Effect of Soil Structure Interaction on Seismic Performance of Step Back Building Resting on Sloping Ground

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Abstract - *On sloping ground, construction of framed structure is adopted either step back or step back and set back configuration. Due to varying in height of column towards slope and also these buildings are unsymmetrical in nature, hence attract large amount of forces like shear forces, Bending moments, torsional moments and unequal distribution. Over the years, it has been extensively established that the practice of assuming structure being fixed at the base which may leads to errors in evaluation during dynamic loading. These errors are mainly depend on type of soil at the base. To capture the real behaviour of R.C.C framed building resting on slope, in this paper Response spectrum analysis has been carried out to study the effect of soil structure interaction (SSI) on seismic performance of R.C.C framed building of G+5(step back system) with under laying soil types (Hard, Medium and soft soil) and variation in angle of slope from 10^0 to 40^0 by using ETABS software. The Building shall be also analyzed with shear wall with respect to various slope of ground and soil type. The results shall be analyzed in the form of base shear, bending moment, torsional moment, time period, storey displacement and storey drift.*

Key Words: step back building, Soil Structure Interaction, Sloping ground, Response spectrum Analysis

1. INTRODUCTION

In all Hill regions, scarcity of plain ground to construct a building so in hilly region the building is needs to be constructed on sloping ground. Earthquake is the largely danger due to its huge power of seismic wave and which is unpredictable. It themselves do not injured the people, but it is mainly due to collapse and devastation of structures. The buildings which are constructed in hilly region are subjected to the harsh earthquake because for the most part of the hilly regions of India are under the earthquake Zone.

Buildings in hilly areas are irregular and asymmetric, therefore are subjected to severe torsion in addition to lateral forces under the action of seismic force. On sloping ground the following configuration of building are used:

a) Step back system
b) Step back and set back building

While construction it must be noted that Hill buildings are different from resting on the plain ground. i.e. they are irregular and unsymmetrical in horizontal and vertical planes, and torsionally coupled.

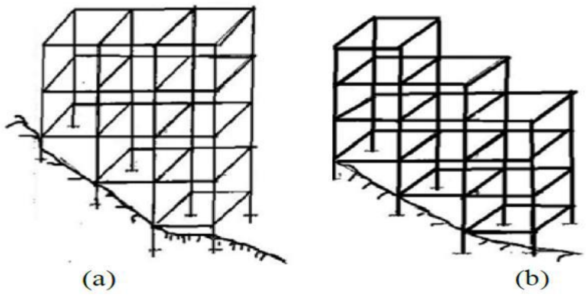


Fig -1: a) Step back system b) Step back and set back system

The study is specifically emphasis on step back system. During previous earthquakes, R.C frame building which have columns at different heights within one storey, are likely to damage more in short columns as compared to long columns in same story. Example of short columns in buildings on sloping ground shown in Fig-2.

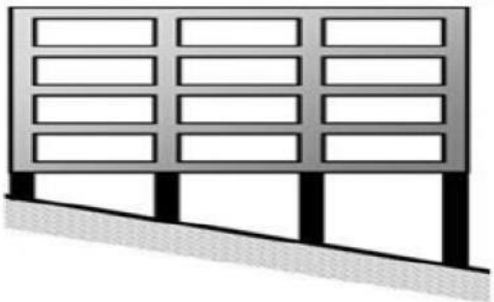


Fig -2: Building frame with short columns

1.1 Soil Structure Interaction (SSI)

The process in which the response of soil influences the motion of the structure and the motion of the structure influences the response of the soil is called Soil Structure Interaction (SSI).SSI effect is more for the stiff and heavy structures resting on the soft soil. For light structure resting on stiff and heavy structures resting on soft soil. SSI can have following type of phenomenon: 1) Kinematic Interaction 2) Inertial interaction. The degree of Influence of SSI on response of structure depends on the following factors:

- Stiffness of Soil
- Dynamic Characteristics of structures itself i.e Natural Period and damping factor.
- Stiffness and mass of structure.

It has been established that the practice of assuming a structure being fixed at base, leads to gross errors in evaluation of its overall response due to dynamic loadings and over estimations in design. These errors are depends on main factor like Soil type.

2. OBJECTIVE OF THE STUDY

1. Modelling of R.C framed building (step back system) on slope with varying angle and variation in soil type.
2. To study the behaviour of building under the soil structure interaction and varying slope angle.
3. To study the effect on base shear, bending moment, torsional moment, fundamental time period, top storey displacement and maximum storey drift with respect to variation in ground slope angle and different type of soil.

3. MODELLING

In this research work, realistic existing G+5 building is used to model as RC frame having structural data as follows:

3.1 Structural data of ETABS

A RC framed building resting on the sloping ground, G+5 realistic plan is chosen for the study which is shown in Fig.-3. The angle of sloping ground is considered from 10^0 to 40^0 with increment of 5^0. The type of Soil considered for the study are Hard, Medium and Soft as per IS code 1893:2016. In all models it is assumed that the depth of footing from ground level is uniform for all footings.

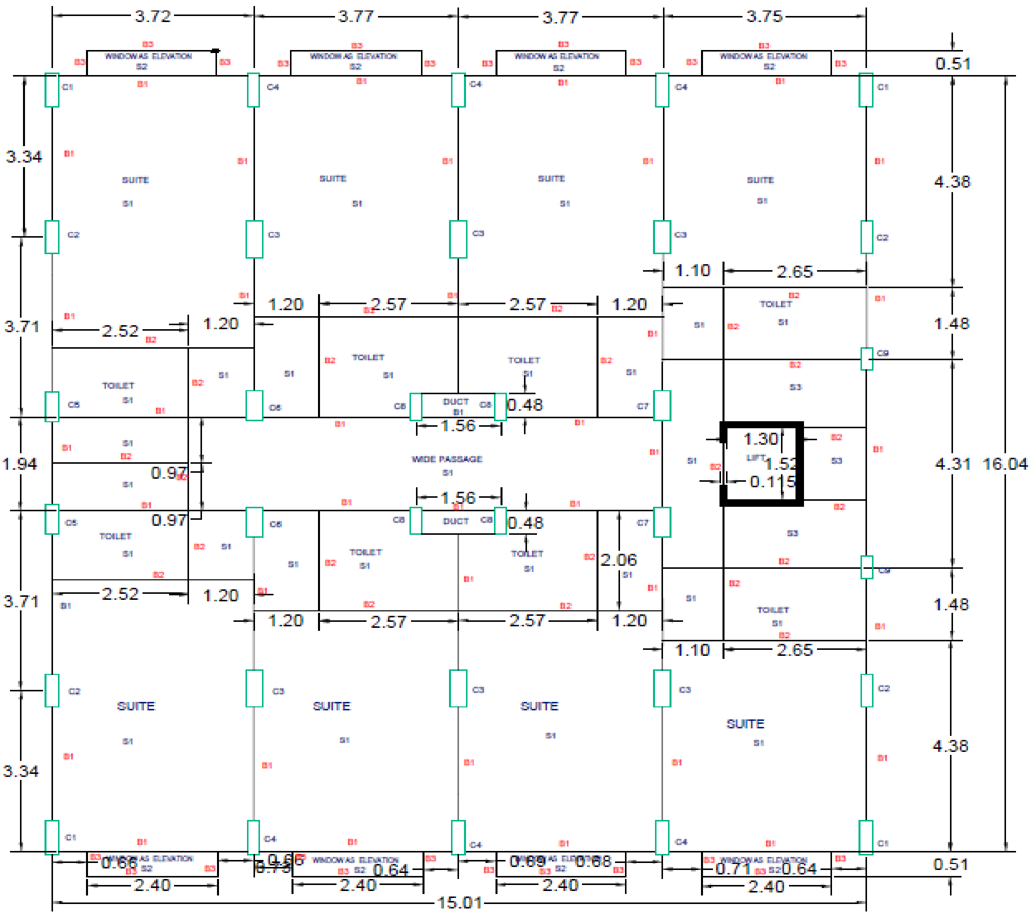


Fig -3: Plan and structural layout of Step back system

The following are details of size of frame and slab sections:

Table-1: Basic detail of model

Sr. No.	Data	Value
1	Materials	M25 Concrete (ϒ=25 kN/m³) Fe500 Steel (ϒ=78.5 kN/m³) Density of brick (ϒ=20 kN/m³)
2	Number of stories	G+5
3	Storey to Storey height	3.3 m
4	Depth of footing below ground level	3 m
5	Height of parapet wall	1 m
6	Height of Staircase Cabin	2.3 m
7	External Wall thickness	0.230 m
8	Internal wall thickness	0.115 m
9	Parapet wall thickness	0.230 m
10	Shear wall thickness	0.115 m

Table-2: Sectional detail structural components considered in Model

Sr. No.	Description	Width (B)	Depth (D)
1	Column (C_1)	300 mm	700 mm
	Column (C_2)	300 mm	700 mm
	Column (C_3)	350 mm	750 mm
	Column (C_4)	300 mm	700 mm
	Column (C_5)	250 mm	600 mm
	Column (C_6)	300 mm	600 mm
	Column (C_7)	300 mm	600 mm
	Column (C_8)	230 mm	550 mm
	Column (C_9)	300 mm	600 mm
2	Primary Beam (B_1)	300 mm	600 mm
	Secondary Beam (B_2)	230 mm	450 mm
	Secondary Beam (B_3)	230 mm	400 mm
3	Slab (S_1)	-	125 mm
	Slab (S_2)	-	100 mm
	Slab (S_3)	-	150 mm
	Slab (S_4)	-	150 mm

S1=Slab of typical floors, S2=Slab of Balcony, S3=Slab of Staircase, S4=Slab of Lift core at the top.

Table-3: Earthquake Load data (as per IS 1893:2016)

Sr. No.	Data	Value
1	Zone and Zone factor	Zone III and 0.16
2	Site type	Hard (I) Medium (II) Soft (III)
3	Importance factor	1
4	Response reduction factor	5
5	Time period	$0.075X(25.3)^{0.75}$=0.85 sec

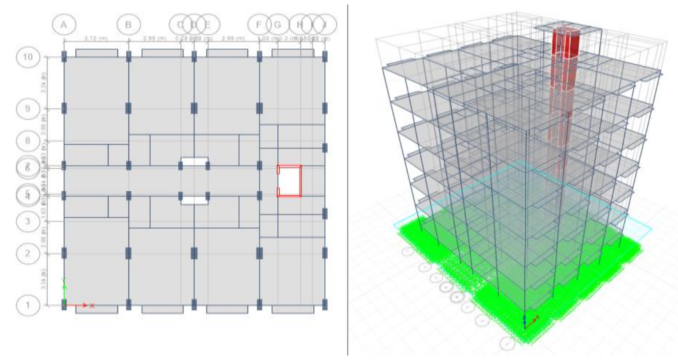


Fig -4: Model of building resting on ground slope of 10^0

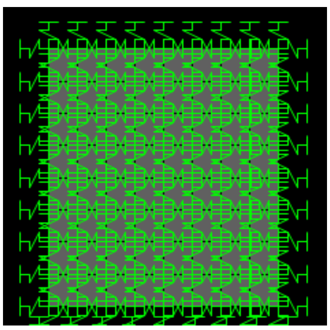


Fig -5: Spring model of soil

Table-4: Load data of Model

Description	Story	DL	LL
Beam (Wall load)	Terrace floor	4.5 kN/m (on Periphery Beams) 230 mm thick wall and 1m height	-
	Ground to 5	12.5 kN/m (Primary Beams B1) 230 mm thick wall 6.5 kN/m (Secondary Beams B2) 115 mm thick wall 5.75 kN/m (B3) Balcony RCC wall	-
Slab (S125)	6	2.5 kN/m² (F.F + W.P)	2 kN/m²
	Ground to 5	1.5 kN/m² (F.F)	2 kN/m² 3 kN/m² for passage
Staircase(S150)	Ground to 6	1.5 kN/m²	3 kN/m²
Sunk Slab (S125)	Ground to 5	6.7 kN/m²	2 kN/m²
Stair cabin slab (S150)	-	7.5 kN/m²	1.5 kN/m²

F.F=Floor finish, W.P=Water proofing

3.2 Soil spring modelling

Interaction of structural system with the soil below as an effect of response of the structure under dynamic loading. The interaction between foundation and soil depends on the elastic properties of soil and foundation dimensions. The dynamic analysis has been carried out for the flexible base replacing with fix base condition to study the Soil Structure Interaction. The foundation flexibility in the analysis is considered by means of replacing the foundation by statically equivalent spring with six degree of freedom which is shown in Fig-5. Modelling of foundation soil has been done by using spring constants and as mentioned in the Book "HANDBOOK OF MACHINE FOUNDATIONS by C.V.VAIDYANATHAN" and they are as follow:

Horizontal spring constant in X direction

$$K_x = \frac{32(1-\nu)G\,R_0}{(7-8\nu)} \qquad R_0 = \sqrt{\frac{Af}{\pi}}$$

Horizontal spring constant in Y direction

$$K_y = \frac{32(1-\nu)G\,R_0}{(7-8\nu)} \qquad R_0 = \sqrt{\frac{Af}{\pi}}$$

Vertical spring constants in Z direction

$$K_z = \frac{4G\,R_0}{(1-\nu)} \quad R_0 = \sqrt{\frac{Af}{\pi}}$$

Rocking spring constant in X direction

$$K_{Rx} = \frac{8G\,R_0^3}{3(1-\nu)} \quad R_0 = \sqrt[4]{\frac{4I_{yf}}{\pi}}$$

Rocking spring constant in Y direction

$$K_{Ry} = \frac{8G\,R_0^3}{3(1-\nu)} \quad R_0 = \sqrt[4]{\frac{4I_{xf}}{\pi}}$$

Torsional spring constant in Z direction

$$K_{Rz} = \frac{16G\,R_0^3}{3} \quad R_0 = \sqrt[4]{\frac{4(I_{yf}+I_{xf})}{\pi}}$$

R_0 =Equivalent Radius

G= Shear modulus of soil
v= Poisson's ratio of soil
A_f =Area of footing
I_{xf} =Moment of inertia of footing about X
I_{yf} =Moment of inertia of footing about Y

Table -5: Elastic properties of foundation soil

Types of Soil	Poisson's ratio v	Elastic Modulus E (kN/m²)	Shear Modulus G (kN/m²)
Hard	0.25	65000	26000
Medium	0.35	35000	12963
Soft	0.5	15000	5000

For the all types of footings and soils the point spring values are shown in below tables:

Table-6: Spring constant values for hard soil

Footing identity	Size (m)	Contributing area for single spring (m)	K_x	K_y	K_z	K_{RX}	K_{RY}	K_{RZ}
F1 F4	2.6 x 3 x 0.7	0.325 x 0.375	24580.85	24580.85	27312.06	656.81	814.07	1105.26
F2	2.8 x 2.8 x 0.7	0.35 x 0.35	24643.80	24643.80	27380	736	736	1105.28
F3	3.2 x 2.8 x 0.7	0.4 x 0.35	26345.33	26345.33	29272.59	995.09	814.47	1359.43
CF1	2.6 x 3.8 x 0.6	0.65 x 0.64875	39635.44	39635.44	44039.37	3803.76	2470.62	4741.30
CF2	2.6 x 5 x 0.5	0.64 x 0.485	39533.68	39533.68	43926.31	3789.12	2442.20	4710
CF3	3.6 x 4.8 x 0.5	0.52 x 0.6467	40831.26	40831.26	45368.06	2845.85	3946.95	5116.95
Mat Foundation	6.8 x 5.6 x 0.6	0.2 x 0.225	14936.40	14936.40	16596	150.19	179.21	247.37

Table-7: Spring constant values for medium soil

Footing identity	Size (m)	Contributing area for single spring (m)	K_x	K_y	K_z	K_{RX}	K_{RY}	K_{RZ}
F1 F4	2.6 x 3 x 0.7	0.325 x 0.375	12644.51	12644.51	15712.11	377.85	468.32	551.06
F2	2.8 x 2.8 x 0.7	0.35 x 0.35	12676.89	12676.89	15752.35	423.9	423.9	551.07
F3	3.2 x 2.8 x 0.7	0.4 x 0.35	13552.16	13552.16	16839.97	572.46	468.55	677.78
CF1	2.6 x 3.8 x 0.6	0.65 x 0.64875	20388.66	20388.66	25335.02	2188.23	1421.3	2363.9
CF2	2.6 x 5 x 0.5	0.64 x 0.485	20336.31	20336.31	25269.97	2179.81	1404.95	2348.3
CF3	3.6 x 4.8 x 0.5	0.52 x 0.6467	21003.79	21003.79	26099.39	1637.16	2270.60	2551.19
Mat Foundation	6.8 x 5.6 x 0.6	0.2 x 0.225	7683.35	7683.35	9547.36	86.40	103.10	123.33

Table-8: Spring constant values for soft soil

Footing identity	Size (m)	Contributing area for single spring (m)	K_x	K_y	K_z	K_{RX}	K_{RY}	K_{RZ}
F1 F4	2.6 x 3 x 0.7	0.325 x 0.375	5252.32	5252.32	7878.48	189.464	234.827	212.55
F2	2.8 x 2.8 x 0.7	0.35 x 0.35	5265.77	5265.77	7898.65	212.554	212.554	212.554
F3	3.2 x 2.8 x 0.7	0.4 x 0.35	5629.34	5629.34	8444.02	287.04	234.94	261.428
CF1	2.6 x 3.8 x 0.6	0.65 x 0.64875	8469.11	8469.11	12703.7	1097.24	712.678	911.788
CF2	2.6 x 5 x 0.5	0.64 x 0.485	8447.37	8447.37	12671	1093.02	704.48	905.76
CF3	3.6 x 4.8 x 0.5	0.52 x 0.6467	8724.63	8724.63	13086.9	820.92	1138.54	984.03
Mat Foundation	6.8 x 5.6 x 0.6	0.2 x 0.225	3191.54	3191.54	4787.31	43.3	51.69	47.57

Unit of K_x K_y K_z is kN/m and unit of K_{RX} K_{RY} and K_{RZ} is kN m/rad.

By using trigonometric function level of footing was calculated and sloping ground was modelled for 10^0 to 40^0. All models (21 models) were analyzed by Response spectrum method and results were compared. In the below elevation views internal columns C8 act as combined footing which are provided at same level. The sizes of all footing are mentioned in above tables.

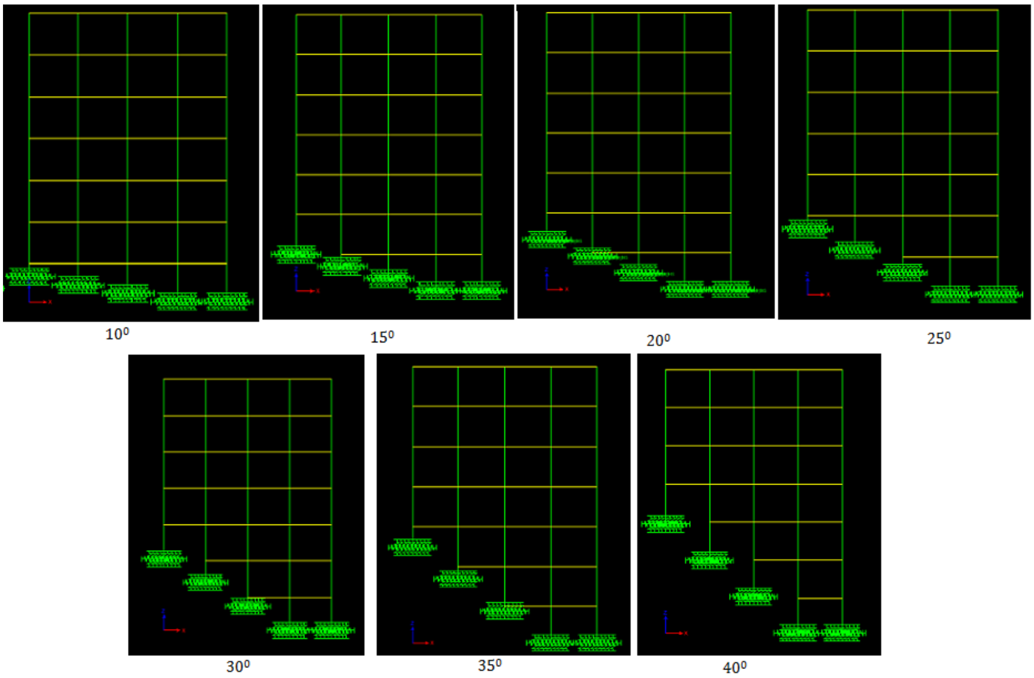
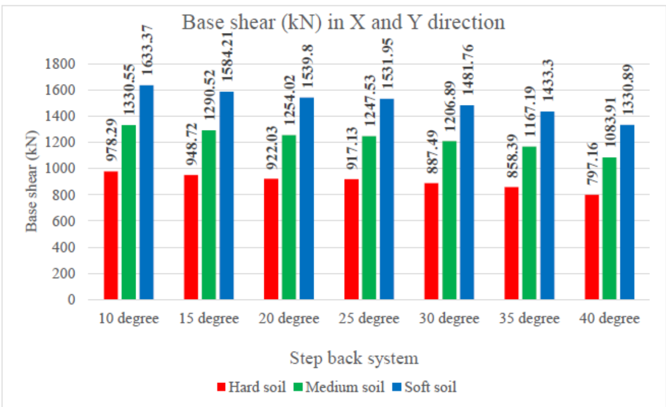


Fig -6: Sectional views of step back building model resting on 10^0 to 40^0

4. RESULTS AND COMPARISON

Following are the results which are obtained in the ETABS software.

4.1 Comparison of Base shear



Graph -1: Comparison of Base shear

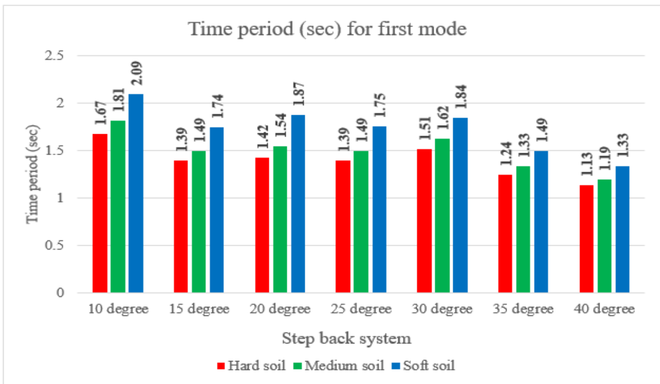
In the above graph for the same slope of RC frame building base shear is averagely increased 35.99% in medium soil and 66.9% in soft soil as compared to hard soil because as per the IS code 1893:2016 clause 6.4.2, Design acceleration coefficient (Sa/g ratio) for medium soil and soft soil is more as compared to hard soil for the same time period.

In step back system models, with increase in angle of slope the mass of building is decreased for the same elevation of building so the base shear also decreased as compared to 10^0 degree model as shown in below table:

Table-9: Change in base shear as compared to 10^0 model

Slope/Type of soil	15^0	20^0	25^0	30^0	35^0	40^0
Hard	-3.0%	-5.7%	-6.2%	-9.2%	-12.2%	-18.5%
Medium	-3.0%	-5.7%	-6.2%	-9.2%	-12.2%	-18.5%
Soft	-3.0%	-5.7%	-6.2%	-9.2%	-12.2%	-18.5%

4.2 Comparison of Time period



Graph -2: Comparison of Time period

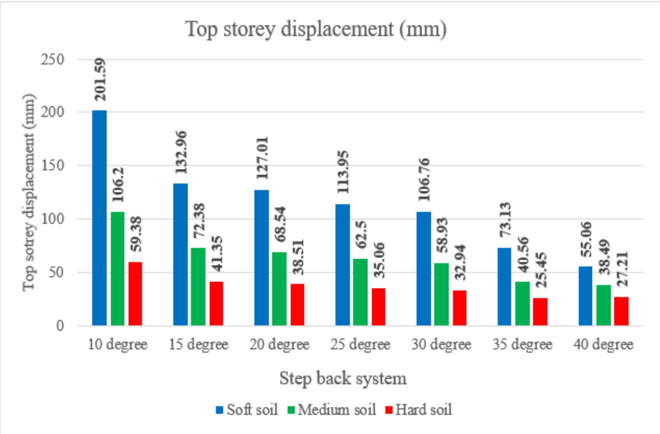
In the above graph for the same slope of RC frame building time period averagely increased 7.29% in medium and 23.94% soft soil as compared to hard soil because increase in the flexibility of soil foundation gives more flexibility to the structure so the time period of building is increased.

In step back system models, with increase in angle of slope the vertical stiffness of the structure is changed so the time period also changed and decreased as compared to 10^0 model which is shown in below table:

Table-10: Change in time period as compared to 10^0 model

Slope/ Type of soil	15^0	20^0	25^0	30^0	35^0	40^0
Hard	-16.7%	-14.9%	-16.7%	-9.5%	-25.7%	-32.3%
Medium	-17.6%	-14.3%	-17.6%	-10.4%	-26.5%	-34.2%
Soft	-16.7%	-10.5%	-16.2%	-11.9%	-28.7%	-36.3%

4.3 Comparison of Top storey displacement



Graph -3: Comparison of Top storey displacement

In the above graph for the same slope of RC framed building top storey displacement averagely decreased 43.35% in medium and 66.18% in hard soil as compared to soft soil because decrease in the flexibility of soil foundation gives less flexibility to the structure so the top storey displacement of building is decreased.

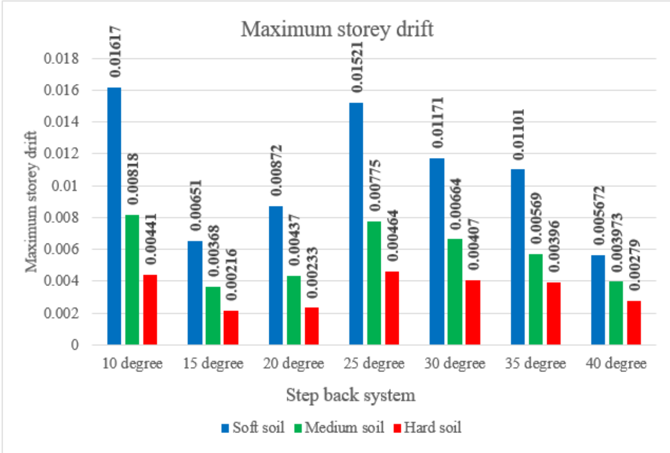
In step back system models, with increase in angle the vertical stiffness of the structure is changed so the top storey displacement also changed and decreased as compared to 10^0 model which is shown in below table:

Table-11: Change in top storey displacement as compared to 10^0 model

Slope/Type of soil	15^0	20^0	25^0	30^0	35^0	40^0
Hard	-34.0%	-36.9%	-43.4%	-47.0%	-63.7%	-72.6%
Medium	-31.8%	-35.4%	-41.1%	-44.5%	-61.8%	-63.7%
Soft	-30.3%	-35.1%	-40.9%	-44.5%	-57.1%	-54.1%

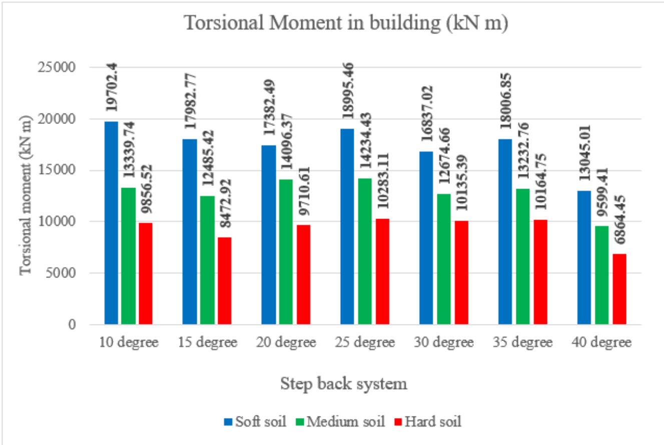
4.4 Comparison of maximum storey drift

In the above graph for the same slope RC framed building maximum storey drift averagely decreased 44.76% in medium and 66.05% times in hard soil as compared to soft soil because decrease in the flexibility of soil foundation gives less flexibility to the structure so maximum storey drift between two storey of building is decreased. From the graph it can be said that in 15^0 and 20^0 models, storey drift is obtained less as compared to other models.



Graph -4: Comparison of maximum storey drift

4.5 Comparison of torsional moment in building



Graph -5: Comparison of torsional moment in building

In the above graph torsional moment of building is decreased 26.35% in medium and 46.22% in hard soil as compared to soft soil because decrease in the flexibility of soil foundation gives less flexibility and allow less torsional (twisting) moment to the structure so torsional moment of building is decreased.

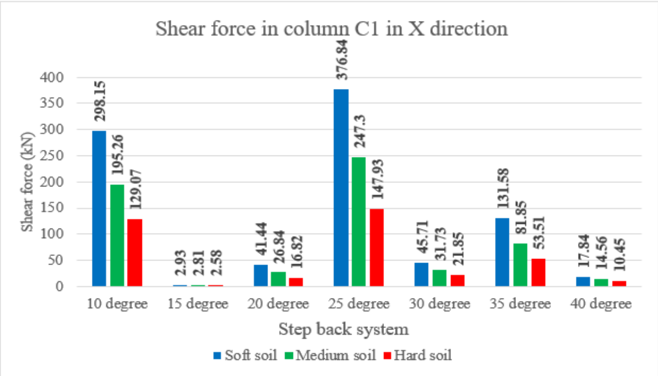
In step back system, with increase in angle the rotational stiffness of the structure is changed so the torsional moment of building is changed as compared to 10^0 model because its depend upon stiffness of building and type of soil on which building is rest. Which is shown in below table:

Table-12: Change in torsional moment as compared to 10^0 model

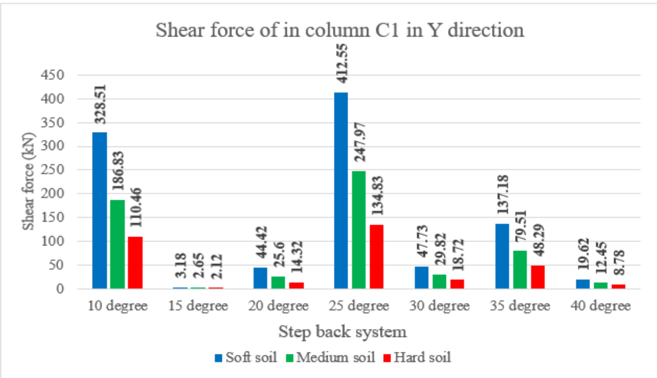
Slope/Type of soil	15^0	20^0	25^0	30^0	35^0	40^0
Hard	-34.0%	-36.9%	-43.4%	-47.0%	-63.7%	-72.6%
Medium	-31.8%	-35.4%	-41.1%	-44.5%	-61.8%	-63.7%
Soft	-30.3%	-35.1%	-40.9%	-44.5%	-57.1%	-54.1%

4.6 Comparison of S.F in column C1

In the below two graphs shear force of corner column C1 was compared.



Graph -6: Comparison of S.F in column C1 in X direction



Graph -7: Comparison of S.F in column C1 in Y direction

In the graph with decrease in flexibility of soil shear force in X direction averagely decreased 27.84% in medium soil and 48.81% in hard soil as compared to soft soil and shear force in Y direction averagely decreased 36.87% in medium soil and 59.36% in hard soil as compared to soft soil. In the above graphs maximum shear force of column C1 is obtained in the 25^0 model and minimum shear force obtained in 15^0 model.

5. CONCLUSIONS

1. The base shear is increased 35.9% in medium soil and 66.9% in soft soil as compared to hard soil and decreased 18.51% in all type of soil when ground slope changes from 10^0 to 40^0.
2. Time period is increased 7.29% in medium soil and 23.94% in soft soil as compared to hard soil and decreased 34.31% in all type of soil when ground slope changes from 10^0 to 40^0.
3. Top storey displacement is decreased 43.35% in medium soil and 66.18% in hard soil as compared to soft soil and decreased 63.53% in all type of soil when ground slope changes from 10^0 to 40^0.
4. Maximum storey drift is decreased 44.76% in medium soil and 66.05% in hard soil as compared to soft soil. Location and value of Maximum storey drift is changed with increased in the slope of ground because it is depend upon the stiffness of the individual floor and according to that it will change.
5. Torsional moment is decreased 26.35% in medium soil and 46.22% in hard soil as compared to soft soil and when the sloping ground is increased the stiffness of building is changed so according to stiffness it is increased and decreased as compared to 10^0 model.
6. In column C1 with increase in angle of sloping ground column length is changed. According to the column length the shear force is generated. When the length of the column is decreased it has more stiffness as compared to other column and attracts more force as compared to other columns so in short columns shear force is more.
7. By considering parameters like storey drift, torsional moment in building and shear force of column, the performance of the **20^0 model** is very good among all models of the step back system.

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