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EXPERIMENTAL INVESTIGATION ON THE DYNAMIC RESPONSE OF STEPBACK AND STEPBACK - SETBACK STRUCTURES

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ABSTRACT

The seismic response of the buildings resting on sloping ground is significantly different from the response of the buildings resting on the level topography due to arise of irregularities in both horizontal and vertical planes. The present study deals with computation of degree of irregularities in the form of irregularity indices as per the recommendations by previous researchers. Experimental and numerical studies have been carried out to explore the dynamic behaviour of five storey buildings resting on suitable slope adopted as per irregularity indices. Prototype five storey building has been scaled to construct a model by applying suitable scaling laws. The scaled building models are subjected to seismic excitations at resonant frequencies using shake table facility. A comparative study has been carried out between experiments and Numerical front. The outcome of the study indicates that setback – stepback building configuration is not vulnerable significantly to seismic activity.

KEYWORDS: Sloping ground; Irregularity indices; Prototype; Scaled model

INTRODUCTION

The expansion of infrastructure in hilly terrain regions has necessitated a review of structures built on sloping land in terms of construction material and structural systems. Buildings resting on sloping ground induces irregularities in the structure because of the variation in the column heights with respect to building height so that it leads to the stiffness and mass irregularities. Buildings located on slopes pose unique construction and structural challenges [1]. Slope failures of seismic origin are generally disastrous, resulting in major destruction to residences, buildings, roads, foundations, embankments, etc. [2, 3 and 4]. Behaviour of reinforced concrete (RC) structures resting on sloping terrain are comparatively different than the buildings resting on the flat terrain. Due to the presence of the steepness of the slope, buildings are characteristically constructed in a stepback arrangement, even though an integrated stepback – setback arrangement is also common. Torsional moments are developed because of the unsymmetrical geometry of these structures along with the eccentricity developed due to the variations in the alignments of the stiffness and center of mass at each story. In addition to this, there is an increased stress concentration at the setback zones, during seismic activity [1]. Due to the design failures in RC and masonry buildings during recent earthquakes, e.g. Nepal (2015) and Sikkim (2011) have resulted in massive casualties.

Buildings which are constructed on sloping ground are mainly classified in to two forms such as stepback and stepback–setback buildings. Due to the presence of irregularities in both horizontally and vertical directions, buildings founded on sloping ground are different from those founded on plain ground. The vertical irregularity arises due to existence of the stepback and stepback – setback configurations, wherein the centre of mass and centre of stiffness of a story do not accord with each other. The variation of mass and stiffness in both horizontal and vertical planes impart a substantial role in the seismic behavior of a building during an earthquake [5]. Since these buildings are irregular in both horizontal as well as vertical axis, they are subjected to torsional effect during lateral shaking. Also, at the setback location, there is an increase in stress concentration during an earthquake [6].

The structure subjected to seismic forces are always vulnerable to damage especially if it occurs on a building located on hills which is at some inclination to the ground. The chances of damage increase much more due to increased lateral forces on short columns on uphill side and thus leads to the formation of plastic hinges. Buildings built on sloping ground are different from those built on plain ground because they are irregular horizontally as well as vertically. The distribution of mass and stiffness in horizontal and vertical planes, plays a significant role in the seismic behaviour of building during an earthquake.

PREVIOUS STUDIES

[7] studied the seismic behaviour of stepback and stepback – setback buildings when subjected to response spectrum analysis using Finete Element analysis. They observed the torsional effect of these buildings by varying the story height and number of bays along a sloping ground of inclination 27°. From the results, it is noted that stepback buildings were found to be the most susceptible compared to other configurations and the development of torsional moment was highest in stepback building.

[8] performed linear and nonlinear time history analysis for a nine story RC frame building (stepback) located on 45^0 slope and also considered buildings with vertical cuts considering five ground motions. The buildings were subjected to cross-slope excitations and they observed torsional effects in the buildings. [9] considered stepback, setback, and stepback – setback buildings having building heights varying between 15.2 and 52.6 m (4 – 15 story) for their study. These buildings were subjected to seismic excitations and their performance were compared in terms of top story displacement and base shear and concluded that stepback buildings are more susceptible in the sloping ground condition.

[10] considered two kinds of irregularities, i.e., plan irregularity and vertical irregularity with setback on sloping ground for their study. Pushover analysis was performed in all three directions using numerical analysis. They observed that the buildings located on sloping ground are more likely to damage than buildings located on level ground. [11] performed pushover analysis on a 10 story bare frame and infill frame building resting on a sloping ground at an inclination of 27° to the horizontal. They concluded that, base shear, story displacement, and formation of plastic hinges are more in case of bare frame compared to infill frame.

[12] analysed the behaviour of stepback and stepback–setback buildings by varying the number of bays and slope inclination of the ground. These buildings were subjected to response spectrum analysis using FEM based software. They studied the dynamic characteristics of the building, i.e., base shear, top story displacement, and natural time period with respect to variations in the number of stories (13 – 9) and number of bays (12 – 14) along the slope. They concluded that increasing the number of bays makes the structure less vulnerable as it increases the time period and reduces the top-story displacement. However, in a response spectrum analysis, only the maximum response can be estimated but not the time evolution of response. Further, no information is available about the time when the maximum response takes place.

Based on the earlier studies, it is seen that most of the studies have been carried out on stepback and stepback – setback buildings on sloping ground at various slopes using numerical studies. Therefore, in the present study, a five-story three - bay RC building frame was considered for the analysis and scaled models representing the prototype were developed using appropriate scaling laws. These models were subjected to seismic excitations to determine the dynamic characteristics of the building resting on sloping ground.

DESIGN SPECIFICATION OF BUILDING

The five-story stepback and stepback – setback buildings were modelled and analysed using FEM - based software [15] on sloping land with slope angles ranging from 20^0 to 35^0. The model consists of five storeys with a storey height of 3 m having 3 bays with a spacing of 4 m along longitudinal direction and one bay with a spacing 4 m along transverse direction. Figure 1 shows the plan of a building along with the column orientation and Figure 2 shows the three - dimensional view of the sloped building.

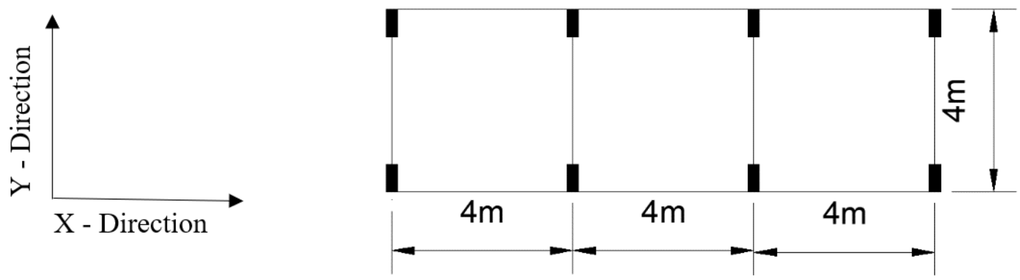
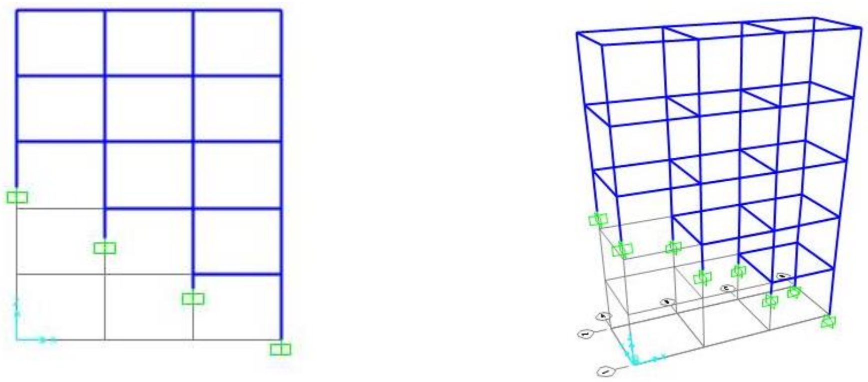


Fig. 1 Plan of the building along with column orientation



(a) Elevation (b) 3 - Dimensional View

Fig. 2 Three - dimensional view of the stepback building (30^0 slope)

Both dead load and live loads are considered as per [16] and the details are shown in Table 1. Structural elements have been designed as per [17] and [14] by considering M 25 grade concrete and Fe 415 grade steel. The dynamic parameters considered for the analysis (Response spectrum) is given in Table 2. Table 3 indicates the designed dimensions of the building components.

Table 1: Details of load

Storey	Dead Load	Live Load
1, 2, 3, 4	1 kN/m^2	3 kN/m^2
Roof	2 kN/m^2	1.5 kN/m^2

Table 2: Details of dynamic parameters

Sl. No.	Contents	Description
1	Seismic Zone	V
2	Soil Type	TYPE-I
3	Importance Factor	1
4	Response Reduction Factor	5

Table 3: Details of dimensions of building components

Structural element	Dimension
Column	250 × 600 mm
Beam	300 × 400 mm
Slab thickness	150 mm

COMPUTATION OF IRREGULARITY INDEX

Irregularity indices for stepback and stepback – setback buildings have been computed by using the approaches adopted by [18] and [19]. However, both of them used their approaches for computing irregularity indecies for the buildings resting on the level ground.

[18] proposed an approach for quantifying the irregularity in stepped building on level ground that accounts for properties associated with mass and stiffness distribution in the frame. They proposed a measure of vertical irregularity, called 'regularity index', as given in Equation 1.

$$\eta = \frac{\Gamma_1}{\Gamma_{ref}} \tag{1}$$

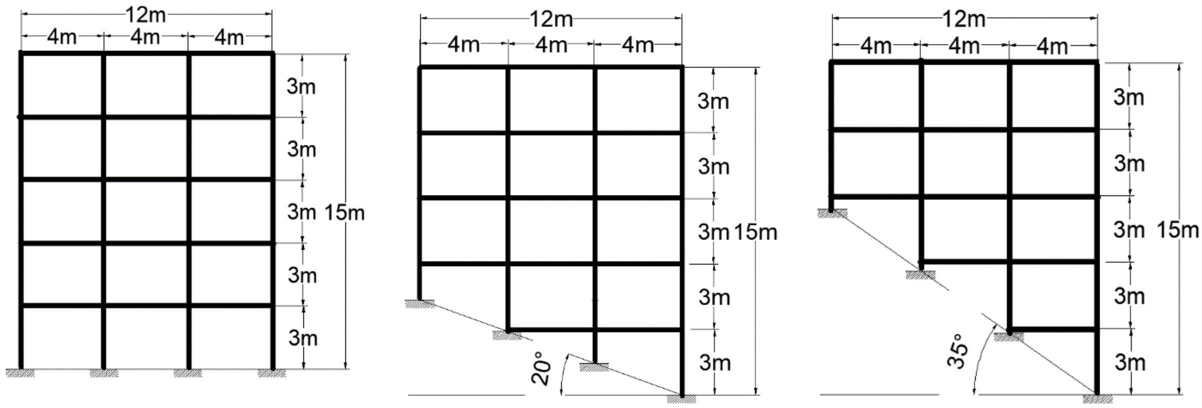
where, Γ_1 is the 1st mode participation factor for the setback building frame under consideration and Γ_{ref} is the 1st mode participation factor for the similar regular building frame without steps.

[19] arrived with an expression to quantify irregularity indices for the irregular buildings resting on level ground using dynamic characteristics of the buildings. They proposed a measure of vertical irregularity, called 'irregularity index', as given in Equation 2.

$$\psi = \frac{V_{f,\ regular}}{V_{f,\ irregular}} \tag{2}$$

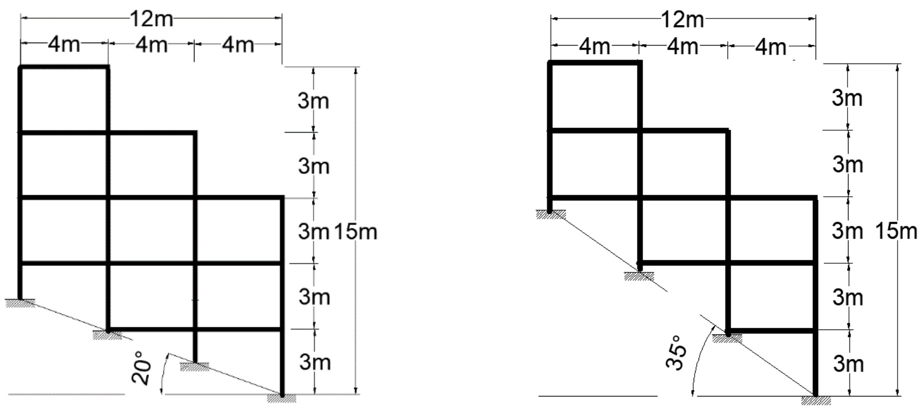
here ψ is the irregularity index, $V_{f,\ irregular}$ is the fundamental mode base shear of the irregular frame and $V_{f,\ regular}$ is the fundamental mode base shear of a similar regular frame without any irregularities.

Using [18] and [19] approachs, regularity indices and irregularity indices of stepback and stepback – setback medium rise five storey buildings are computed. For this, 17 different stepback and stepback – setback buildings were considered by varying slope angles from 20^0 to 35^0 along with regular building which are as shown in Figure 3 and Figure 4.



(a) Regular Building (b) Stepback Building - 20^0 (c) Stepback Building - 35^0

Fig. 3 Elevation of the stepback building (20^0 to 35^0 slope)



(a) Stepback-Setback Building - 20^0 (b) Stepback- Setback Building - 35^0

Fig. 4 Elevation of the stepback – setback building (20^0 to 35^0 slope)

Tables 4 and 5 shows the computed values of regularity indices along with fundamental frequencies using [18] approach, followed by graphical representation of the same in Figure 5 and Figure 6. Tables 6 and 7 shows the computed values of irregularity indices along with fundamental frequencies using [19] approach. Further the obtained results i.e., irregularity indices were plotted against frequencies and sloping angle, the same has been presented in Figure 7 and Figure 8.

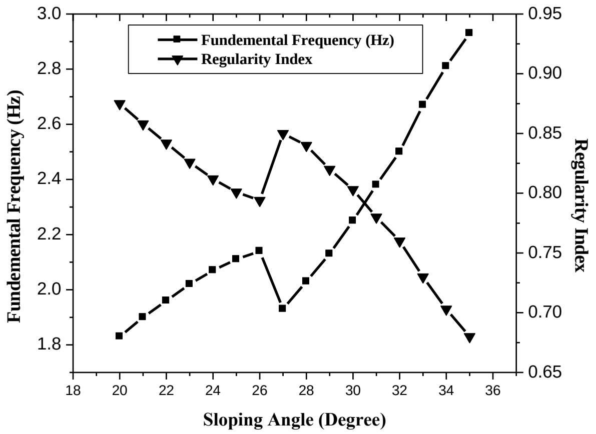


Fig. 5 Variation of fundamental frequency and regularity index along with sloping angle (stepback building)

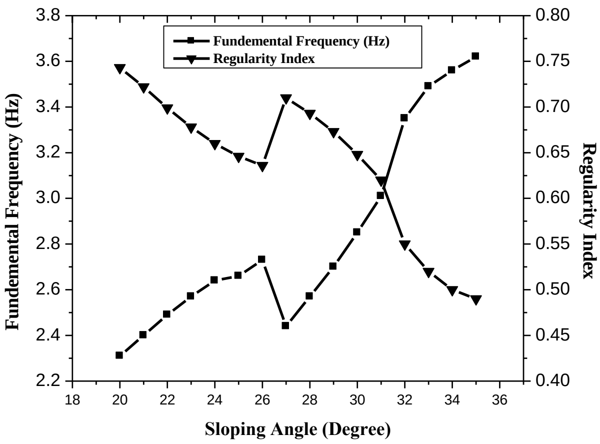


Fig. 6 Variation of fundamental frequency and regularity index along with sloping angle (stepback - setback building)

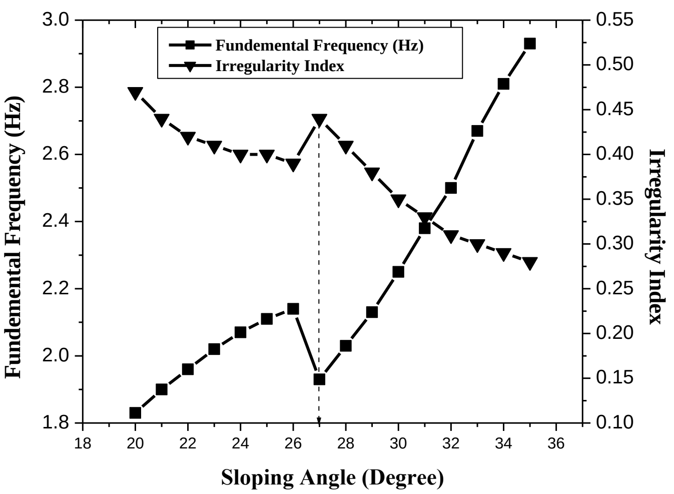


Fig. 7 Variation of fundamental frequency and irregularity index along with sloping angle (Stepback building)

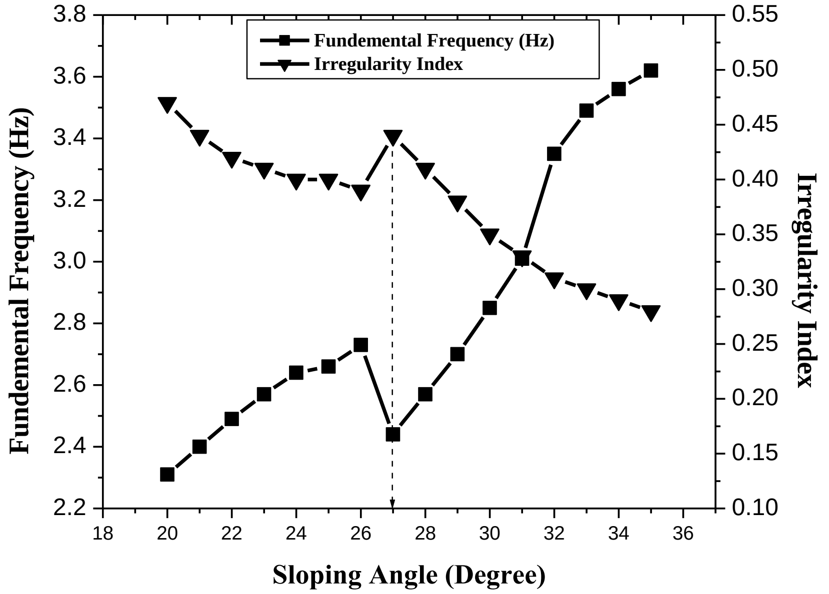


Fig. 8 Variation of fundamental frequency and irregularity index along with sloping angle (Stepback – setback building)

Table 4: Calculation of Regularity Index as per [18] approach for Stepback Building

Sl. No.	Vertical regularity calculation as per [18]	Sloping Angle	Fundemental Frequency (Hz)	Regularity Index
1	Γ_1 =14.32 KN-m, Γ_{ref} =14.32 KN-m	0	1.36	1
2	Γ_1 =12.53 KN-m, Γ_{ref} =14.32 KN-m	20	1.83	0.875
3	Γ_1 =12.30 KN-m, Γ_{ref} =14.32 KN-m	21	1.90	0.858
4	Γ_1 =12.07 KN-m, Γ_{ref} =14.32 KN-m	22	1.96	0.842
5	Γ_1 =11.84 KN-m, Γ_{ref} =14.32 KN-m	23	2.02	0.826
6	Γ_1 =11.63 KN-m, Γ_{ref} =14.32 KN-m	24	2.07	0.812
7	Γ_1 = 11.48 KN-m, Γ_{ref} =14.32 KN-m	25	2.11	0.801
8	Γ_1 = 11.38 KN-m, Γ_{ref} =14.32 KN-m	26	2.14	0.794
9	Γ_1 = 12.18 KN-m, Γ_{ref} =14.32 KN-m	27	1.93	0.85
10	Γ_1 =11.99 KN-m, Γ_{ref} =14.32 KN-m	28	2.03	0.84
11	Γ_1 = 11.77 KN-m, Γ_{ref} =14.32 KN-m	29	2.13 Hz	0.82
12	Γ_1 = 11.51 KN-m, Γ_{ref} =14.32 KN-m	30	2.25 Hz	0.803
13	Γ_1 = 11.20 KN-m, Γ_{ref} =14.32 KN-m	31	2.38 Hz	0.78
14	Γ_1 = 10.85 KN-m, Γ_{ref} =14.32 KN-m	32	2.50 Hz	0.76
15	Γ_1 = 10.47 KN-m, Γ_{ref} =14.32 KN-m	33	2.67 Hz	0.73
16	Γ_1 = 10.08 KN-m, Γ_{ref} =14.32 KN-m	34	2.81 Hz	0.703
17	Γ_1 = 9.76 KN-m, Γ_{ref} =14.32 KN-m	35	2.93 Hz	0.68

Table 5: Calculation of regularity Index as per [18] approach for Stepback - Setback Building

Sl. No.	Vertical regularity calculation as per [18]	Sloping Angle	Fundamental Frequency (Hz)	Regularity Index
1	Γ_1 =14.32 KN-m, Γ_{ref} =14.32 KN-m	0	1.36	1
2	Γ_1 = 10.65 KN-m, Γ_{ref} =14.32 KN-m	20	2.31	0.743
3	Γ_1 =10.34 KN-m, Γ_{ref} =14.32 KN-m	21	2.40	0.722
4	Γ_1 = 10.02 KN-m, Γ_{ref} =14.32 KN-m	22	2.49	0.699
5	Γ_1 = 9.72 KN-m, Γ_{ref} =14.32 KN-m	23	2.57	0.678
6	Γ_1 = 9.44 KN-m, Γ_{ref} =14.32 KN-m	24	2.64	0.66
7	Γ_1 = 9.26 KN-m, Γ_{ref} =14.32 KN-m	25	2.66	0.646
8	Γ_1 = 9.11 KN-m, Γ_{ref} =14.32 KN-m	26	2.73	0.636
9	Γ_1 = 10.18 KN-m, Γ_{ref} =14.32 KN-m	27	2.44	0.71
10	Γ_1 = 9.93 KN-m, Γ_{ref} =14.32 KN-m	28	2.57	0.693
11	Γ_1 = 9.64 KN-m, Γ_{ref} =14.32 KN-m	29	2.70	0.673
12	Γ_1 = 9.28 KN-m, Γ_{ref} =14.32 KN-m	30	2.85	0.648
13	Γ_1 = 8.87 KN-m, Γ_{ref} =14.32 KN-m	31	3.01	0.62
14	Γ_1 = 7.92 KN-m, Γ_{ref} =14.32 KN-m	32	3.35	0.55
15	Γ_1 = 7.44 KN-m, Γ_{ref} =14.32 KN-m	33	3.49	0.52
16	Γ_1 = 7.21KN-m, Γ_{ref} =14.32 KN-m	34	3.56	0.5
17	Γ_1 = 7.07 KN-m, Γ_{ref} =14.32 KN-m	35	3.62	0.49

Table 6: Calculation of irregularity Index as per [19] approach for Stepback Building

Sl. No.	Sloping Angle	Fundemental Frequency (Hz)	Base Shear (kN)	Irregularity Index (ψ)
1	0	1.36	1050.65	1
2	20	1.83	1664.26	0.63
3	21	1.90	1754.81	0.59
4	22	1.96	1835.26	0.57
5	23	2.02	1907.45	0.55
6	24	2.07	1969.19	0.53
7	25	2.11	2017.59	0.52
8	26	2.14	2058.87	0.51
9	27	1.93	1809.43	0.58
10	28	2.03	1955.25	0.53
11	29	2.13	2119.02	0.49
12	30	2.25	2308.93	0.45
13	31	2.38	2511.27	0.42
14	32	2.50	2711.14	0.38
15	33	2.67	3153.43	0.33
16	34	2.81	3211	0.32
17	35	2.93	3316.53	0.31

Table 7: Calculation of irregularity Index as per [19] approach for Stepback - Setback Building

Sl. No.	Sloping Angle	Fundemental Frequency (Hz)	Base Shear (kN)	Irregularity Index (ψ)
1	0	1.36	1050.65	1
2	20	2.31	2240.5	0.47
	21	2.40	2357.24	0.44
4	22	2.49	2453.41	0.42
5	23	2.57	2532.02	0.41
6	24	2.64	2593.35	0.40
7	25	2.66	2594.49	0.40
8	26	2.73	2678.67	0.39
9	27	2.44	2395.12	0.44
10	28	2.57	2584.51	0.41
11	29	2.70	2778.22	0.38
12	30	2.85	2985.93	0.35
13	31	3.01	3178.205	0.33
14	32	3.35	3498.82	0.31
15	33	3.49	3497.6	0.30
16	34	3.56	3599.94	0.29
18	35	3.62	3668.36	0.28

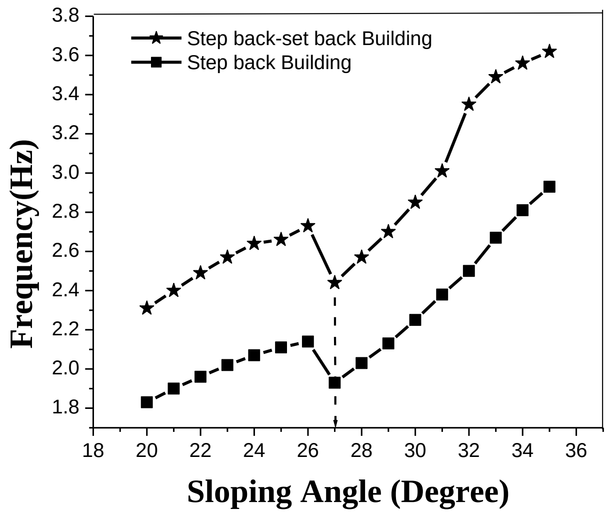
From Table 4 and Figure 5 it is seen that there is a sudden dip in the fundamental frequency and sudden increase in the regularity indices of stepback buildings resting on at 27^0 slope.

From Table 5 and Figure 6 it is observed that at a sloping angle of 27^0 regularity index is increased and fundamental frequency is reduced in stepback – setback buildings.

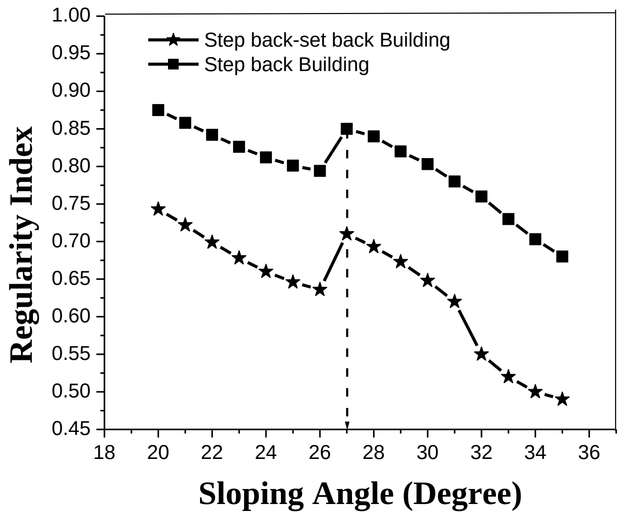
From Table 6 and Figure 7 it can be noted that the irregularity index is increased and fundamental frequency is decreased in case of stepback buildings at an angle of 27^0.

From Table 7 and Figure 8 it is seen that, at a sloping angle of 27^0 irregularity index is found to increase and fundamental frequency is found to decrease in case of stepback – setback building configuration.

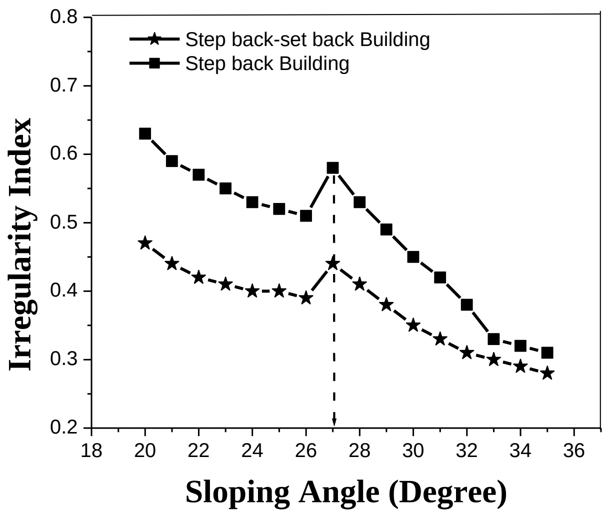
Furthermore, for both stepback and stepback - setback building configurations, the basic frequencies, regularity index, and irregularity index are compared. Figure 9 shows the relationship between sloping angle and frequency for both stepback and stepback - setback buildings, as well as the relationship between sloping angle, regularity and irregularity indices.



(a) Sloping angle v/s Frequency



(b) Sloping angle v/s Regularity Index

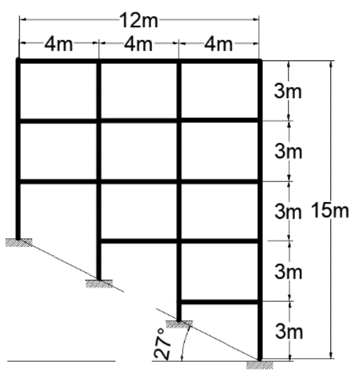


(c) Sloping angle v/s Irregularity Index

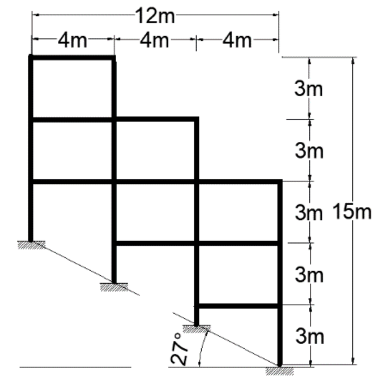
Fig. 9 Variation of Fundamental frequency, regularity index and irregularity index along with sloping angle

From Figure 9 it is observed that the fundamental frequencies of stepback - setback buildings are substantially higher than stepback buildings. In addition, when the sloping angle increases, the frequency of buildings rises, but regularity and irregularity indices fall. However, at 27^0, the regularity and irregularity indices are found to be higher, while fundamental frequency is lower.

Hence, an experimental study has been carried out to observe the behavior of buildings resting at a sloping angle of 27^0. Figure 10 shows the geometry and dimensions of the buildings considered for experimental study. Here after regular RC building is referred to as a prototype, while scaled down versions are referred to as scaled models.



(a) Stepback Building(SB)



(b) Stepback-Setback Building (SSB)

Fig. 10 Elevation of the Buildings resting on 27^0 slope

SCALING OF PROTOTYPE STRUCTURE

The most important aspect of the experiment is to create an experimental model that can accurately reflect the prototype with minimal distortion. Hence geometric scaling, dynamic scaling and material scaling have been chosen properly in the present study, as per [20]. Table 8 shows the parameters for scaling along with scale factor.

Adopting a scale factor of 30, stepback and stepback - setback models are scaled down. The scaling principles in Table 8 show that mass density should be equal to equity. An appropriate and nearest modulus of elasticity of concrete have been adopted and also it has to be help full in fabrication of the model. The obtained geometric and material parameters of the scaled model are shown in Table 9.

Table 8: Scaling relationships in terms of Geometric Scaling Factor [20]

Sl. No.	Parameters	Scale Factor
1	Mass density	1
2	Stiffness	S^2
3	Force	S^3
4	Modulus	S
5	Acceleration	1
6	Frequency	$S^{-1/2}$
7	Time	$S^{1/2}$
8	Shear wave velocity	$S^{1/2}$
9	Length	S
10	Stress	S
11	Strain	1
12	EI	S^5

Table 9: Geometric and material properties of scaled model

Sl. No.	Contents	Description
1	No. of stories	5
2	Storey height	0.1 m
3	Bay width (X-axis) each	0.133 m
4	Bay width (Y-axis)	0.133 m
5	Slab thickness	11 mm
6	Size of Columns	2 mm X 12 mm
7	Material	Aluminium
8	Modulus of Elasticity	69 GPa
9	Poisson's Ratio	0.2

Another important aspect of the scaling down process is to establish "Dynamic Similarity", which means that the model and prototype should be subjected to the same forces. According to this method, the prototype's inherent frequency should be scaled using an appropriate scaling relation to the scaled model. Equation 3 shows the relationship between model and prototype natural frequencies.

$$f_m/f_p = S^{1/2} \tag{3}$$

Natural frequency of the stepback prototype building as obtained by modal analysis is f_p = 1.93 Hz and stepback - setback building is 2.4 Hz. Therefore, required frequency of the model (f_m) is to be 10.57 Hz ($f_m = F_p \times S^{1/2}$) and 13.14 Hz respectively for both Stepback building (SB) and stepback - setback building (SSB). Also, the mass density of the prototype should be identical to the mass density of the scaled model, according to scaling relations. Table 10 shows the obtained mass density of the prototype and scaled model. As a result, the mass of the scaled model (Mm) for both SB and SSB buildings is 7.1 kg and 5.4 kg, respectively, using slab thickness and column dimensions from Table 9.

Table 10: Mass by volume ratios of both the models

Description	Type SB	Type SSB
Scaled Model	450.51 kg/m^3	445.99 kg/m^3
Prototype	457.38 kg/m^3	455.53 kg/m^3

[15] is used to numerically model and analyse both the scaled model and the prototype. These models were subjected to Time history analysis employing ground motion of the 2001 Bhuj (N-S) and El-Centro 1942 (N-S) earthquakes by altering the time step for scaled model ($t_m = t_p/\sqrt{30}$) and preserving the constant acceleration for both scaled model and prototype, as shown in Table 8.

The peak acceleration details of the Bhuj Earthquake (N-S) and the El-Centro Earthquake are shown in Table 11. (N-S). For stepback and stepback - setback buildings, Tables 12 and 13 show the displacement variation of scaled models and prototype buildings, respectively. Figure 11 indicates time history of Bhuj Earthquake (N-E) and El-Centro Earthquake(N-S). From the Table 12 and 13 it is observed that by scaling down the time step by $\sqrt{30}$ the displacement of prototype is observed to be increased nearly 30 times of the displacement of the scaled model. The same principle is adopted for the experimental scaled model.

Table 11: Type of loading and scaling of time period

Sl. No.	Type of Loading	Prototype		Scaled model	
		Time step (sec)	Peak Acceleration (g)	Time step (sec)	Acceleration (g)
1.	Bhuj Earthquake	0.005	0.1	0.000912	0.1
2.	El-Centro Earthquake	0.02	0.318	0.00365	0.318

Table 12: Top storey Displacement along shaking direction for stepback building

Sl. No.	Model Description	Resonance Frequency (Hz)	Time period (sec)	Displacement (mm) For Bhuj Earthquake	Displacement (mm) For El-Centro Earthquake
1	Scaled Numerical Model	10.72	0.0932	0.741	2.088
2	Prototype	1.93	0.517	24.72	62.65

Table 13: Top storey Displacement along shaking direction of stepback - setback building

Sl. No.	Model Description	Resonance Frequency (Hz)	Time period (sec)	Displacement (mm) For Bhuj Earthquake	Displacement (mm) For El-Centro Earthquake
1	Scaled Numerical Model	13.72	0.0729	0.357	1.15
2	Prototype	2.40	0.416	9.423	44.033

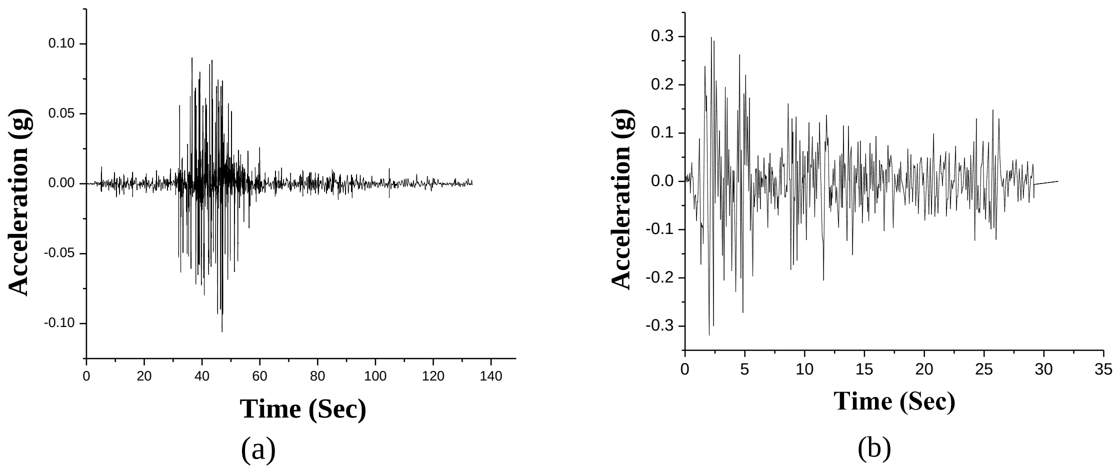


Fig. 11 Time History of (a) Bhuj Earthquake (N-S) and (b) El-Centro Earthquake (N-S)

EXPERIMENTAL INVESTIGATION

Table 9 shows the slab thicknesses and column dimensions. Bolts with a diameter of 6 mm are used to connect slabs to columns. 4 outside columns are joined by bolts with a diameter of 6 mm that are driven into the plates. Small angle sections with bolts are used at the junction, which is where the plates meet the internal columns. As indicated in Figure 12, a base plate of the same thickness is used to connect the scaled model to the shake table using 10 mm diameter bolts spaced 100 mm apart.

1. Shake Table

The shake table facility available at the Department of Civil Engineering, UVCE, Bangalore, is an uniaxially driven having table size 1 m x 1 m with maximum payload capacity of 100 kg. The table has an operating frequency range of 0.05–25 Hz. In the present study the objective is to evaluate the dynamic characteristics such as natural frequency and time period for fixed base condition.

RESULTS AND DISCUSSIONS OF SCALED MODEL

The model was subjected to a gradually increasing unidirectional harmonic excitation (sine sweep wave) with an amplitude in the range of 0.5 Hz–15 Hz in order to obtain the natural frequency of the scaled model. The response parameters such as displacements, accelerations, and resonant frequencies were recorded by Data Acquisition System (DAQ), as shown in Figure 12.

(a) Stepback building (SB)

(b) Stepback-Setback building (SSB)

Fig. 12 View of the experimental scaled model

The resonance frequency is recorded at 10.57 Hz and 13.12 Hz for stepback and stepback - setback building respectively which is about $\sqrt{30}$ times of resonant frequency of prototype. The acceleration recorded in the shaketable at resonance and the displacement (half side) of the scaled setback models are presented in Table 14.

Table 14: Acceleration at the base of models

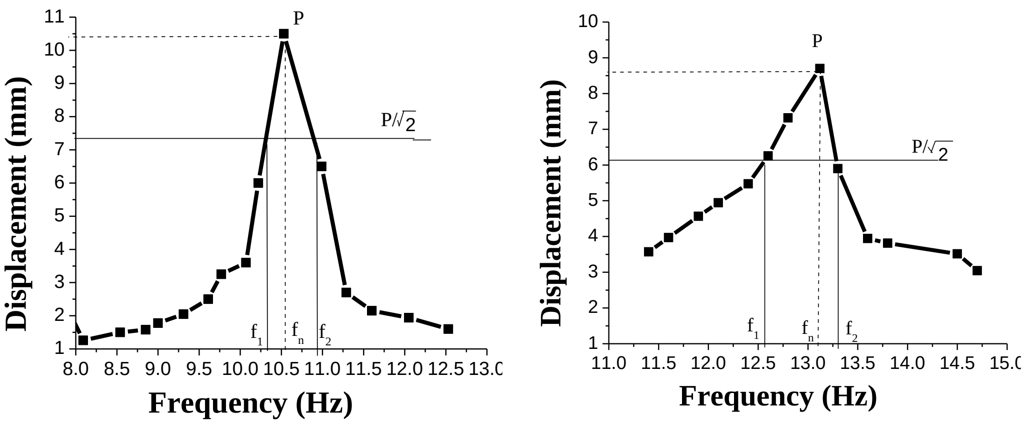
Description	Type SB	Type SSB
Base Acceleration	0.197 g	0.386 g
Base Displacement	0.45 mm	0.62 mm

Figure 13 depicts displacement vs. frequency, with ‘P' denoting the peak displacement. The damping ratio of the scaled model building is calculated from "Half power band width" using the Equation 4.

$$\xi = \left(\frac{f_2 - f_1}{2f_n}\right) \tag{4}$$

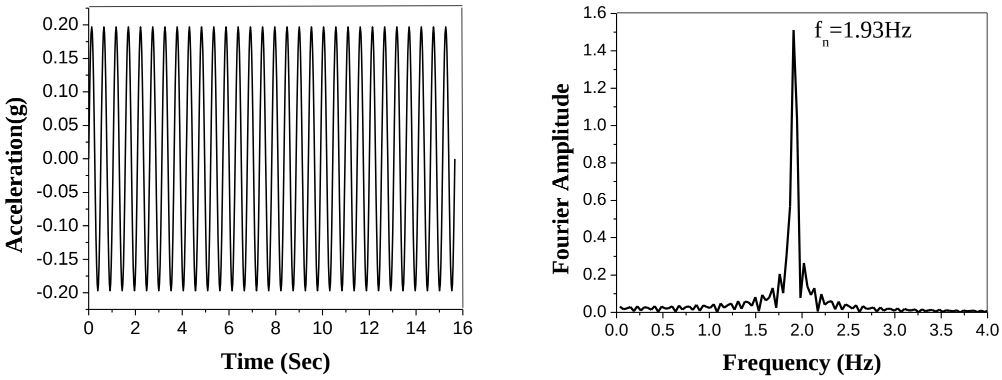
here is ξ = damping ratio, f_1 and f_2 are the frequencies corresponding to half power band width, and f_n is the resonant frequency. Structural damping has been computed for these stepback and stepback - setback models are 2.6% and 2.8% respectively.

By using the acceleration from the experimental research, a harmonic load was created to serve as an input motion for the study of prototypes. Figure 14 depicts the stepback building's harmonic load as well as a plot of Fourier amplitude. Figure 15 shows the harmonic load created for the stepback - setback building, as well as a plot of fourier amplitude.



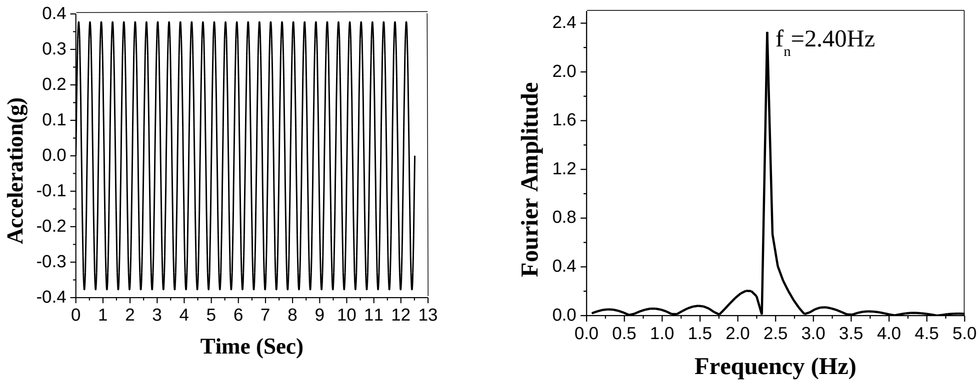
(a) Stepback Building (b) Stepback - Setback Building

Fig. 13 Displacement versus Frequency of Setback scaled models



(a) Harmonic input motion (b) Fourier amplitude spectrum

Fig. 14 Harmonic motion and fourier amplitude spectrum for stepback building



(a) Harmonic input motion (b) Fourier amplitude spectrum

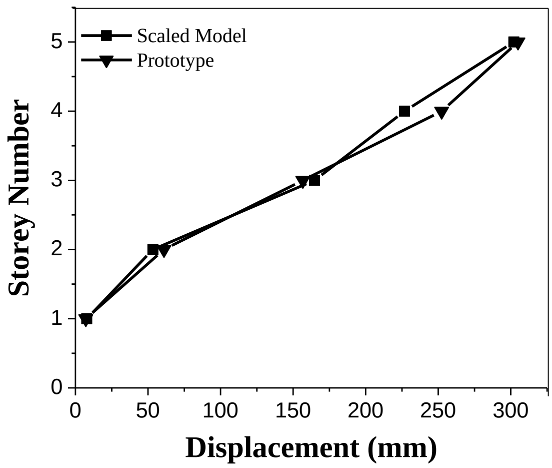
Fig. 15 Harmonic input motion and fourier amplitude spectrum for stepback – setback building

Prototypes are numerically analysed using these generated harmonic loads (Figures 14 and 15) and their respective damping. Tables 15 and 16 show the storey displacements of stepback building and stepback – setback building for both experimental and numerical studies. Figure 16 depicts the storey displacements from both experimental and numerical investigations for stepback and stepback- setback buildings.

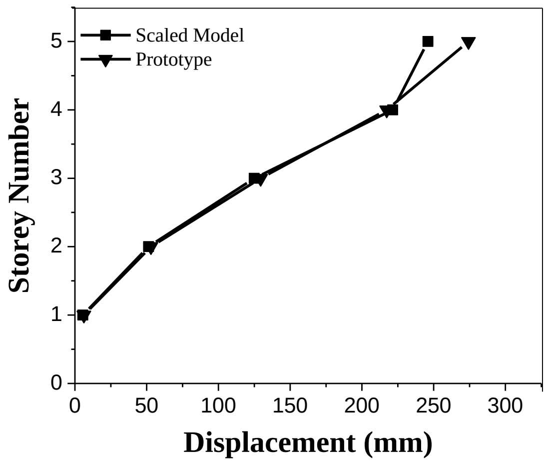
From Tables 15 and 16 and Figure 16 it is observed that storey displacements of prototypes and scaled models are in good correlation. The comparison of storey displacements and storey drifts for stepback and stepback-setback buildings is shown in Figures 17 and 18. Equation 5 is used to calculate the interstory drifts of the model and prototype structures.

$$D\,(i, i+1) = \frac{d_{i+1} - d_i}{h} \tag{5}$$

where D (i, i+1) = drift between the (i) and (i+1) levels; d_{i+1} = deflection at the (i+1) level; di = deflection at the (i) level; and h = story height.



(a) Stepback building



(b) Stepback - setback building

Fig. 16 Comparison of displacements of prototype and scaled models

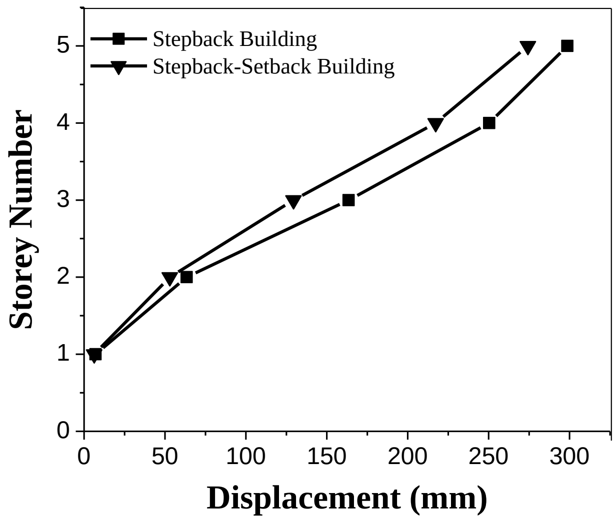


Fig. 17 Comparison of displacements of prototype and scaled setback buildings

Table 15: Storey displacement of scaled model and prototype for stepback building

Storey No's	Displacement of Scaled Model 'Δ' (mm)	Displacement of Prototype Building Δx30 (mm)	Displacement of Prototype Building -Numerical
1	0.26	7.8	7.13
2	1.78	53.4	61.01
3	5.49	164.7	156.69
4	7.56	226.8	252.39
5	10.07	302.1	304.98

Table 16: Storey displacement of scaled model and prototype stepback - setback building

Storey No's	Displacement of Scaled Model 'Δ' (mm)	Displacement of Prototype Building Δx30 (mm)	Displacement of Prototype Building -Numerical
1	0.185	5.55	6.23
2	1.71	51.37	52.94
3	4.165	124.95	129.39
4	7.38	221.40	217.29
5	8.2	246.00	274.26

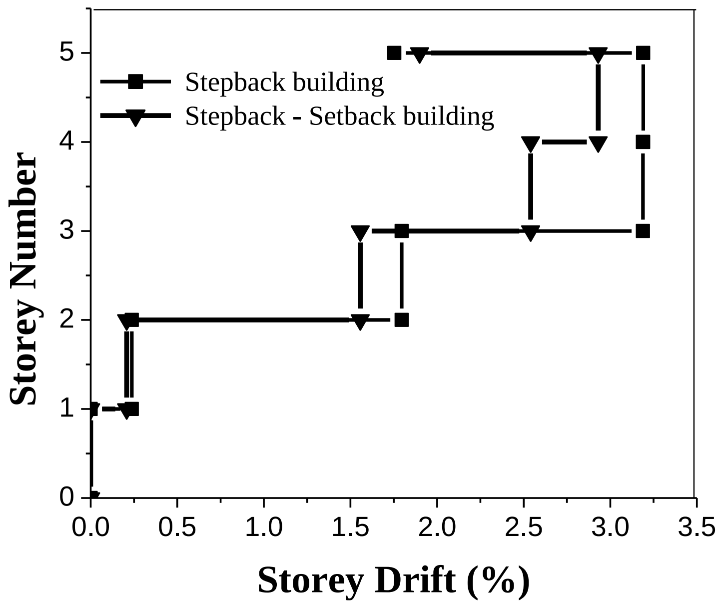


Fig. 18 Variation of storey drift with number of storeys for prototype buildings

From Figure 17 it is observed that, stepback building have maximum storey displacements in comparison with stepback - setback building. From, experimental study it is observed that these buildings possess different damping values (2.6% and 2.8%) and subjected to an input motion of different acceleration content (Table 14). Therefore, to check the displacement variation of these two building models' numerical analysis has been performed on prototypes. For this, structural damping of 5% is adopted for both prototypes and subjected to an input motion Bhuj earthquake (Figure 13 (a)). The obtained storey displacements of prototypes are tabulated in Table 17 and graphically presented in Figure 19. Comparison of storey drift is presented in Figure 20.

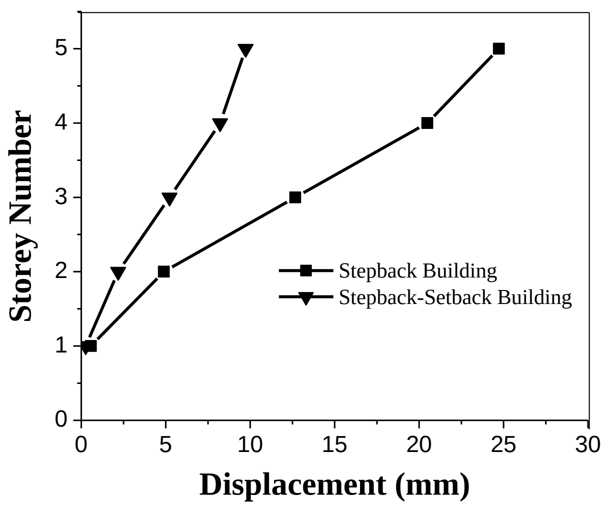


Fig. 19 Variation of displacement with storey height for Bhuj Eearthquake (N-E)

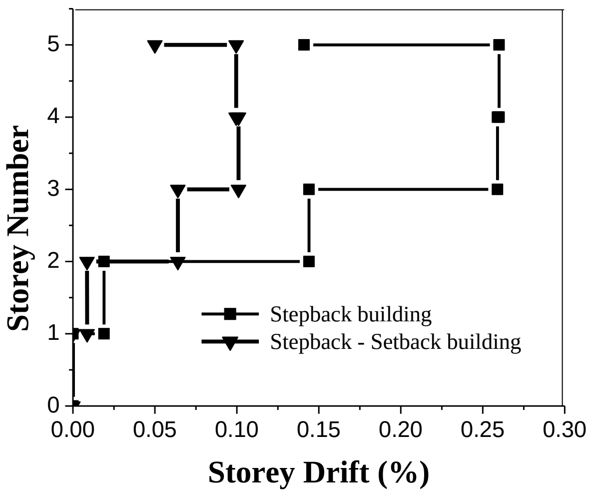


Fig. 20 Variation of storey drift with number of storeys for Bhuj Earthquake (N-E)

Table 17 Storey displacement (mm) of prototype buildings for Bhuj Eearthquake (N-E)

Storey No's	Type SB	Type SSB
1	0.57	0.26
2	4.89	2.19
3	12.67	5.23
4	20.49	8.22
5	24.725	9.73

From numerical study also it is observed that the storey displacements of stepback buildings are nearly twice the storey displacements of stepback - setback buildings, as shown in Figure 19.

SUMMARY AND CONCLUSIONS

Since the design of an earthquake-resistant structure significantly depends on how the building would respond under resonance conditions, several tests have been conducted in the current study to analyse the seismic response of stepback and stepback – setback buildings. There is also a shortage of experimental research on these stepback and stepback - setback structures utilising appropriate scaling principles. Further, there is a void in studies regarding computation of irregularity indices of these buildings as they are geometrically irregular in nature.

Hence, in the present study regularity and irregularity indices have been computed for these buildings resting on slope angles ranging from 20^0 to 35^0 from the approaches available for buildings resting on flat ground. From the computation of the both regularity and irregularity indices it is observed that, for both stepback and stepback -setback buildings regularity and irregularity indices are increased and fundamental frequencies are reduced at 27^0 slope angles. For both experimental and numerical study stepback and stepback -setback buildings resting on 27^0 angle slopes are considered because of lesser frequency. From the study, experimental results such as storey displacements and storey drifts at resonant frequencies are found to be in close agreement with the numerical studies for respective damping value. Also, it is found that storey displacements of stepback building are more compared to stepback - setback building. Additionally, it has been observed that the stepback - setback buildings have a greater resonant frequency about 23% than stepback buildings.

REFERENCES

1. Mohammad, Z., Baqi, A. and Arif, M. (2017). "Seismic Response of RC Framed Buildings Resting on Hill Slopes", *Procedia Engineering, Vol. 173, pp. 1792-1799.*

2. Nakamura, S., A. Wakai, J. Umemura, H. Sugimoto, and T. Takeshi. (2014). "Earthquake-Induced Landslides: Distribution, Motion and Mechanism", *Soils and Foundations, Vol. 54, No. 4, pp. 544–59.*
3. Hyodo, M., R.P. Orense, S. Noda, S. Furukawa and T. Furui. (2012). "Slope Failures in Residential Land on Valley Fills in Yamamoto Town", *Soils and Foundations, Vol. 52, No. 5, pp. 975–86.*
4. Koseki, J., M. Koda, S. Masuo, H. Takasaki, and T. Fujiwara. (2012). "Damage to Railway Earth Structures and Foundations Caused by the 2011 Off the Pacific Coast of Tohoku Earthquake", *Soils and Foundations, Vol. 52, No. 5, pp. 872–89.*
5. Soni, D.P. and Mistry, B.B. (2006). "Qualitative Review of Seismic Response of Vertically Irregular Building Frames", *ISET Journal of Earthquake Technology, Technical Note, Vol. 43, No. 4, pp. 121-132.*
6. Duan, X.N. and Chandler, A.M. (1995). "Seismic Torsional Response and Design Procedures for a Class of Setback Frame Buildings", *Earthquake Engineering & Structural Dynamics, Vol. 24, No. 5, pp. 761-777.*
7. Birajdar, B.G. and Nalawade, S.S. (2004). "Seismic Analysis of Buildings Resting on Sloping Ground", *In 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, Vol. 1, No. 6.*
8. Singh, Y., Gade, P., Lang, D.H. and Erduran, E. (2012). "Seismic Behavior of Buildings Located on Slopes—an Analytical Study and Some Observations from Sikkim Earthquake of September 18, 2011", *In Proceedings of the 15th World Conference on Earthquake Engineering.*
9. Nagargoje, S.M. and Sable, K.S. (2012). "Seismic Performance of Multi-Storeyed Building on Sloping Ground", *Elixir International Journal, Vol. 7, pp. 11980-11982.*
10. Ravikumar, C.M., Babu Narayan, K.S., Sujith, B.V. and Venkat Reddy, D. (2012). "Effect of Irregular Configurations on Seismic Vulnerability of RC buildings", *Architecture Research, Vol. 2, No. 3, pp. 20-26.*
11. Prashant, D. and Kori, J.G. (2013). "Seismic Response of One Way Slope RC Frame Building with Soft Story", International *Journal of Emerging Trends in Engineering and Development, Vol. 3, No. 5, pp. 311-320.*
12. Halkude, S.A., Kalyanshetti, M.G. and Ingle, V.D. (2013). "Seismic Analysis of Buildings Resting on Sloping Ground with Varying Number of Bays and Hill Slopes", *Int J Eng Res Technol (IJERT), Vol. 2, No. 12, pp. 3632-3640.*
13. Hokmabadi, A.S., Fatahi, B. and Samali, B. (2015). "Physical Modeling of Seismic Soil-Pile-Structure Interaction for Buildings on Soft Soils", International *Journal of Geomechanics, Vol. 15, No.* 2, pp. 04014046.
14. IS 1893-Part 1 (2016). "Indian Standard Criteria for Earthquake Resistant Design of Structures", *Bureau of Indian Standards, New Delhi.*
15. SAP, (2000). "Advanced 14.2.4", *Computers and Structures Inc., University Avenue Berkeley, California, United State.*
16. IS 875-Part 2 (1987). "Imposed loads", *Bureau of Indian Standards, New Delhi.*
17. IS 456 (2000). "Plain and Reinforced Concrete—Code of Practice", *Bureau of Indian Standards, New Delhi.*
18. Pradip Sarkar, Prasad, A.M. and Menon, D. (2010). "Vertical Geometric Irregularity in Stepped Building Frames", *Engineering Structures, Vol. 32, No. 8, pp. 2175-2182.*
19. Rathnasiri, H.M.S.C., Jayasinghe, J.A.S.C. and C.S. Bandara, (2020). "Development of Irregularity Index Based on Dynamic Characteristics to Quantify the Vertical Geometric Irregularities", *The Institution of Engineers, Sri Lanka, Vol. 53, No. 1, pp. 41-51.*
20. Vivek Hirave, and M. Kalyanshetti, (2018). "Seismic Response of Steel Braced Building Frame Considering Soil Structure Interaction (SSI): An Experimental Study", *Journal of the Institution of Engineers (India): Series A, Vol. 99, No. 1, pp. 113-122.*