16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 563

Registration Code: S-V1464645111

EFFECT OF FOUNDATION SOIL STIFFNESS ON DYNAMIC BEHAVIOR OF RC FRAME BUILDING

Ajoy Paul[(1)], Mohammad Jahangir Alam[(2)]

[(1)] Post Graduate, Department of Civil Engineering, Bangladesh University of Engineering & Technology, ajoy050472@gmail.com
[(2)] Professor, Department of Civil Engineering, Bangladesh University of Engineering & Technology, mjahangiralam@ce.buet.ac.bd

Abstract

This study was to investigate the effect of foundation soil stiffness on dynamic behavior of a 5-story (low-rise), a 10-story (medium-rise) and a 20-story (high-rise) Reinforced Concrete (RC) frame building. Each building was supported on soft clay, stiff clay and very stiff clay with shear wave velocity of 100 m/s, 300 m/s and 600 m/s respectively. From this study it was found that there was no significant variation of natural period due to variation of stiffness of foundation soil. However, past research works showed that there is significant variation of natural period in similar cases. This is because of using same foundation sizes for different types of soil. Lateral deflection and base shear decreased with the increase of stiffness of foundation soil. Drift ratio and percent base shear decreases with the increase of number of story for same soil condition. The most important conclusion is that there is no significant variation of lateral deflection and base shear for same building and soil condition if soil structure interaction is considered. This means that if response spectrum for different soil types given in BNBC (2014) is used and foundation design is done properly, reasonably accurate result of analysis can be found without considering soil-structure interaction.

Keywords: Soil stiffness; Response spectrum; Shear wave velocity

1. Introduction

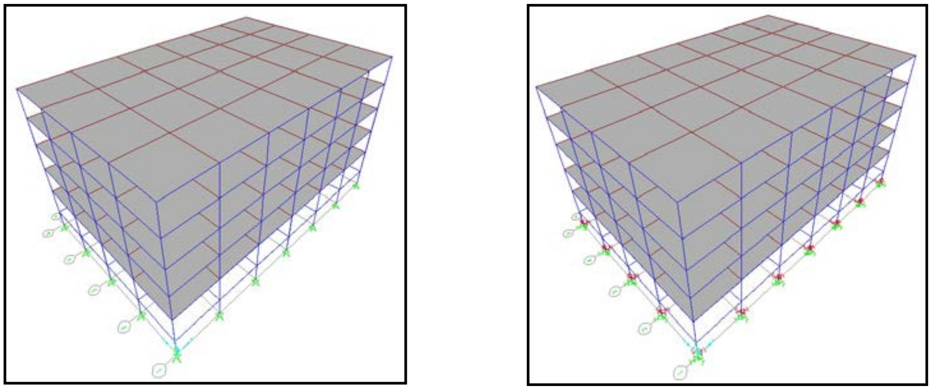
The effect of soil on the response of structure depends on the properties of soil, structure and the nature of the excitation. The process, in which the response of the soil influences the motion of the structure and vice versa, is referred to as soil-structure interaction [1]. Implementing soil-structure interaction effects enables the designer to assess the inertial forces and real displacements of the soil-foundation-structure system precisely under the influence of free field motion.

During an earthquake event, the structure interacts with the foundation soil causing it to deform. The soil deformations, in turn, cause the motion of the supports or the interface region of the soil and the structure to be different than that of the free field ground motion [2]. Such ongoing interactions cause a substantial change in the response of both the structure and the soil. For very stiff soils or when the stiffness of the foundation soil is relatively high compared to the stiffness of the structure, this change is extremely small and can be neglected. Therefore, consideration of base fixity remains a valid assumption for the superstructure constructed on firm soil. On the other hand, in the case of medium firm to loose soils, it is known that flexibility of foundation is usually accompanied with lengthening of the fundamental period of the soil-structure system and an increase in damping. Using typical code spectra, it is usual to assume that this may always lead to a reduction in the spectral acceleration and consequently, lower seismic demands for the superstructure. Hence, fixed based models are assumed to be too conservative [3].

The possible severities of neglecting the effects of SSI are fore grounded in previous research works by Roy and Dutta [4] and Mylonakis et al [5]. According to available literature, generally when the shear wave velocity of the supporting soil is less than 600 m/s, the effects of soil-structure interaction on the seismic response of structural systems, particularly for moment resisting building frames, are significant (Veletsos and Meek [6]). These effects can be summarized as: (i) increase in the natural period and damping of the system, (ii) increase in the lateral displacements of the structure, and (iii) change in the base shear depending on the frequency content of the input motion and dynamic characteristics of the soil and the structure. If a structural design is performed with reference to design acceleration response spectra, the effect of an increasing in fundamental period and damping leads invariably to a reduction of the design base shear. For this reason, neglecting SSI effects is currently being suggested in many seismic codes e.g. ATC-40 (1996) [7], NEHRP (2012) [8] as a conservative simplification that supposedly leads to improve safety margins, at least for ordinary structures.

2. Idealization of the Structure

To study the dynamic behavior while considering the effect of soil-structure interaction, building frames of 5, 10 and 20 stories namely Structure A, Structure B and Structure C respectively has been idealized as 3D space frames using standard two-noded beam and column element with three longitudinal degrees of freedom and three rotational degrees of freedom at each node. Slab at different story level was modeled as four-noded shell element of adequate thickness. The story height was chosen as 3.0 m which is reasonable for domestic or office buildings. The depth of foundation for all structures was considered as 2.0 m below the grade. The reinforced concrete frame structure considered in Zone 3 (Z=0.28) has been adopted for the purpose of study. The typical plan area of the building is 30.0 m × 20.0 m. It consists of 6 bays in X-direction and 4 bays in Y-direction. The building is symmetrical about both the axis. All structures are considered as Special Moment Resisting Frame (SMRF) as lateral force-resisting system. The idealized form of typical 6×4 bay structure is represented schematically in Fig. 1. Floor and roof solid reinforced concrete slab are assumed to satisfy all criteria to be treated as rigid diaphragms.



(a) (b)

Fig. 1 – SAP2000 [9] model of Structure A, (a) Rigid base (pinned) (b) Flexible-base

2.1 Properties of the Structure and Element

For all the cases, the dimensions of reinforced concrete beams are taken as 300 mm × 500 mm and the thickness of the slab element is taken as 150 mm. The columns have uniform cross sections along their height with a reinforcement ratio 1.5%. These dimensions were arrived on the basis of the design following the respective Bangladesh National Building Code [10] for design of reinforced concrete structures. The materials considered for design of the elements are C28 concrete (f'_c =28.0 MPa) and 60 Grade steel (f_y =414.0 MPa). The geometric, sectional and material properties of structure and the structure elements have been summarized in Table 1, Table 2 and Table 3 respectively.

Table 1 – Geometric Properties of the Structure

Structure		No. of bay		Length of bay		Total length		Height	
Symbol	No. of story	X	Y	X	Y	X	Y	Story	Total
		nos	nos	m	m	m	m	m	m
A	5	6	4	5.0	5.0	30.0	20.0	3.0	15.0
B	10	6	4	5.0	5.0	30.0	20.0	3.0	30.0
C	20	6	4	5.0	5.0	30.0	20.0	3.0	60.0

Table 2 – Sectional Properties of the Elements

Story	Column (m)			Beam (m)	Slab (m)
	Up to 5 story	Up to 10 story	Up to 20 story		
5	0.40×0.40	-	-	0.30×0.50	0.15
10	0.60×0.60	0.60×0.60	-	0.30×0.50	0.15
20	0.80×0.80	0.80×0.80	0.80×0.80	0.30×0.50	0.15

Table 3 – Material Properties of the Structural Elements

Sl	Material	Properties	Symbol	Unit	Value
1	Concrete	Unit weight	γ_c	kN/m^3	24.0
2	Concrete	Compressive strength	f'_c	MPa	28.0
3	Concrete	Modulus of Elasticity	E_c	MPa	2.5×10^4
4	MS bar	Yield strength	f_y	MPa	414.0

2.2 Load Considered as per BNBC

The design loads including Dead Load (DL), Live Load (LL), and Superimposed Dead Load (SDL) have been determined in accordance with the provisions and in conformance with the general design requirements provided in BNBC and summarized in Table 4.

Table 4 – Dead and Live loads as per BNBC

Sl	Item	Type	Location	Unit	Value
1	Brick wall	SDL	Typical floor	kN/m^2	1.91
2	Tiles/Pavers	SDL	Typical floor	kN/m^2	0.268
3	Cement Plaster	SDL	Typical floor	kN/m^2	0.287
4	Cement concrete	SDL	Typical floor	kN/m^2	0.527
5	Occupancy	LL	Typical floor	kN/m^2	2.0

3. Idealization of the Soil

For soil-structure interaction analysis, the soil has been treated as isotropic, homogeneous and elastic half space medium. The site classification according to BNBC that are based on the soil properties and characterized on the shear wave velocity namely V100, V300 and V600 have been presented in Table 5. The other elastic properties of soil e.g. poisson's ratio, unit weight are adapted from ATC40 guidelines and are presented in Table 6.

Table 5 – Site Classification based on soil properties according to BNBC

Soil name	Description	Site class	Site Coefficient (S)	Shear wave velocities (V_s)	Undrained Shear Strength (c_u)
				m/s	kN/m^2
V100	Soft clay	SD	1.35	100	30.0
V300	Stiff clay	SC	1.15	300	170.0
V600	Very Stiff clay	SB	1.20	600	400.0

Table 6 – Details of Soil Parameters considered

Soil name	Shear wave velocities (V_s)	Poisson's coefficient (ν)	Unit weight (γ)	Mass density (ρ)	Shear Modulus (G_{max})
	m/s		kN/m^3	kg/m^3	MPa
V100	100	0.50	16	1631	16.31
V300	300	0.40	18	1835	165.14
V600	600	0.35	20	2039	733.94

One of the main parameters in the calculation of properties of soil is Shear modulus and the expression of the initial shear modulus or the maximum shear modulus is to be:

$$G_{max} = \rho V_s^2 \tag{1}$$

3.1 Sectional Properties of Footing

Since the stiffness of spring used to represent the soil flexibility are highly sensitive to the size of footing below which they are attached to, dimensions of various footing have been rigorously computed separately based on safe bearing capacity. For this study different size of isolated footing were selected for Structure A, Structure B and Structure C according to their height as shown in Table 7. The footing area has been determined using the Skempton's bearing capacity equation for cohesive soils.

Table 7 – Sectional Properties of Footing

Soil name	5 Story (Structure A)					10 Story (Structure B)					20 Story (Structure C)				
	L	*W*	*MOI*		*Area*	L	W	MOI		Area	L	W	MOI		Area
	L_x	L_y	I_{xf}	I_{yf}	A_f	L_x	L_y	I_{xf}	I_{yf}	A_f	L_x	L_y	I_{xf}	I_{yf}	A_f
	m	m	m^4	m^4	m^2	m	m	m^4	m^4	m^2	m	m	m^4	m^4	m^2
V100	3.35	3.35	10.50	10.50	11.22	4.90	4.90	48.04	48.04	24.01	7.58	7.58	275.10	275.10	57.46
V300	1.41	1.41	0.33	0.33	1.99	2.07	2.07	1.53	1.53	4.28	3.20	3.20	8.74	8.74	10.24
V600	0.91	0.91	0.06	0.06	0.83	1.33	1.33	0.26	0.26	1.77	2.04	2.04	1.44	1.44	4.16

Note: L= Length of footing, W= Width of footing, MOI= Moment of Inertia of footing section.

3.2 Calculation of Spring Stiffness

Effect of soil-structure interaction is considered by equivalent springs with six degrees of freedom (DOF). The stiffness along these six DOF is determined by the expressions presented by Wolf (1985). The value of stiffness of equivalent soil spring for three types of soil namely V100, V300 and V600 for isolated footing of Structure A, Structure B and Structure C are presented in Table 8, Table 9 and Table 10. The soil-structure interaction effect is incorporated by considering the springs beneath the isolated footing. In this study, two orthogonal springs, a vertical spring and three rotational springs are used in main direction of structures. These springs are modeled in foundation nodes uniformly.

Table 8 – Stiffness of Equivalent Soil Spring for Isolated footing of Structure A (5 Story)

Soil name	Spring Constants										
	Vertical		Horizontal			Rotation				Torsion	
	k_v	R_o	Longitud-inal k_{hx}	Lateral k_{hy}	R_o	Longitud-inal $k_{\theta x}$	R_o	Lateral $k_{\theta y}$	R_o	k_t	R_o
	kN/m		kN/m	kN/m		kN-m /rad		kN-m/rad		kN-m/rad	
V100	826143	6.33	550762	550762	6.33	607967	1.91	607967	1.91	607967	1.91
V300	1234859	1.12	935893	935893	1.12	382487	0.80	382487	0.80	458984	0.80
V600	2110170	0.47	1698185	1698185	0.47	421831	0.52	421831	0.52	548381	0.52

Note: R_o = equivalent radius of footing

Table 9 – Stiffness of Equivalent Soil Spring for Isolated footing of Structure B (10 Story)

Soil name	Spring Constants										
	Vertical		Horizontal			Rotation				Torsion	
	k_v	R_o	Longitu-dinal k_{hx}	Lateral k_{hy}	R_o	Longitu-dinal $k_{\theta x}$	R_o	Lateral $k_{\theta y}$	R_o	k_t	R_o
	kN/m		kN/m	kN/m		kN-m/rad		kN-m/rad		kN-m/rad	
V100	1497875	13.55	1121313	1121313	13.55	1612322	2.80	1612322	2.80	1902540	2.80
V300	2575607	2.42	2000128	2000128	2.42	1171197	1.18	1171197	1.18	1452284	1.18
V600	4507523	1.00	3627483	3627483	1.00	1316951	0.76	1316951	0.76	1712037	0.76

Table 10 – Stiffness of Equivalent Soil Spring for Isolated footing of Structure C (20 Story)

Soil name	Spring Constants										
	Vertical		Horizontal			Rotation				Torsion	
	k_v	R_o	Longitu-dinal k_{hx}	Lateral k_{hy}	R_o	Longitu-dinal $k_{\theta x}$	R_o	Lateral $k_{\theta y}$	R_o	k_t	R_o
	kN/m		kN/m	kN/m		kN-m/rad		kN-m/rad		kN-m/rad	
V100	3584445	32.42	2683323	2683323	32.42	5968583	4.33	5968583	4.33	7042927	4.33
V300	6155153	5.78	4779880	4779880	5.78	4326820	1.83	4326820	1.83	5365257	1.83
V600	10604618	2.35	8534192	8534192	2.35	4752315	1.16	4752315	1.16	6178010	1.16

4. Structural Response due to Soil Flexibility

The effects of soil-structure interaction on dynamic behavior of the Structure A, Structure B and Structure C and the response in terms of natural period, lateral deflection and base shear are studied. There are four cases of analysis have been considered in this study. They are as follows:

Case 1: Dynamic analysis with rigid base (pinned) condition

Case 2: Dynamic analysis with rigid base (fixed) condition

Case 3: Dynamic analysis with flexible base condition

Case 4: Equivalent Static analysis with rigid base (pinned) condition

The response of the Structure A, Structure B and Structure C resting on different soil condition (e.g. soft clay, stiff clay and very stiff clay) have been presented in Fig. 2 to Fig. 6. The responses are also compared with the rigid base (fixed) condition. The drift ratio (*d*/*h*) and percent (%) base shear (*V*/*W*) have also been compared with different soil conditions and presented in Fig. 7 to Fig. 10.

4.1 Natural Time Period

The natural time period increases with soil flexibility for Structure A, Structure B and Structure C. So all the structures have increased natural time period supported on V600, V300 and V100 as compared to rigid (fixed) support condition. Structure A shows a significant variation in natural time period than Structure C. The soft clay (V100) shows higher natural period compared to other soils.

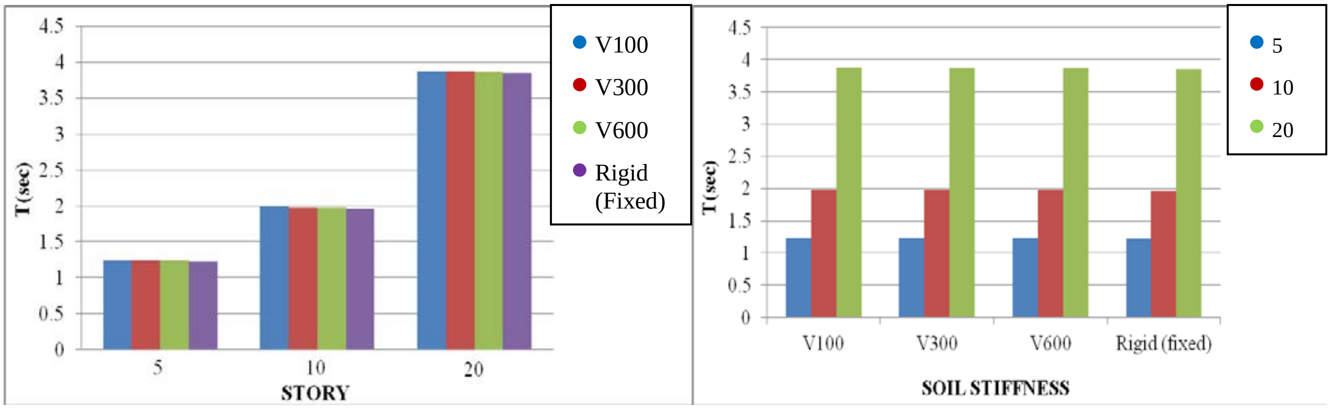


Fig. 2 – Natural Time Period (First Mode) of different structures on different support conditions

4.2 Lateral Deflection

The lateral deflection for all the structures increase as the soil becomes softer. Structure A and Structure B show a significant variation in lateral deflection than Structure C. The soft clay (V100) shows higher lateral deflection compared to other soils.

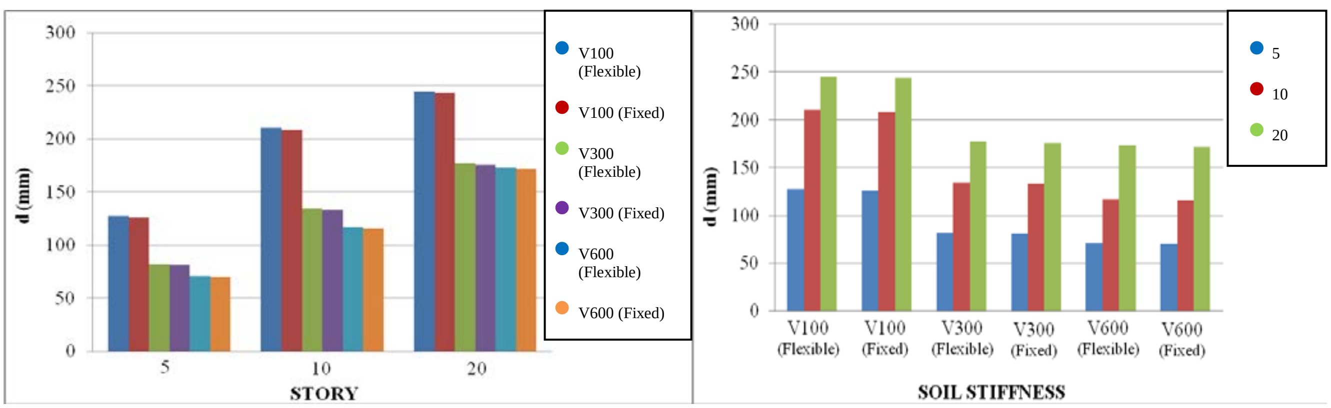


Fig. 3 – Lateral Deflection (X direction) of different structures on different support conditions

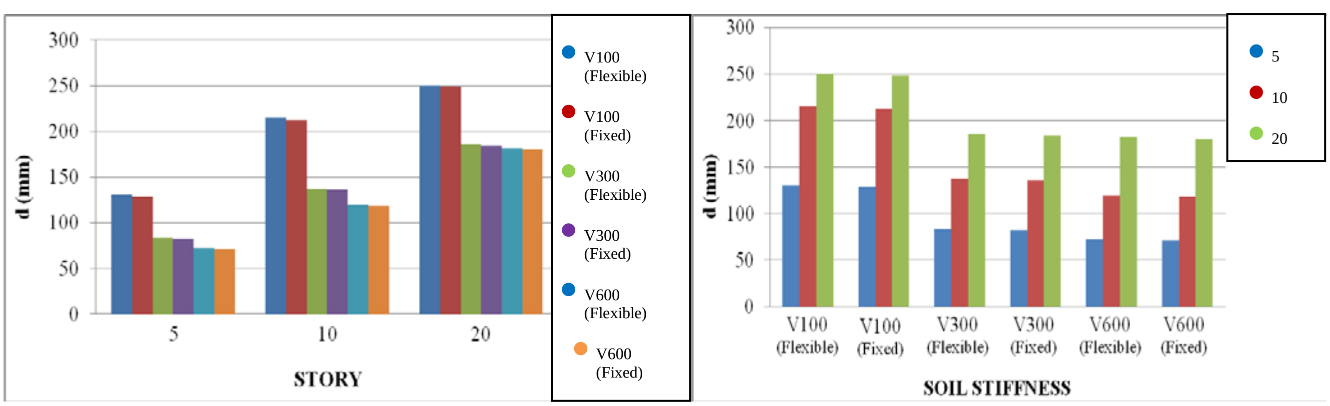


Fig. 4 – Lateral Deflection (Y direction) of different structures on different support conditions

4.3 Base Shear

Base shear decreases in X direction by 0.64%, 0.54%, 0.43% for Structure A, Structure B and Structure C respectively in case of V100 as shown in Fig. 5. Base shear decreases by 0.83%, 0.47% for Structure A and Structure B respectively in case of V300. But in case of Structure C base shear increases by 0.26%. However, In case of V600 the base shear decreases by 0.33% for Structure B. But in case of Structure A and Structure C the base shear increases by 1.94% and 0.28% respectively. The same behavior exhibits in Y direction as shown in Fig. 6.

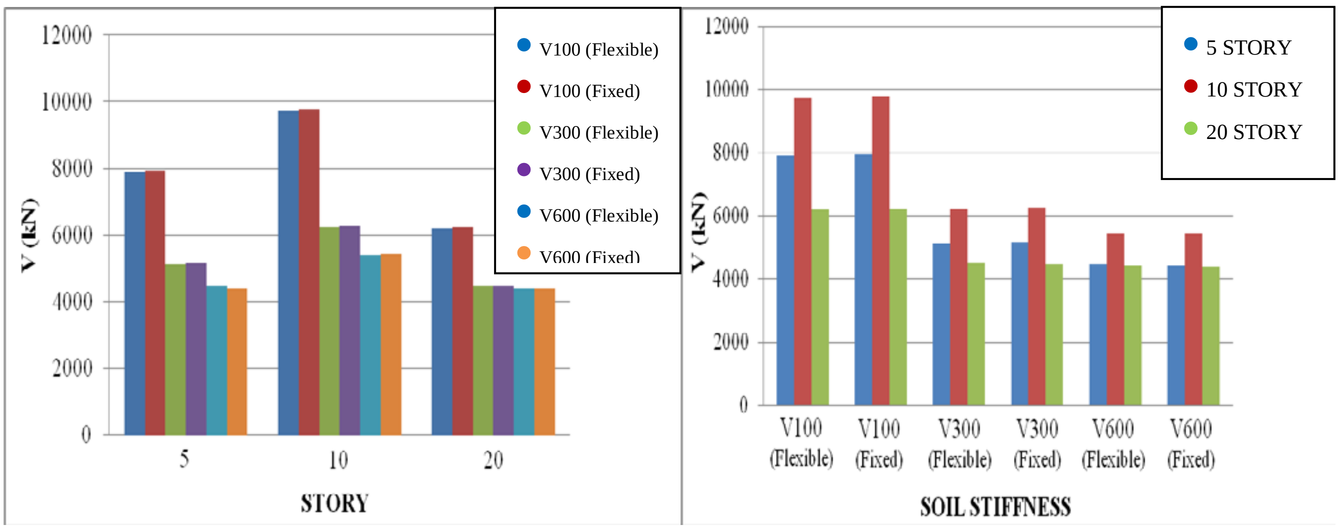


Fig. 5 – Base Shear (X direction) of different structures on different support conditions

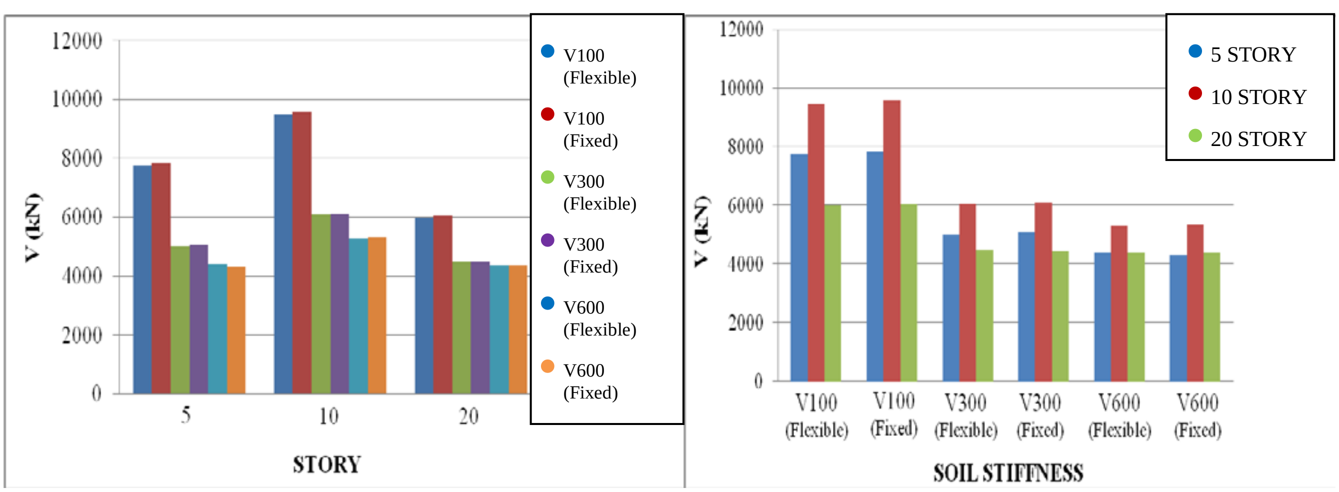


Fig. 6 – Base Shear (Y direction) of different structures on different support conditions

4.4 Drift Ratio

The drift ratio (*d/h*) for Structure A, Structure B and Structure C supporting on different soils in both X and Y direction are presented in Fig. 7 and Fig. 8. In all the cases the drift ratio decreases with the increase of soil stiffness. Structure A has higher drift ratio as compared to Structure B and Structure C. The soft clay (V100) has also higher drift ratio as compared to stiff clay (V300) and very stiff clay (V600).

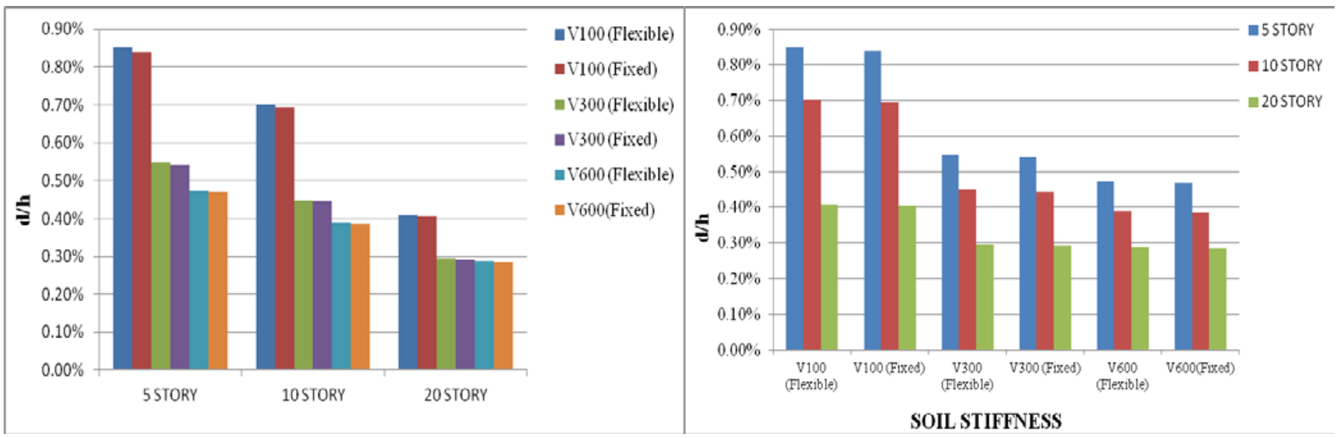


Fig. 7 – Drift ratio (X direction) of different structures on different support conditions

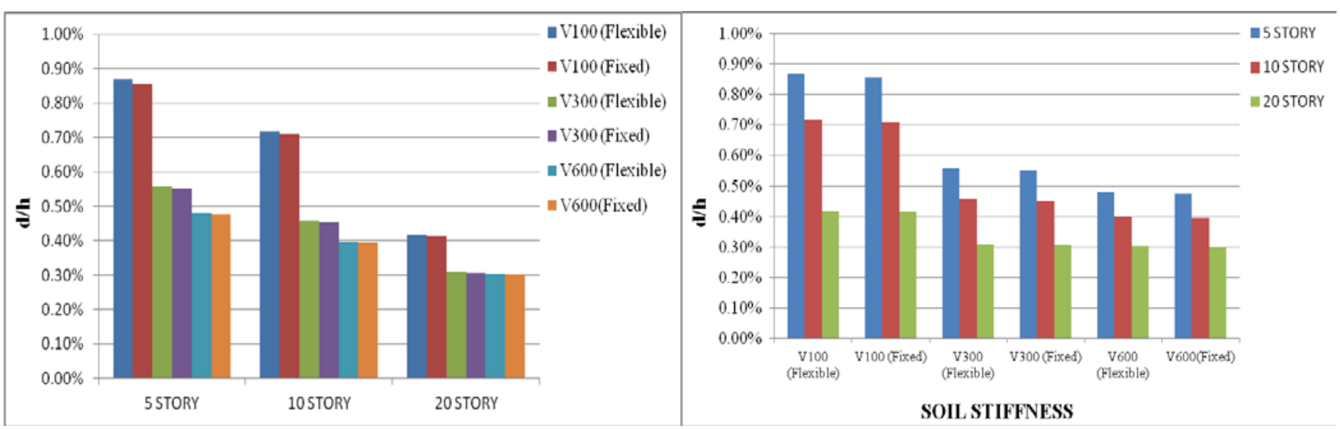


Fig. 8 – Drift ratio (Y direction) of different structures on different support conditions

4.5 Percent (%) Base Shear

The percent (%) base shear (*V/W*) for Structure A, Structure B and Structure C supporting on different soils in both X and Y direction are presented in Fig. 9 and Fig. 10. In all the cases the percent (%) base shear decreases with the increase of soil stiffness. Structure A has higher percent base shear as compared to Structure B and Structure C. The soft clay (V100) has also higher percent (%) base shear as compared to stiff clay (V300) and very stiff clay (V600).

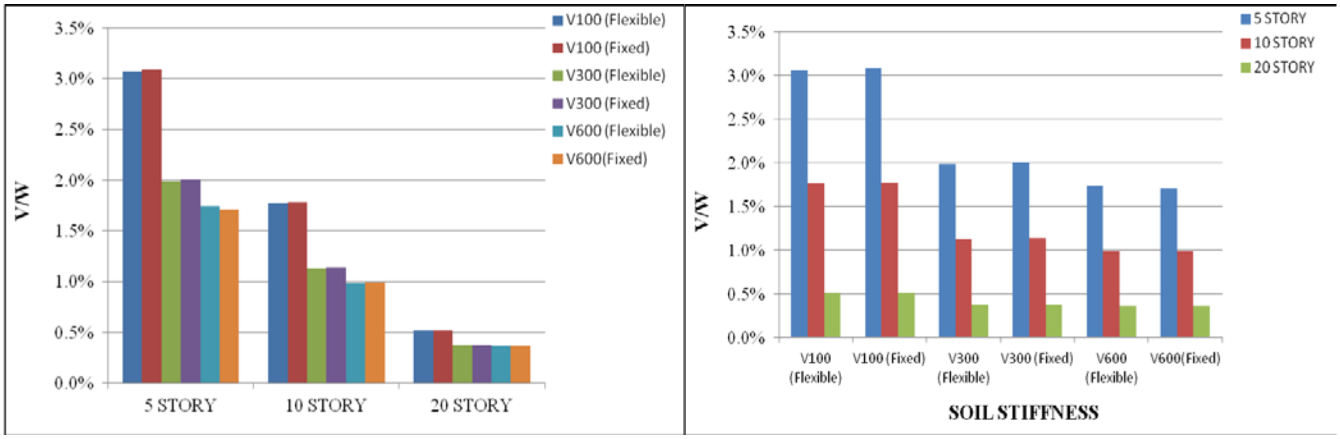


Fig. 9 – Percent (%) Base Shear (X direction) of different structures on different support conditions

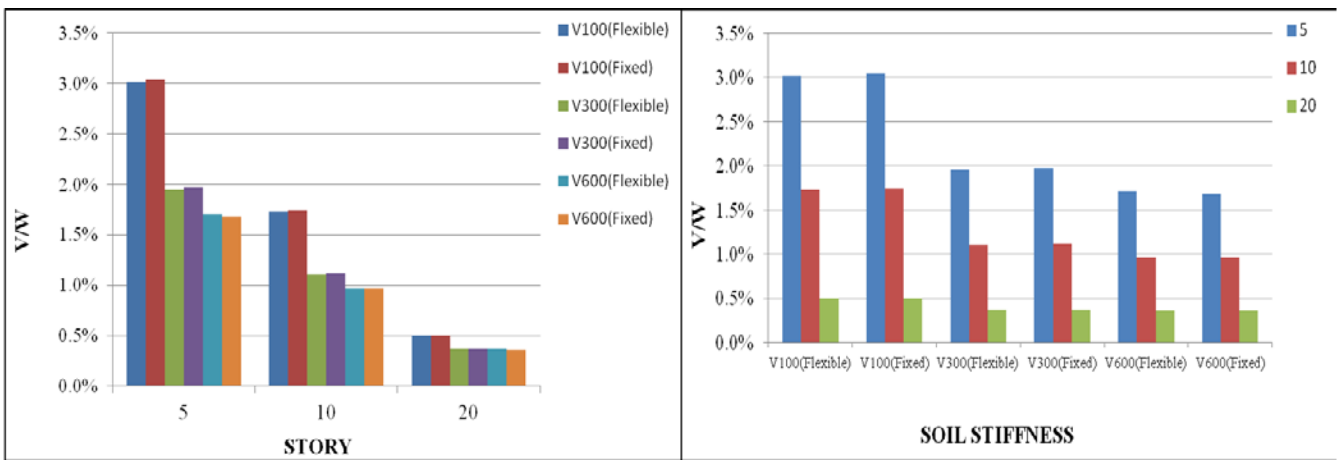


Fig. 10 – Percent (%) Base Shear (Y direction) of different structures on different support conditions

5. Conclusions

The present study makes an effort to evaluate the effect of soil-structure interaction on dynamic behavior of RC frame building resting on different soils e.g. soft clay, stiff clay and very stiff clay. The following conclusions can be derived according to results presented in this study:

a) There was no significant variation of natural period due to variation of stiffness of foundation soil. But past research works showed that there is variation of natural period due to variation of stiffness of foundation soil. This is because of using same foundation sizes for different types of soil. In this study foundation sizes were changed with the variation of soil stiffness.

b) Lateral deflection and drift ratio (d/h) decreases with the increase of the stiffness of foundation soil for same story of building even the foundation sizes are smaller for stiffer foundation soils. However, drift ratio (d/h) decreases with the increase of number of story for same soil condition. This is because of change in natural period with the increase of number of story. From the response spectra it is seen that value of response spectra decreases with the increase of natural period after peak value.

c) Base shear and percent base shear (V/W) decreases with the increase of foundation soil stiffness. However, percent base shear decreases with the increase of number of story for same soil condition. This is because of change in natural period with the increase of number of story.

d) Overall, the variation of natural period, lateral deflection and base shear with the variation of the stiffness of the foundation soil is not significant as compared to the respective fixed-base condition. This means if response spectrum for different soil types given in BNBC (2014) is used and foundation design is done properly, reasonably accurate result of analysis can be achieved without considering soil-structure interaction.

6. Acknowledgements

The authors would like to thank to all who wished for success. Above all the author renders his gratitude to the Almighty who bestowed self-confidence, ability and strength to complete this research work.

7. Copyrights

8. References

[1] Wolf, J. P. (1985). *Dynamic Soil-Structure Interaction*, Prentice Hall, Englewood Cliffs, New Jersey.

[2] Bielak, J. (1974): *Dynamic behavior of structures with embedded foundations*, International Journal of Earthquake Engineering and Structural Dynamics, 3(3), 259–274.

[3] Dutta, S. C., Bhattacharya, K. and Roy, R. (2004). *Response of low-rise buildings under seismic ground excitation incorporating soil-structure interaction*, Soil Dynamics and Earthquake Engineering, 24, 893-914.

[4] Roy, R. and Dutta, S. C. (2001). *Effect of soil–structure interaction on dynamic behaviour of building frames on grid foundations*," Proc. of Structural Engineering Convention (SEC 2001), Roorkee, India, 694-703.

[5] Mylonakis, G. and Giarlelis, C. (2014). *The role of soil-structure interaction in the inelastic performance of multi-storey buildings*, Proceedings of the 9th International Conference on Structural Dynamics (EURODYN 2014), Porto, Portugal, 30 June- 2 July, ISSN: 2311-9020.

[6] Velestos, A. S. and Meek, J. W. (1974). *Dynamic Behaviour of Building-Foundation system*, Journal of Earthquake Engineering and Structural Dynamics, 3, 121-138

[7] ATC-40 (1996). *Seismic Evaluation and Retrofit of Concrete Buildings*, Volume-1, Seismic Safety Commission, California.

[8] NEHRP (2012). *Soil-Structure Interaction for Building Structures*, NIST GCR, 12-917-21, NEHRP Consultants Joint Venture A partnership of the Applied Technology Council and the Consortium of Universities for Research in Earthquake Engineering.

[9] Computer and Structures Inc., SAP2000 Nonlinear Version 14. Berkeley, California, USA.

[10] *Bangladesh National Building Code* (2014). Housing and Building Research Institute, Mirpur, Dhaka, Bangladesh.