important, as it may be inevitable to build such a structures for the sites with less favorable geotechnical conditions due to ever-increasing difficulty in acquiring new construction sites.

Damage sustained in recent earthquakes, such as the 2015 Gorkha earthquake, 1995 Kobe earthquake, have also highlighted that the seismic behavior of a structure is highly influenced not only by the response of the superstructure, but also by the response of the foundation and the ground as well.

2. LITERATURE REVIEW

Few research has been conducted related to seismic response of high rise building with pile foundation due to soil structure interaction.

Dr. SushmaPulikanthi and Prof. Pradeep Kumar Ramancharla,2013 observed that there is two times increase in the acceleration response of the top floor while considering the SFSI over fixed base analysis for nonlinear case of buildings supported on pile foundation under transient loading.

Kraus & D.dzakic,2013 observed that story drift is increased when the soil is modeled using Winkler springs.

MuberraEserAydemir investigated the seismic behavior of multi storied structures considering SSI according to Turkish Seismic design code and he found that there is increase in natural period of the structure considering SSI corresponding to rigidly supported structure.

3. METHODOLOGY

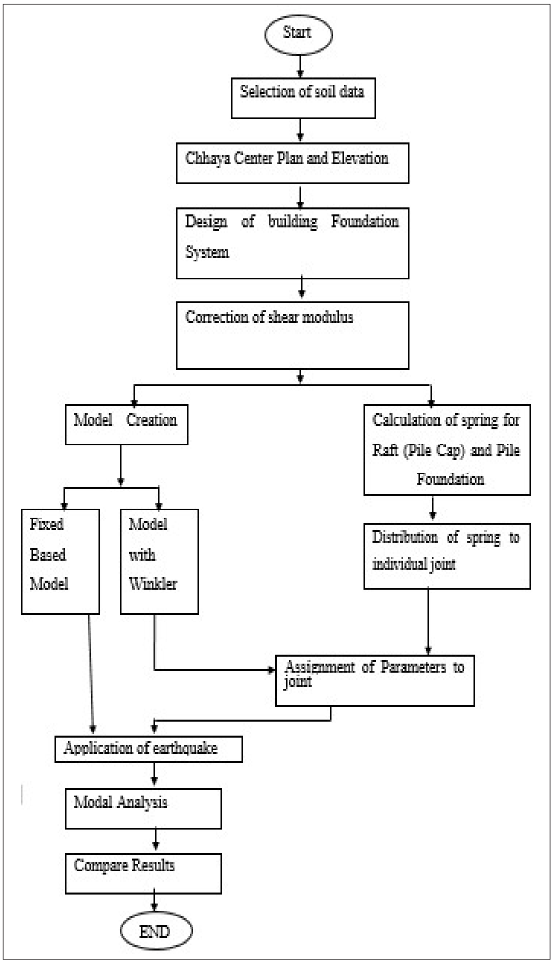


Fig: Flowchart for the methodology

3.1 Method Adopted

- Simplified Approach
- Follows Code ASCE 41-06
- Follows Hien Manh Nghiem, "*Soil Pile Structure Interaction Effects on high rises under seismic shaking*" University of Colorado at Denver and health science, Denver, USA
- The Fixed Support is replaced by one parameter property i.e. Linear Springs

3.2 Steps of SSI Followed

1. Calculation of shear modulus
2. Calculation of spring stiffness
3. Distribution of spring on each joint

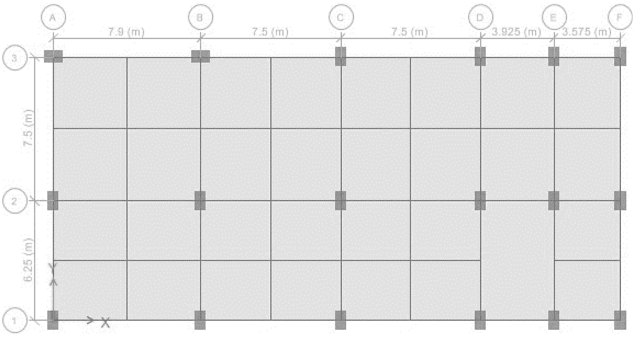


Figure: *Typical Plan of Chhaya Center*

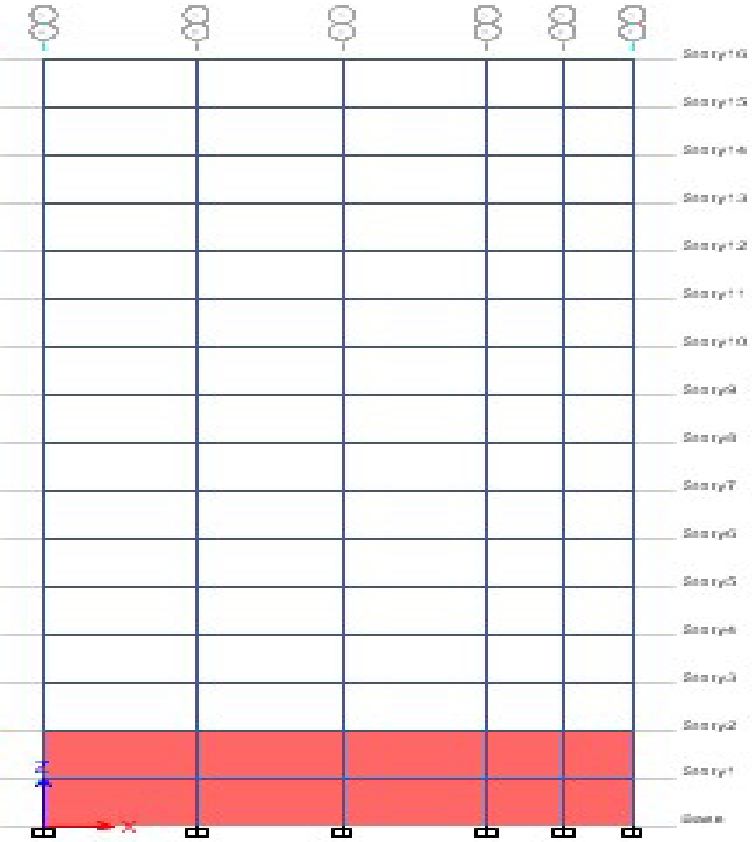


Figure: Typical Elevation of Chhaya Center (16 Story)

3.3 Stiffness for Raft Foundation (Pile Cap), Shear wall and Pile Foundation

Table: Formula for Calculating Spring Stiffness (ASCE, 2010)

Degree of Freedom	Stiffness of Foundation at surface
Translation along x-axis	$K_x,sur = \frac{GB}{2-v}[3.4(\frac{L}{B})^{0.65} + 1.2]$
Translation along y-axis	$K_y,sur=\frac{GB}{2-v}[3.4(\frac{L}{B})^{0.65} + 0.4\frac{L}{B} + 0.8]$
Translation along z-axis	$K_z,sur=\frac{GB}{1-v}[1.55(\frac{L}{B})^{0.75} + 0.8]$
Rocking about x-axis	$K_{xx},sur = \frac{GB^3}{1-v}\left[0.4\left(\frac{L}{B}\right)+0.1\right]$
Rocking about y-axis	$K_{yy}, sur = \frac{GB^3}{1-v}[0.47(\frac{L}{B})^{2.4} + 0.034]$
Rocking about z-axis	$K_{zz}, sur = GB^3[0.53(\frac{L}{B})^{2.45} + 0.51]$

Table: Formula for Calculating Spring Stiffness (ASCE, 2010)

Degree of Freedom	Correction Factor for Embedment
Translation along x-axis	β=(1+0.21$\sqrt{\frac{D}{B}}$)[1+1.6($\frac{hd(B+L)}{BL^2}$)$^{0.4}$]
Translation along y-axis	β_y =(1+0.21$\sqrt{\frac{D}{L}}$)[1+1.6($\frac{hd(B+L)}{BL}$)$^{0.4}$]
Translation along z-axis	β_z =(1+$\frac{1}{21}\frac{D}{B}$(2+2.6$\frac{B}{L}$))[1+0.32($\frac{d(B+L)}{BL}$)$^{\frac{2}{3}}$]
Rocking about x-axis	β_{xx} = 1+2.5$\frac{d}{B}$[1+$\frac{2d}{B}$ ($\frac{d}{D}$)$^{-0.2}$ $\sqrt{\frac{B}{L}}$]
Rocking about y-axis	β_{yy}=1+1.4($\frac{d}{L}$)$^{0.6}$[1.5 + 3.7($\frac{d}{D}$)$^{1.9}$($\frac{d}{D}$)$^{-0.6]}$
Rocking about z-axis	β_{zz} = 1+2.6 $\left(1+\frac{B}{L}\right)$ ($\frac{d}{B}$)$^{0.9}$

3.4 Stiffness for Pile Foundation

Hien Manh Nghiem, "*Soil Pile Structure Interaction Effects on high rises under seismic shaking*" University of Colorado at Denver and health science, Denver, USA

3.4.1 Torsional Stiffness

For constant K_{qz} or G_s:

$$K_{66}^{i} = \frac{L_e(12G_pJ_pk_{\theta z} + k_{\theta}^2L_e^2}{4(3G_pJ_p + k_{\theta z}L_e^2 + 3k_{\theta z}L_e)} + \frac{K_{\theta zb}(3G_pJ_p + k_{\theta z}L_e^2}{(3G_pJ_p + k_{\theta z}L_e^2 + 3k_{\theta zb}L_e)} \quad (3\text{-}1)$$

Where,

L_e is the Length of the pile.

G_p is Pile material shear modulus.

J_p is polar moment of inertia of pile section.

$$= 4\pi^2 G \quad (3\text{-}1a)$$

$$k_{\theta b} = r_o^3 G \quad (3\text{-}1b)$$

3.4.2 Vertical Stiffness

For constant K_{uz} or E_s:

$$K_{33}^{i} = \frac{L_e(12E_pA_pk_{uz} + k_{uz}^2L_e^2}{4(3E_pA_p + k_{uz}L_e^2 + 3k_{uzb}L_e)} + \frac{K_{uzb}(3E_pA_p + k_{uz}L_e^2}{(3E_pA_p + k_{uz}L_e^2 + 3k_{uzb}L_e)} \quad (3\text{-}2)$$

Where,

L_e is the Length of the pile.

E_p is Elastic modulus of pile.

A_p is Area of Pile.

$$k_{uz} = 2\pi r_0 \frac{G}{r_0 \text{ in}\left(\frac{r_m}{r_o}\right)} = 2\pi \frac{G}{\text{In}\left(\frac{r_m}{r_o}\right)} \tag{3-2a}$$

Where,

$$r_m = 2.5\ L\rho(1 - v) \tag{3-2b}$$

$$k_{uzb} = \frac{2DG_S}{1-v} \tag{3-2c}$$

Where,

D is the diameter of the pile.

3.4.3 Lateral Stiffness, Rotation Stiffness and Couple Stiffness

3.4.3.1 Lateral Stiffness

$$k_{11} = \frac{60480EI^2k_{uy}\ L + 1956EIk^2{}_{uy}L^5 + k^3{}_{uy}\ L^9}{4\ (15120EI^2 + 1224EIk_{uy}\ L^4 + k^2{}_{uy}\ L^8)} \tag{3-3}$$

3.4.3.2 Rotation Stiffness

$$k_{55} = \frac{1512000EI^2k_{uy}\ L^3 + 5220EIk^2{}_{uy}L^7 + k^3{}_{uy}\ L^{11}}{300\ (15120EI^2 + 1224EIk_{uy}\ L^4 + k^2{}_{uy}\ L^8)} \tag{3-4}$$

Couple Stiffness

$$k_{15} = \frac{k_{uy}\ L^2 + (k^2{}_{uy}\ L^8 + 302400EI^2 + 3060EIk_{uy}\ L^5)}{40\ (15120EI^2 + 1224EIk_{uy}\ L^4 + k^2{}_{uy}\ L^8)} \tag{3-5}$$

Where,

L_e is the Length of the pile.

E_p is Elastic modulus of pile.

A_p is Area of Pile.

$$I = \frac{1}{4}\pi r^4$$

$$K_{uy} = \frac{0.65\ E_S}{1-{}^{\gamma}S^{2}}\left(\frac{E_S D^4}{EI}\right)^{\frac{1}{12}} \tag{3-5a}$$

Where,

D is the diameter of the pile.

Again,

$$K_{11} = \frac{k_{14}^2 k_{33} - 2k_{13}k_{14}k_{34} + k_{13}^2 k_{44}}{k_{34}^2 - k_{33}k_{44}} + k_{11} \tag{3-5b}$$

$$K_{55} = \frac{k_{24}^2 k_{33} - 2k_{23}k_{24}k_{34} + k_{23}^2 k_{44}}{k_{34}^2 - k_{33}k_{44}} + k_{22} \tag{3-5c}$$

$$K_{15} = \frac{k_{24}^2 (k_{24}k_{33} - k_{23}k_{24}) + k_{13}(k_{23}k_{44} - k_{24}k_{34})}{k_{34}^2 - k_{33}k_{44}} + k_{12} \tag{3-5d}$$

Where,

$$k_{11} = \frac{EI}{L^3}\left(12 + \frac{13}{35}A\right) \tag{3-5e}$$

$$k_{12} = \frac{EI}{L^2}\left(6 + \frac{11}{210}A\right) \tag{3-5f}$$

$$k_{13} = \frac{EI}{L^3}\left(-12 + \frac{9}{70}A\right) \tag{3-5g}$$

$$k_{14} = \frac{EI}{L^2}\left(6 - \frac{13}{420}A\right) \tag{3-5h}$$

$$k_{22} = \frac{EI}{L}\left(4 + \frac{1}{105}A\right) \tag{3-5i}$$

$$k_{23} = \frac{EI}{L^2}\left(-6 + \frac{13}{420}A\right) \tag{3-5j}$$

$$k_{24} = \frac{EI}{L}\left(2 + \frac{1}{140}A\right) \tag{3-5k}$$

$$k_{33} = \frac{EI}{L^3}\left(12 + \frac{13}{35}A\right) + \overline{K}_{11}; \tag{3-5l}$$

$$k_{34} = \frac{EI}{L^2}\left(-6 - \frac{11}{210}A\right) + \overline{K}_{15} \tag{3-5m}$$

$$k_{44} = \frac{EI}{L}\left(4 + \frac{1}{105}A\right) + \overline{K}_{55} \tag{3-5n}$$

And $$A = \frac{k_{uy} L^4}{EI} \tag{3-5o}$$

Where $\overline{K}_{11}$, $\overline{K}_{55}$, and $\overline{K}_{15}$ are equivalent lateral, rotation and couple stiffness of lower pile segments located at the current pile segment.

4. CALCULATION

Details of soil profile in site obtained from lab and insitu test are shown in table 1 which are used in SSI.

Table 1: Details of soil properties

Depth (m)	Thickness (m)	Soil Type		N		Vs(f)	Vs(Cor)	ρ(g/cm³)
0-2	2	Silty clay	18.69	9	14	172.143	261.810	1.35
2-6	4	Silty sand	60.045	31	35	215.593	244.915	1.46
6-9	3	Clay	87.615	29	27	202.092	208.883	1.46
9-10.5	1.5	Sand	101.4	71	65	252.08	251.205	1.46
10.5-13.5	3	Sand	128.97	50	40	223.767	209.978	1.47
13.5-15	1.5	Silty sand	142.755	50	38	220.911	202.102	1.47

Where,

Vs(f)=87.8 [Brandenberg et al. (2010)] (4.3a)

and,

Vs(corr)=Vs(f)* [Brandenberg et al. (2010)] (4.3b)

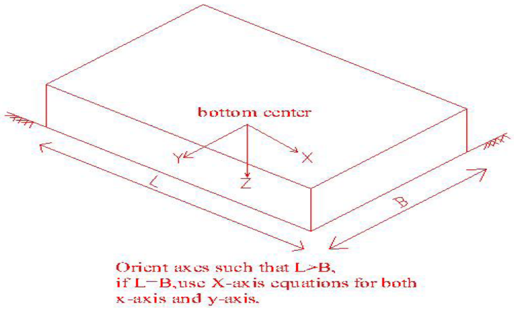
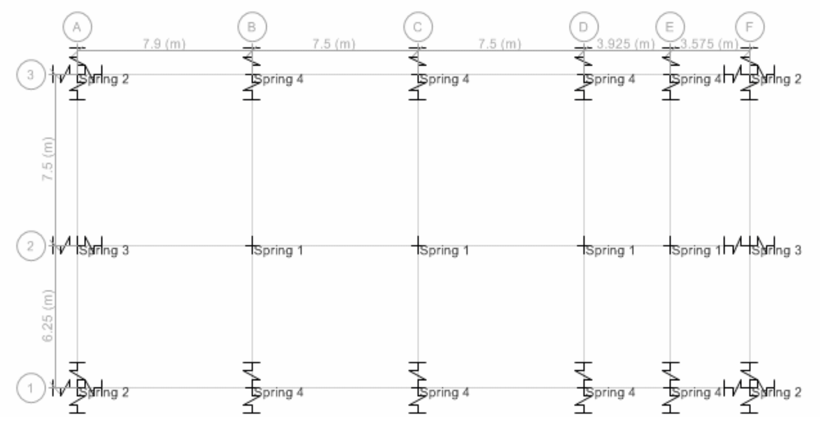


Figure 44: Raft Foundation Plan

Orient axis such that L>B, if L=B use x-axis equations for both x-axis and y-axis.

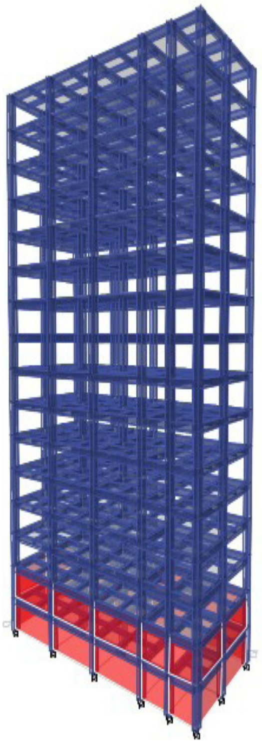


The calculated parameters of damping and springs are individual parameters acting at a defined direction. However, the assignment of the spring and dashpot occur in group.In ETABS, more than two springs cannot be assigned to a single joint. Hence, a group of individual parameter are combined to form a single joint. i.e. joint S1, S2, S3, S4, S5, S6 and S7 are the set of individual spring parameters k1, k2, k3, k4, k5, k6.

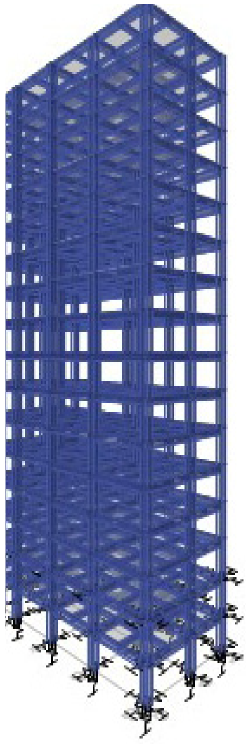
Table: Spring Distribution

Parameter	Spring Type						
	S1	S2	S3	S4	S5	S6	S7
Spring	k3	k1, k2, k3, k4, k5	k1, k3, k4	k2, k3, k5	k1,k4	k2,k5	k1, k2, k4, k5

5. RESULT OBTAINED



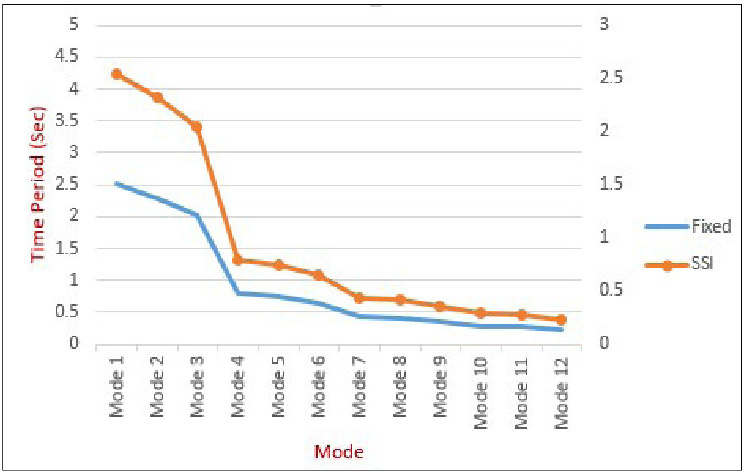
3D model with fixed base



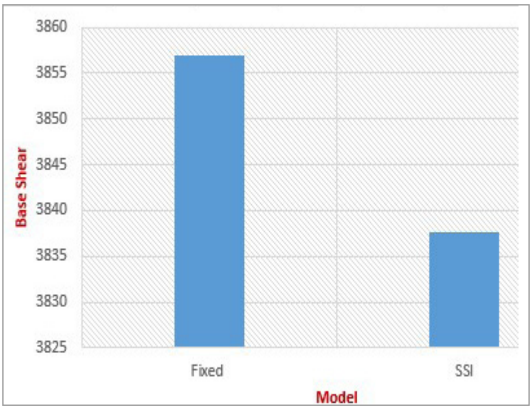
3D model with SSI

5.1 Comparison of Output-Time Period

Mode	Fixed	SSI
Mode 1	2.515	2.54
Mode 2	2.291	2.318
Mode 3	2.028	2.04
Mode 4	0.791	0.795
Mode 5	0.737	0.741
Mode 6	0.645	0.646
Mode 7	0.433	0.435
Mode 8	0.417	0.419
Mode 9	0.356	0.357
Mode 10	0.284	0.286
Mode 11	0.282	0.284
Mode 12	0.233	0.234

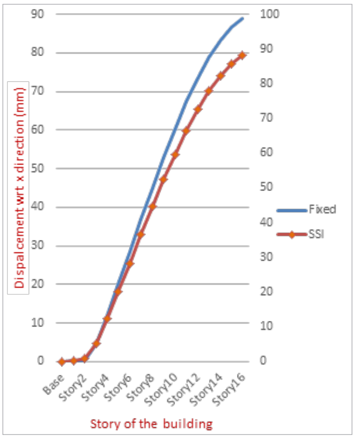


5.2 Comparison of Output-Base Shear



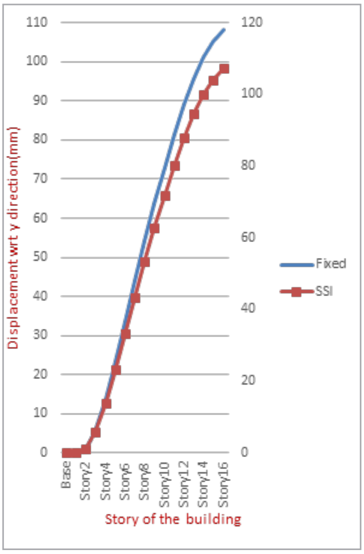
5.3 Comparison of output-Displacement w.r.t. x

Story	Displacement w.r.t. x for fixed case (mm)	Displacement w.r.t. x for SSI case (mm)
Base	0	0
Story1	0.11	0.172
Story2	0.318	0.817
Story3	4.815	5.075
Story4	12.074	12.204
Story5	20.058	20.031
Story6	28.464	28.263
Story7	36.836	36.502
Story8	45.032	44.565
Story9	52.93	52.337
Story10	60.41	59.699
Story11	67.34	66.527
Story12	73.582	72.688
Story13	78.993	78.041
Story14	83.428	82.45
Story15	86.772	85.802
Story16	89.066	88.136



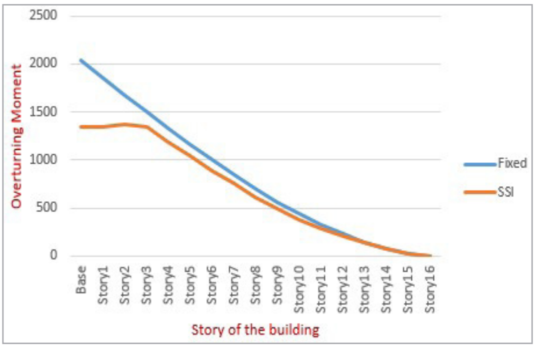
5.4 Comparison of output-Displacement w.r.t. y

Story	Displacement w.r.t. y for fixed case (mm)	Displacement w.r.t. y for SSI case (mm)
Base	0	0
Story1	0.208	0.097
Story2	0.749	0.982
Story3	5.591	5.682
Story4	13.866	13.786
Story5	23.469	23.224
Story6	33.676	33.268
Story7	43.95	43.384
Story8	54.036	53.32
Story9	63.751	62.899
Story10	72.932	71.96
Story11	81.416	80.345
Story12	89.035	87.893
Story13	95.624	94.441
Story14	101.035	99.85
Story15	105.194	104.045
Story16	108.241	107.163

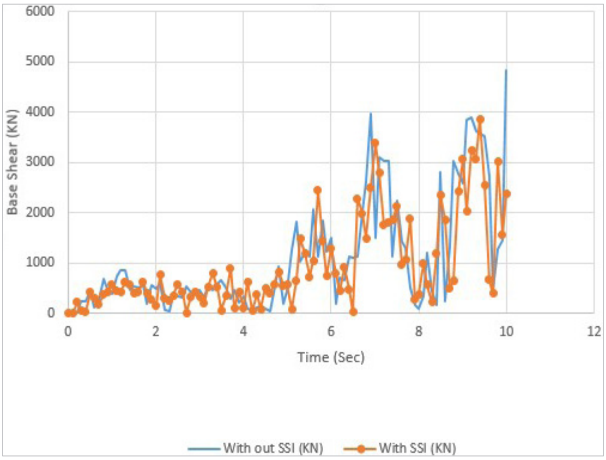


5.5 Comparison of Output-Overturning Moment

Story	Fixed Base (mm)	Winkler approach considering SSI (mm)
Base	2036.112	1342.597
Story1	1853.323	1342.309
Story2	1673.221	1370.336
Story3	1496.792	1344.868
Story4	1325.277	1189.447
Story5	1159.104	1037.755
Story6	998.8839	890.4173
Story7	846.1835	750.0687
Story8	701.8881	618.5974
Story9	565.5118	495.7521
Story10	438.1567	383.1397
Story11	324.4241	286.4841
Story12	228.1264	208.4841
Story13	147.1475	141.9164
Story14	77.8231	79.1684
Story15	24.4523	26.0304
Story16	0	0



5.6 Comparison of Output-Base Shear w.r.t Time History of El Centro Earthquake (1940)



6. CONCLUSION

- The soil structure interaction effects increase the time period of the structure.
- It was observed that the base shear decreases in SSI based Winkler approach model than fixed based model as the base becomes more flexible by the inclusion of SSI effects.
- It was observed that the displacement decreases in SSI based Winkler approach model than fixed based model.

  Overturning moment is decreased in SSI based Winkler approach model than fixed based model.

  Base shear is increased in some time and decreased in rest while analyzing the model with time history of El Centro earthquake between fixed and SSI cases.[2]

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1. *ASCE (2007), Seismic Rehabilitation of Existing Buildings, ASCE/SEI 41-06, American Society of Civil Engineers, Reston, Virginia.*
2. *ASCE(2010), Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10,*

American Society of Civil Engineers, Reston, Virginia.

3. *Bielak, J.(1975), Dynamic behavior of structures with embedded foundations, Earthquake Engineering and Structural Dynamics, Vol. 3, pp. 259-274.*
4. *Clough, R.W., and Penzien, J.(1993), Dynamics of Structures, McGraw Hill, New York.*
5. *Dutta, S. and R. Roy (2002), A Critical Review on Idealization and Modeling forInteraction Among Soil Foundation–Structure System, Computers and Structures, 80, pp. 1579-1594.*
6. *Dutta, S., Bhattacharya, K., and R. Roy (2004), Response of Low-Rise Buildings Under Seismic Ground Excitation Incorporating Soil–Structure Interaction, Soil Dynamics and Earthquake Engineering, 24, pp. 893-914.*
7. *Hayashi, Y. and Takahashi, I. (2004), Soil-Structure Interaction Effects on Building Response in Recent Earthquakes, Third UJNR Workshop on Soil-Structure Interaction,Menlo Park, California, USA.*
8. *HienManh Nghiem (2009), Soil Pile Structure Interaction Effects on high rises under seismic shaking, University of Colorado at Denver and health science, Denver, USA.*
9. *IS 1893 (Part I):2002 (2002),Criteria for earthquake resistant design of structures-generalprovisions and buildings, Bureau of Indian standards, New Delhi,.*
10. *IS: 456, (2000), Plain and reinforced concrete code of practice (fourth revision), Bureau of Indian Standards, New Delhi.*
11. *Kramer, S. L. (1996), Geotechnical earthquake engineering, Prentice Hall, 2007, ISBN 81-317-0718-0.*
12. *Kraus& d. Dzakic (2013), Soil-structure interaction effects on seismic behaviour of reinforced concrete frames, josephJurajStrossmayer university of Osijek, faculty of civil engineering Osijek,Croatia.*
13. *Muberraeseraydemir (2009), Soil-structure interaction effects on multi-storey r/c structures, international journal of electronics; mechanical and mechatronics engineering vol.2 num.3 pp.(298- 303).*
14. *Naim F., S. Tileyliouglu, A. Alimoradi, and J. Stewart (2008), Impact of Foundation Modeling on the Accuracy of Response History Analysis of a Tall Building,SMIP08 Seminar Proceedings.*
15. *Raychowdhury P. (2010), Seismic Response of Low-Rise Steel Moment-Resisting Frame (SMRF) Buildings Incorporating Nonlinear Soil–Structure Interaction (SSI), Soil Dynamics and Earthquake Engineering, 33, pp. 958-967.*
16. *S.Hamidrezatabaiefar, behzadfatahia and bijansamali (2012) , Lateral seismic response of building frames considering dunamic soil-structure interaction effects, structural engineering and machanics, vol. 45, no. 3 311-321.*
17. *SushmaPulikanti (2013), Effect of Soil-Foundation-Stucture interaction on seismic behavior of pile supported frame building, International Institute of Information Technology, Hyderabad.*
18. *Stewart, J.P., Kim, S., Bielak, J., Dobry, R., and Power, M. (2003), Revisions to soil structure interaction procedures in NEHRP design provisions,EarthquakeSpectra, Vol. 19, No. 3, pp. 677-696.*
18. *Tabatabaiefar R. and A. Massumi (2010),A Simplified Method to Determine Seismic Responses of Reinforced Concrete Moment Resisting Building Frames Under 20.Influence of Soil–Structure Interaction,Soil Dynamics andEarthquake Engineering, 30, pp. 1259-1267.*

21. *Tokimasu, K., Oh-oka, H., Satake, K., Shamoto, Y. and Asaka, Y. (1998), Effects of Lateral Ground Movements on Failure Patterns of Piles, in the 1995 Hyogoken- Nanbu Earthquake. Proc. 3rd Conf. Geotechnical Earthquake Engineering and Soil Dynamics, ASCE, Seattle, pp. 1175-1186.*
22. *Vaibhav Singh and Kanchan Mala (2016), Effect on Seismic Response of Building with Underground Storey Considering Soil Structure Interaction, International Journal of Engineering Research & Technology.*
23. *Wolf, J.P. (1985), Dynamic Soil-Structure Interaction, Prentice-Hall, Upper Saddle River, New Jersey.*
24. *Wong, H.L., and Luco, J.E. (1985), Dynamic interaction between rigid foundations in a layered half space, Earthquake Engineering and Structural Dynamics, Vol. 5, No.3, pp.149-1*