STM JOURNALS

Journal of Geotechnical Engineering

Volume 1, Issue 2
www.stmjournals.com

Performance of Buildings at Different Soils using Pushover Analysis

Ketan Bajaj[1]*, Radha Gonawala[2], Bhavik M. Vyas[1]
[1]Applied Mechanics Department, S.V. National Institute of Technology, Surat, India
[2]Civil Engineering Department, S.V. National Institute of Technology, Surat, India

Abstract
Earthquake has been considered as the most devastating calamity which may lead to loss of lives and properties as seen in 2001 earthquake at Bhuj, India. In India various buildings has been designed irrespective of the effect of dynamic load corresponding to different kinds of soil condition. So, in this study an attempt has been made to analyse different types of buildings viz. G+4, G+8 and G+12 under different soil condition as hard, medium and soft. The behavior of these building models has been studied in SAP: 2000 software considering nonlinear pushover analysis at different seismic zones as III, IV and V (as per IS: 1893, 2002). The spectral displacement and spectral acceleration at performance point has been compared to study the effect of soil-structure interaction (SSI). Pushover curves have also developed to examine the performance of the building at different conditions. It was determined that with the change in soil condition for the same type of building configuration, targeted displacement is not zero at zero base shear condition in nonlinear dynamic analysis. In addition to that, lateral deflection was also compared for different types of building. This study can be used while designing the building at different soil conditions and seismic zones.

Keywords: *Pushover analysis, soil-structure interaction, spectral acceleration and displacement, demand-capacity curve*

****Author for Correspondence*** E-mail: 16ketan1990@gmail.com

INTRODUCTION

Urban cities are more vulnerable to earthquake hazards due to high population density, improper planning, poor land use and substandard construction practices. Also, the type of infrastructure in urban areas are composed of apartments, multi-story buildings, offices, school buildings, utility centers, shopping malls and nonengineered structures etc. where the agglomeration at any time are more as compared to rural areas. Thus, total collapse or partial damages to the buildings during any earthquake can cause loss of lives and infrastructure on a much bigger scale. Vibrations which disturb the earth's surface caused by waves generated inside the earth are termed as earthquakes. Structures damages due to earthquake are attributed by structural defects or subsurface soil/rock layers. At present, major importance is given to earthquake-resistant structures in India for human safety. India is a subcontinent having more than 60% area in earthquake-prone zone. The threats presently India has experienced due to natural calamities will be three times higher in the year 2050 [1]. A majority of buildings constructed in India are designed based on consideration of permanent, semi-permanent, and movable loads. But earthquake is an occasional load which not only leads to loss of human life but also disturbs social conditions of India. The extent to which the structural response changes because of the characteristics of earthquake motions which can be observed at the foundation level depends on the relative mass and stiffness properties of the soil and the structure. Thus the physical property of the soil is an important factor while designing an earthquake-resistant building. The estimation of earthquake motions at any site of structure is the most important phase for its designing. Some designers assumed that the motion in foundation level of any structure is equivalent to the ground-free field motion. This assumption is correct only for the structures constructed on rock or very stiff soil. For the structures constructed on soft soil, foundation motion is usually different from the free field motion and a rocking component caused by the support flexibility on horizontal motion of foundation is also added.

Two models were described, one having fixed base and other with integrated numerical model that includes soil, foundation and structure in SAP-2000 [2]. Soil foundation structure interaction along with time history analysis was also illustrated. The hardness or type of soil, excitation frequency of forcing function and number of stories of building regulates the soil-structure interaction (SSI) on lateral natural period of building frames [3]. The buildings were modelled soil using Winkler spring and it was concluded that the natural periods do not matches with the natural period obtained from the empirical expression given in the codes which leads to damage of building during earthquake [4]. The seismic behaviour of RCC buildings with and without shear wall under different soil conditions has been studied. It was concluded that the SSI must be suitably considered while designing frames for seismic forces [5]. The seismic SSI of buildings on hill slopes has been studied and concluded that response reduction factor decreases with increasing time period, but it was expected to be constant beyond a certain value of time period. The effect of lateral force on tall buildings with different type of irregularities has been examined and it was found that building with soft soil gives more deflection as compared to medium and hard soil for all types of building. An energy method to estimate the damping of seismically isolated structure, taking into account the energy dissipation of the bearing and the radiation damping in the soil has been proposed [6]. The modal properties of base-isolated structure were investigated and it was concluded that when the flexibility of soil and isolators are comparable, the contribution of SSI should not be ignored [7]. An experimental study concerning base-isolated nuclear facilities founded on soft-sites has been carried out which led to the conclusion that the isolator design should be taken into account for significant displacement demands [8, 9]. The effect of SSI on the response of base-isolated bridges by a parametric study has been assessed and an analytical expression to demonstrate the significance of SSI phenomena in influencing the response of the isolated system has been derived [10]. The effects of SSI on the response of base-isolated 4-DOF located on an elastic soil layer overlying rigid bedrock and subjected to a harmonic ground motion has been examined [11]. Frequency-independent expressions were used to determine the stiffness and damping coefficients for the rigid surface foundation on the soil stratum underlined by bedrock at shallow depth [11].

India is having different soil conditions leading to different earthquake intensity because of which buildings should develop earthquake-resistant structures in consideration to IS:1893 (part: I) [12]. India has been classified into four seismic zones namely zone II, III, IV, V. These zones have different zone factor, importance factor and response acceleration coefficient (Sa/g). When a structure is subjected to an earthquake, vibrations first interact with the foundation and soil, and thus change the motion of the ground. It means that the movement of the whole structure system is influenced by the type of soil as well as by the type of structure. Seismic waves transfer from the ground which consist of different layers of soil and performs differently according to their respective properties. So, in this study, nonlinear analytical modelling and pushover analysis for different configuration of building has been done in SAP: 2000. Parametric study has been carried out by considering different types of soil *viz*. Soft (S), Medium (M) and Hard (H), different stories of buildings (G+4, G+8 and G+12), and different seismic zones (III, IV and V). Base shear, lateral displacement, spectral acceleration and spectral displacement corresponding to hard, medium and soft soil is calculated and compared. In this paper, pushover curve for all types of building was considered and compared also**.** All the structures has been analysed as per IS: 1893 (Part: I) [12] named as “Criteria for Earthquake Resistant Design of Structures”. A building is modelled in SAP-2000 having different Winkler’s springs as its foundation correspond to different soil properties. This research has immense benefits in the field of

Geotechnical Earthquake Engineering as well as Structural Dynamics.

PROCEDURE EMPLOYED

For the analysis of different models, firstly different springs were modelled corresponding to different soil properties. Spring stiffness has been calculated using Wolf considering various soil dynamics factors as shear modulus (G), Poisson's ratio (γ) and shear wave velocity (V_s) considering soil as a half space elastic medium as given in Table 1. Three springs were modelled for translation (K_X, K_Y and K_Z) and other three were modelled for rotation (K_{Rx}, K_{Ry} and K_{Rz}) as given in Table 2. For nonlinear structural analysis, pushover analysis has been used considering P-delta effect. According to which lateral loads increased monotonically from zero to ultimate level corresponding to collapse of structure. As increase in the magnitude loading, weak links and failure modes of structure are identified.

MODELLING OF BUILDING IN SAP-2000

In this parametric study, three different types of buildings has been modelled along with change in the zones and type of soil as per IS: 1893 [12] in SAP: 2000 as shown in Table 3. These buildings are analysed with both flexible and fixed-base foundation. Also soft storey has been introduced in each type of building for comparing the lateral displacemen t with other buildings.

Capacity

The global capacity of a structure is administered by the strength and deformation capacities of the specific components of the structure. A pushover analysis procedure practices a series of successive elastic analysis, superimposed to approximate a force–displacement capacity diagram of the complete structure. The mathematical model of the structure is improved to account for reduced resistance of yielding components. A lateral force distribution is again applied up to an encoded limit is reached. Pushover capacity curves approximate how structure performs after exceeding the elastic limits.

Demand

Ground motions during an earthquake create a complex horizontal displacement patterns in structure that may diverge with time. Tracing this motion at each time step to normalize structural design requirements is referred impractical. For nonlinear method it is easier and more uninterrupted to use a set of lateral displacement as a design circumstance for a given structure and ground motion. The displacement is an assessment of the maximum expected response of the building during ground motion. Typical seismic demand versus capacity is shown in Figure 1 showing "B" as the performance point.

RESULT AND DISCUSSION

G+4, G+8 and G+12 building frames with fixed and flexible base has been analysed in SAP-2000 to understand its behaviour under the seismic forces in different soil conditions and different seismic zones. All the structural member has been done as per IS: 456 (2000). The seismic responses along with nonlinear pushover analysis result (Figure 2) for all 54 building frames were compared. The results of all building frames are discussed in Table 3.

Table 1: *Elastic Properties of Foundation Soil.*

Type of soil	Shear modulus G (kN/m^2)	Elastic modulus E (kN/m^2)	Poisson's ratio ν
H	2700	6750	0.25
M	451.1	1200	0.33
S	84.5	250	0.48

Table 2: *Soil Stiffness values for Buildings with Flexible Base.*

Type of soil	Soil stiffness					
	K_X (kN/m)	K_Y (kN/m)	K_Z (kN/m)	K_{Rx} (kN/m)	K_{Ry} (kN/m)	K_{Rz} (kN/m)
H	7309.4	7309.4	8121.6	1777.8	1777.8	2666.7
M	1251.1	1251.1	1518.9	334.1	334.1	444.5
S	251.0	251	366.6	80.3	80.3	83.5

Table 3: *Building Specification for Analysis.*

Building name	No. of stories	Type of soil	Seismic zone
B11		H	
B12	4	M	III
B13		S	
B14		H	
B15	4	M	IV
B16		S	
B17		H	
B18	4	M	V
B19		S	
B21		H	
B22	8	M	III
B23		S	
B24		H	
B25	8	M	IV
B26		S	
B27		H	
B28	8	M	V
B29		S	
B31		H	
B32	12	M	III
B33		S	
B34		H	
B35	12	M	IV
B36		S	
B37		H	
B38	12	M	V
B39		S	
Common configuration			
Height of each floor			3.5 m
Imposed load			2 KN/m^2
Response spectra, Damping factor, Importance factor, Response Reduction factor			As per IS 1893 (Part 1)-2002

(S=soft, M=medium, H=hard)

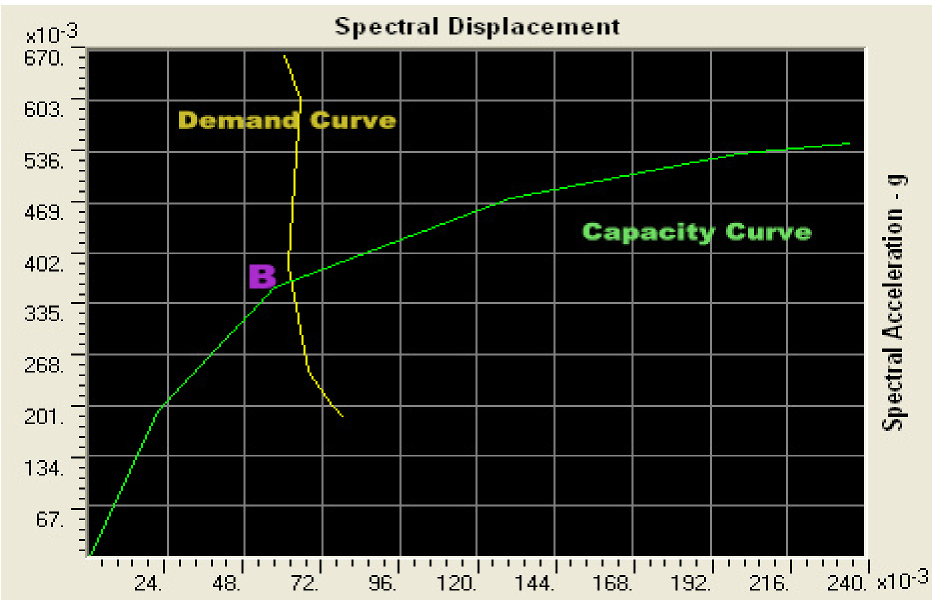


Fig. 1: *Typical Seismic Demand vs. Capacity Curve.*

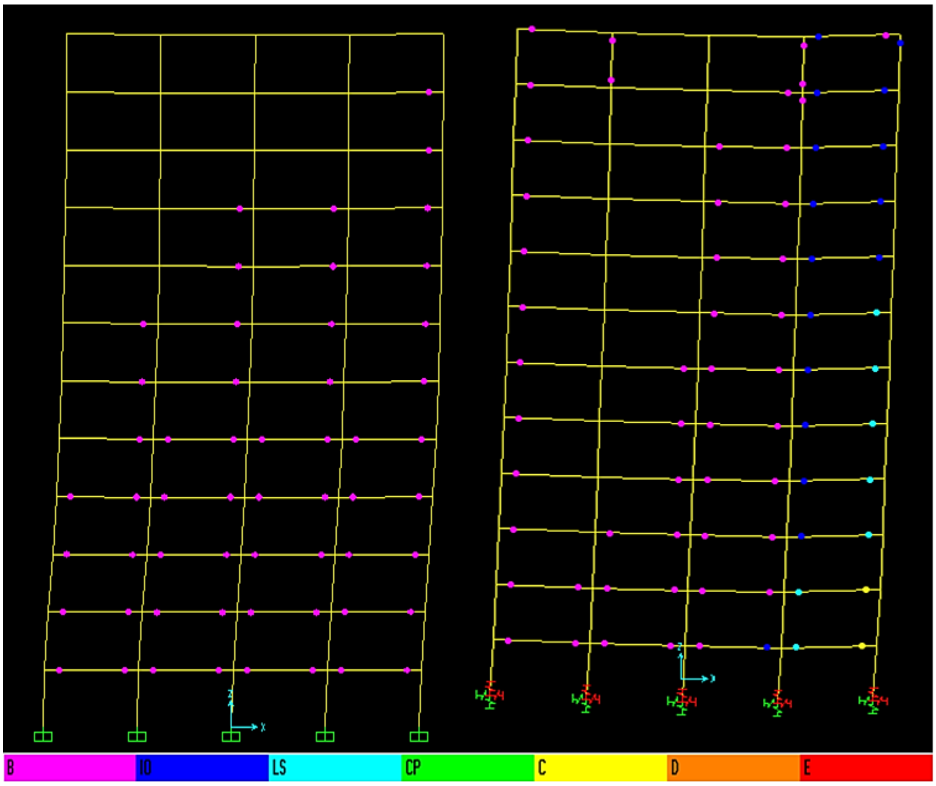


***Fig. 2:** Hinges as per Pushover Analysis of B31 with Fixed and Flexible Base.*

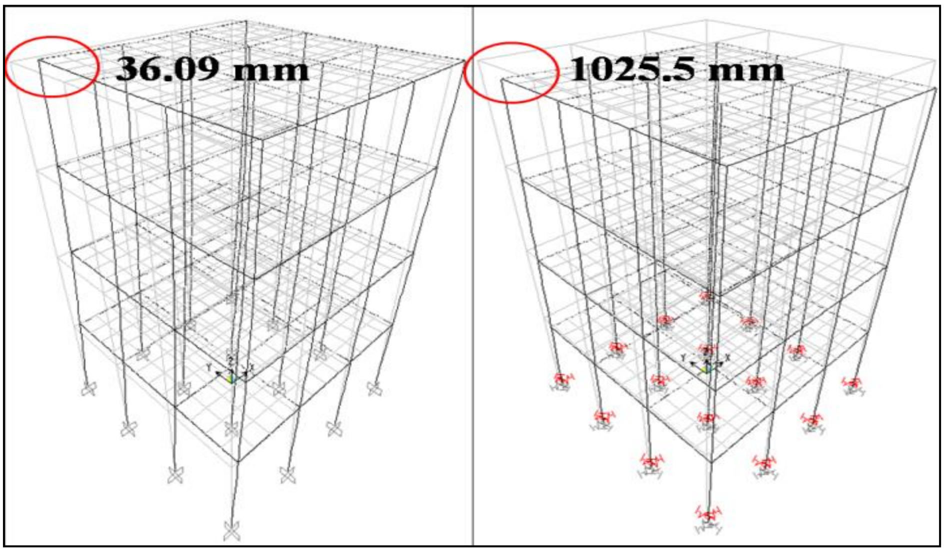


***Fig. 3:** Lateral Deflections of G+4 Building on Hard Soil with Fixed and Flexible Base (B19).*

It has been shown in Figure 3 that G+4 building on soft soil is having 96.44 increments in the lateral deflection at the roof. Lateral deflection at roof level for all the buildings has been given in Table 4 both on flexible and fixed base.

As seen from B11, B12 and B13 with the change in soil property from hard to medium and from hard to soft the lateral deflection has increased by 50–55% and 60–65%, respectively. For flexible base, similar pattern was seen in the building B21, B22 and B23 and B31, B32 and B33. The building shown in bold (Table 4), about 25–50% of the structural member fails as per normal designing, which is generally considering fixed base. It has been also analysed that the building member fails at the floor level during nonliner pushover analysis. For building frames B19, B26, B29, B36 and B39, the stiffness of structural member has increased to 30% to sustain the seismic load. Whereas for building frames B28, B35 and B38, with 20% increase in stiffn ess building sustained seismic loads.

To identify the elastic response and the security margin of all building performance point has been determined (Figure 1). Table 5 shows the performance point of all types of building.

The building shown in bold in Table 5 is unsafe design as demand is more as compared to the capacity of the buildings. This concludes that the buildings should be designed by taking soil condition into consideration.

As in the displacement control nonlinear pushover analysis, buildings are supposed to be pushed either up to target displacement or the point when the structure losses equilibrium. In this study, target displacement is taken which is equal to 4% of the total building height (as per various literatures).

Pushover curve represents a curve between base shear force or base reaction versus roof displacement curve. The peak of the curve symbolizes the upper limit of the lateral load carrying capacity of the structure. The primary stiffness of the structure is attained from the tangent at pushover curve at zero load level. The collapse is considered when the structure losses its 75% strength and corresponding roof displacement is called "maximum roof displacement". The pushover curve of these building frames are shown in Figure 4 (a–c) and 5 (a–c) for G+4 and G+8 building, respectively.

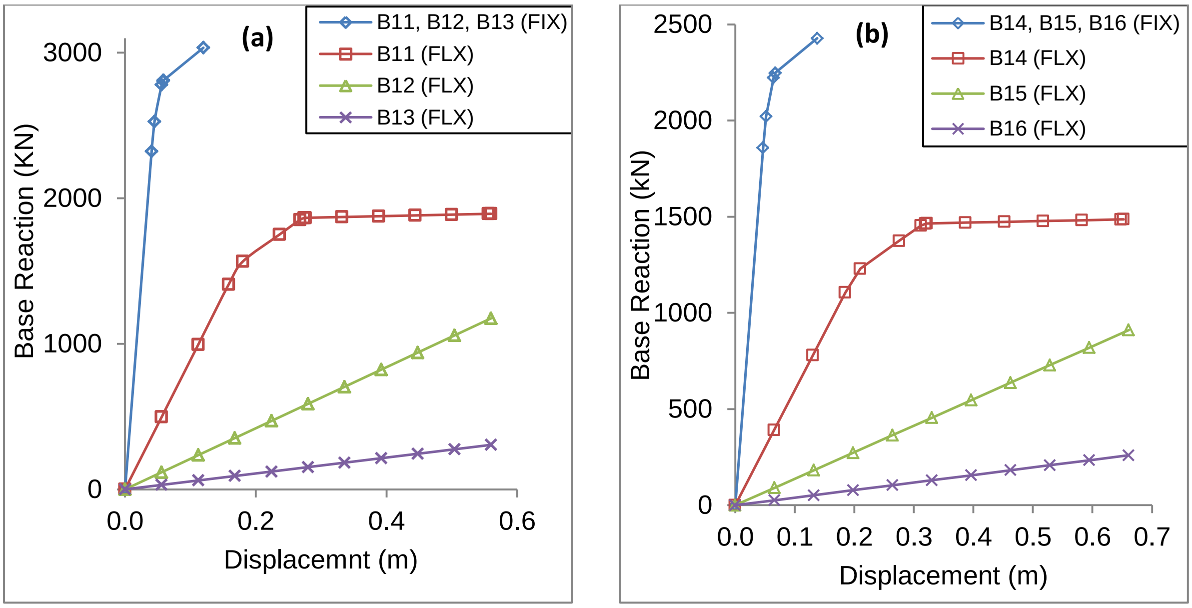
Table 4: *Lateral Deflection of Building on Fixed and Flexible Foundation.*

Building name	**Lateral deflection (mm)**	
	Fixed base	**Flexible base**
B11	28.26	75.85
B12	28.26	89.58
B13	28.26	160.26
B14	32.58	82.52
B15	32.58	95.28
B16	32.58	235.43
B17	36.09	61.07
B18	36.09	102.84
B19	36.09	1025.5
B21	51.25	58.25
B22	51.25	85.25
B23	51.25	165.28
B24	55.25	65.28
B25	55.25	102.58
B26	55.25	688.25
B27	58.47	72.85
B28	58.47	586.58
B29	58.47	1205.25
B31	63.47	78.55
B32	63.47	105.55
B33	63.47	195.75
B34	74.95	96.44
B35	74.95	**1146.94**
B36	74.95	**2157.62**
B37	93.84	105.58
B38	93.84	**1187.58**
B39	93.84	**3105.84**

Table 5: *Performance Point of All Buildings with Flexible and Fixed Base.*

Building name	Performance point			
	Fixed base		Flexible base	
	SA (g)*	SD(g)#	SA (g)	SD(g)
B11	0.7	0.025	0.654	0.088
B12	0.7	0.025	0.325	0.176
B13	0.7	0.025	0.312	0.305
B14	0.65	0.053	0.601	0.105
B15	0.65	0.053	0.300	0.215
B16	0.65	0.053	0.258	0.315
B17	0.54	0.068	0.524	0.127
B18	0.54	0.068	0.278	0.268
B19	0.54	0.068	**0.126**	**0.456**
B21	0.474	0.047	0.302	0.141
B22	0.474	0.047	0.108	0.368
B23	0.474	0.047	**0.106**	**0.783**
B24	0.279	0.084	0.105	0.168
B25	0.279	0.084	0.085	0.298
B26	0.279	0.084	**0.075**	**0.552**
B27	0.054	0.184	**0.078**	**0.644**
B28	0.054	0.184	**0.065**	**0.712**
B29	0.054	0.184	**0.060**	**0.755**
B31	0.461	0.062	0.392	0.044
B32	0.461	0.062	**0.066**	**0.601**
B33	0.461	0.062	**0.056**	**0.786**
B34	0.285	0.085	0.065	0.425
B35	0.285	0.085	**0.085**	**0.752**
B36	0.285	0.085	**0.099**	**0.902**
B37	0.132	0.105	**0.083**	**0.747**
B38	0.132	0.105	**0.099**	**0.902**
B39	0.132	0.105	**0.112**	**0.958**

** Spectral acceleration, # Spectral displacement*



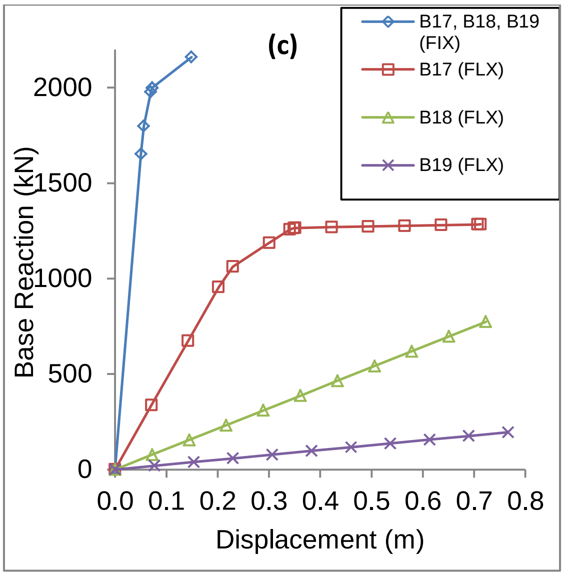


Fig. 4 (a, b & c): *Pushover Curve for G+4 Building.*

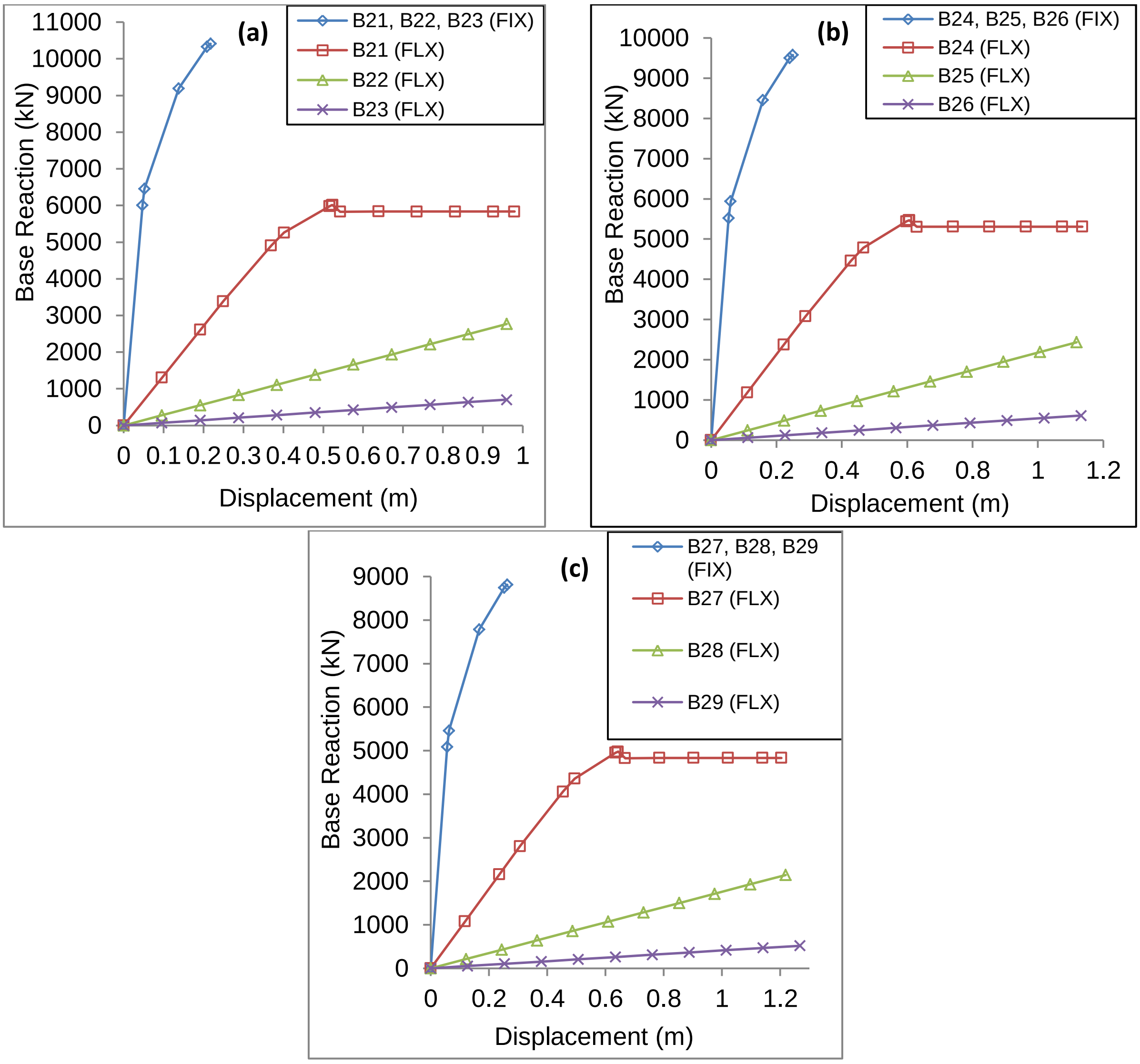


Fig. 5 (a, b & c): *Pushover Curve for G+8 Building.*

These curves are primarily linear but start to deviate from linearity as the beams and columns undergo inelastic actions which can be seen from the pushover curve of B11, B14, B17, B21, B24 and B27. While comparing these building with the fixed base, the target displacement is less as compared to different hinges. It can also be concluded that when the buildings are pushed well into the inelastic range, the curves become linear again but having a smaller slope as seen by the buildings on medium soil for both G+4 and G+8 buildings. The curve could be approximated by a bilinear relationship. From the pushover curve given in Figure 5(a), the target displacement is 1.2E-01 m at the base shear 3034.23 kN, whereas for the same configuration of beam and columns and change in the soil condition the target displacement increases to 5.56 E-01 m at the base shear of 1892.91 kN. Similar increase in target displacement has been seen at different types of buildings given in Table 3 with change in the soil condition. Similarly, the pushover curve for G+12 with different soil conditions was drawn and analysed. The result of target displacement and base shear has been given in Table 6 for G+12 building only. It can be concluded from Table 6 that at zero base shear the building has some target displacement due to its dead weight due to change in soil condition which is an important factor while designing the structure.

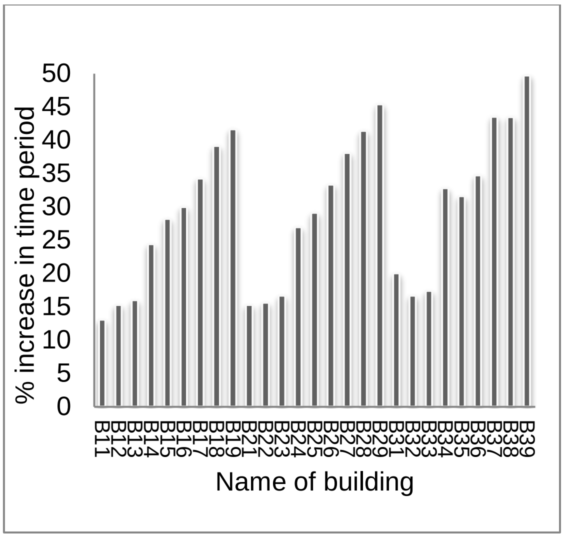


Fig. 6: *Increase in Time Period in Various Buildings (As per Table 3).*

Table 6: *Displacement and Base Shear for G+12 Building at Different Soil Conditions.*

Building	Initial		Final	
	Displacement (m)	Base shear (kN)	Displacement (m)	Base shear (kN)
B31, B32, B33 (FIX)	0.00	0	0.32	15553.30
B31 (FLX)	0.80	0	2.24	6601.30
B32 (FLX)	4.16	0	5.60	2044.38
B33 (FLX)	16.65	0	18.09	511.10
B34, B35, B36 (FIX)	0.00	0	0.36	13686.91
B34 (FLX)	0.92	0	2.06	5891.66
B35 (FLX)	4.85	0	6.53	1768.39
B336 (FLX)	19.48	0	21.16	439.55
B37, B38, B39 (FIX)	0.00	0	0.42	12044.48
B37 (FLX)	1.06	0	2.24	6601.30
B38 (FLX)	5.65	0	7.60	1529.66
B39 (FLX)	22.79	0	24.76	378.01

In addition, natural time period of all the building models has been compared and increment in time period is represented in Figure 6. It can be seen from Figure 6 that there is approximately 10–40 % increase in natural time period when soil condition as well as seismic zones change. This will affect the design of any building.

CONCLUSION

It can be concluded from the study that the effect of soil condition should be taken into consideration while analysing or designing any building or structure. It was seen that the lateral deflection increase with change in soil property from hard to medium and from hard to soft by 50–55% and 60–65%, respectively for flexible base. The target displacement increases approximately 40% while changing the soil condition during pushover analysis corresponding to that base shear also decreases respectively. There is also increase in the natural time period of any structure while changing the soil type in the analysis of any model. It can be further concluded from all the research that nonlinear pushover analysis along with changing soil condition should be taken into consideration while analysing any type of building and structure. This analysis or study will be helpful while doing SSI of any building.

REFERENCES

1. World Bank (2011) [cited 2012 July 9]; Available from:http://web.worldbank.org/ WBSITE/EXTERNAL/COUNTRIES/SOUTHASIAEXT/0,,contentMDK:23064385~menuPK:158843~pagePK:2865106~piPK:2865128~theSitePK:223547,00.html
2. Storie LB, Pender MJ. Soil foundation structure interaction in shallow foundation earthquake response. *Proceedings of the New Zealand Society for Earthquake Engineering Conference*; 2013 April 26–28; New Zealand; 2013.
3. Bhattacharya K, Dutta SC. Assessing lateral period of building frames incorporating soil-flexibility. *J Sound Vibra.* 2004; 26: 795–821p.
4. Arlekar JN, Jain SK, Murty CVR. Seismic response of RC frames buildings with soft first storeys. *Proceedings of the Golden Jubilee Year Conference on Natural Hazards in the Urban Habitat*; 1997 Nov; New Delhi, India. 13–24p.
5. Anand N, Mightraj C. Seismic behavior of RCC shear wall under different soil conditions. *Proceedings of the Indian Geotechnical Conference on Geo-trends;* 2010 Dec 16–18; Mumbai, India. Mumbai: IGS Mumbai Chapter & IIT Bombay; 2010.
6. Constantinou MC, Kneifati MC. (1986). Effect of soil-structure interaction on damping and frequencies of base-isolated structures. *The 3rd US National Conference on Earthquake Engineering*; 1986 Aug 24–28; Charleston, South Carolina, US. Oakland,CA: Earthquake Engineering Research Institute; 1986. 671–81p.
7. Novak M, Henderson P. Base-isolated buildings with soil-structure interaction. *Earthquake Engng Struct Dyn.* 1989; 18: 751–65p.
8. Kelly JM. Shake table tests of long period isolation system for nuclear facilities at soft soil sites. *Transactions of the 11th international conference on structural mechanics in reactor technology;* 1991 Aug 18–23; Tokyo, Japan. USA: University of California; 1991.
9. Kelly JM. Earthquake-Resistant Design with Rubber. In: *International Conference of Building Officials.* 2nd Edn. London, US*:* Springer; 1996.
10. Spyrakos CC, Vlassis AG. Effect of soil-structure interaction on seismically isolated bridges. *J Earthquake Engng.* 2002; 6 (3): 391–429p.
11. Spyrakos CC, Maniatakis CA, Koutromanos IA. Soil-structure interaction effects on base-isolated buildings founded on soil stratum. *Engng Struct.* 2009; 31(3): 729–37p.
12. Bureau of Indian Standard (BSI). IS 1893 (Part1), *Criteria for Earthquake Resistant Design of Structures*. Part 1: General provisions and buildings. 5th Edn. India: BSI; 2002.