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Seismic performance of buildings resting on sloping ground−A review

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Abstract: *This study summarizes the knowledge in the seismic response of buildings on hill slopes. The dynamic response of the structure on hill slope has been discussed. A review of studies on the seismic behaviour of buildings resting on sloping ground has been presented. It is observed that the seismic behaviour of buildings on sloping ground differ from other buildings. The various floors of such buildings step backs towards hill slope and at the same time buildings may have setbacks also. Most of the studies agree that the buildings resting on sloping ground has higher displacement and base shear compared to buildings resting on plain ground and the shorter column attracts more forces and undergo damage when subjected to earthquake. Step back building could prove more vulnerable to seismic excitation.*

Keywords: *Seismic performance, Sloping ground, Step back building.*

I. Introduction

The scarcity of plain ground in hilly areas compels construction activity on sloping ground resulting in various important buildings such as reinforced concrete framed hospitals, colleges, hotels and offices resting on hilly slopes. The various floors of such buildings step back toward the hill slope and at the same time building may have setback also, as shown in Figure 1. Due to the varied configurations of buildings in hilly areas, these buildings become highly irregular and asymmetric, due to variation in mass and stiffness distributions on different vertical axis at each floor. Such construction in seismically prone areas makes them exposed to greater shear and torsion as compared to conventional construction. Further, due to site conditions, buildings on hill slope are characterised by unequal column heights within a story, which results in drastic variation in stiffness of columns of the same storey. The short, stiff columns on uphill side attract much higher lateral forces and are prone to damage. As per IS 1893: (part 1) 2002 ,different vertical irregular configurations of buildings have been defined, as shown in Figure 2.Which are stiffness irregularity (soft storey) ,mass irregularity, vertical irregularity (set back).

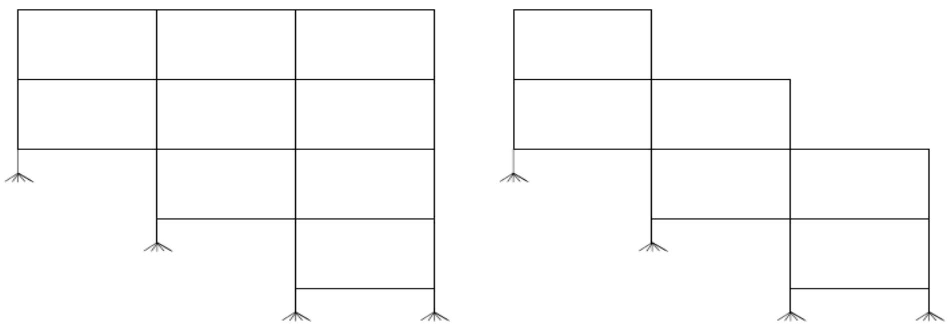
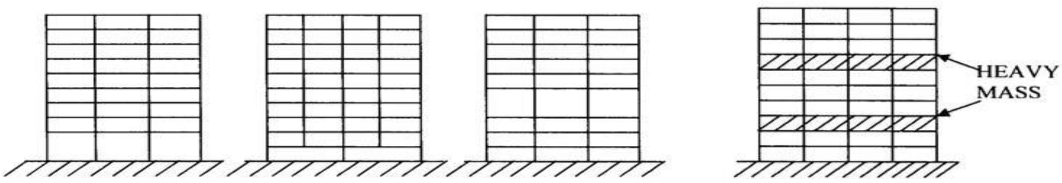
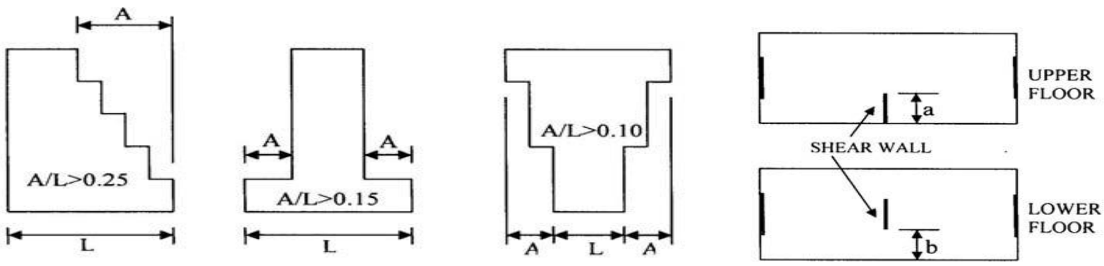


Fig 1**:** (a) Step back building, (b) Step back Set back building



(a) (b)



(c) (d)

Fig-2: (a) Stiffness/strength irregularity (b) Mass irregularity (c) Vertical geometric irregularity or Set back (d) In-plane discontinuity in Vertical elements resisting lateral force when b > a.

II. Review Of Papers On Buildings Resting On Sloping Ground

Birajdar and Nalawade [1] (2004) studied seismic performance of buildings resting on sloping ground. They considered twenty four RC building frames with three different configurations as Step back building, Step back Set back building and Set back building situated at a slope of 27 degree with the Horizontal. They studied the seismic response of buildings with varying storey level ranging from 4 to 11 (15.75m to 40.25m), consist of three bays along slope direction and one bay across slope, located in seismic zone III. They carried out 3D analysis including torsional effect by using Response spectrum method. They observed that their is a linear increase in the value of top storey displacement and fundamental time period as the height of building increases. From comparison they found that, this increase in top storey displacement and fundamental time period as the height of step back building increases is higher than step back set back building, as shown in Figure 3(a) and Figure 3(b). From their study it is observed that the shear force in the column towards extreme left is significantly higher as compared to rest of the columns, in case of step back building it is found to be 55-250% more than step back set back building. Thus they conclude that extreme left column at ground level, which are short are the worst affected and step back building could prove more vulnerable during seismic excitation than other type of configuration. They observed in step back buildings, the uneven distribution of shear force in the various frames suggests development of torsional moment due to static and accidental eccentricity.

Nagargoje and .Sable [2] (2012) studied seismic performance of buildings on hill slope. They carried out 3D space frame analysis to study dynamic response of the buildings, in terms of base shear and top floor displacement. A parametric study was carried out on thirty six buildings with three configurations as step back, step back set back and set back buildings located in seismic zone III. B.G.Biradar and S.S.Nalawade (2004) studied seismic performance of hill buildings by considering story level up to 11, however in this paper the study is carried out by considering storey level ranging from 4 to 15 (15.2 m to 52.6m). They found that the storey displacement of step back buildings is quite high as compared to step back –set back buildings, as shown in Figure 4. They observed that the base shear induced in step back set back buildings is higher in the range of 60 and 260% than set back building. They suggested step back set back buildings may be favoured on sloping ground.

Singh et al [3] (2012) studied seismic behaviour of buildings located on slopes .An analytical study is carried out on buildings considered, by using linear and non linear time history analysis. They considered 9 storey buildings, which include step back building at a slope of 45 degree with the horizontal, a RC frame located on steep slope /vertical cut which was not considered in previous studies, in which foundations are provided at two levels, at base downhill and at the road level, to compare the behaviour, they considered buildings resting on flat ground with 3 and 9 storeys. All buildings are located in seismic zone IV, consist of seven bays along slope and 3 bays across the slope. They have analysed buildings for a set of five ground motions, as shown in Table 1, which is taken from strong motion database of pacific Earthquake Engineering Research Centre. It is observed that, in all buildings on sloping ground, storey shear is resisted by short column. The effect of torsion irregularity in the building configuration can be represented by the ratio of maximum to average inter storey drifts ($\Delta_{max}/\Delta_{avg}$) in a storey. From which they observed that, in step back building torsion is observed in all storeys denoted as SI. Whereas torsion is observed in only top storeys of building located on vertical cut denoted as SII, as shown in Figure 5. They conclude that the step back buildings are subjected to significant torsional effects under cross slope excitation. They also studied the inter storey drifts in the top three storeys of all buildings from which they observed that the inter storey drifts in the top three storey of hill building are quite close to those in the 3 storey regular building and the pattern of inter storey drifts of a storey building differs from other buildings.

Table 1: Earthquake records used in the analysis

S. No.	Event	Magnitude	PGA [g]	PGV [cm/sec]	PGD [cm]
1.	1999 Chi-Chi	M7.6	0.266	38.331	38.331
2.	1979 Imperial Valley	M6.5	0.289	19.915	10.97
3.	1994 Northridge	M6.7	0.249	19.381	6.824
4.	1971 San Fernando	M6.6	0.33	56.3.5	60.017
5.	1995 Kobe	M7.2	0.28	16.369	8.067

Mohammad Umar Farooque patel etal [4] (2014) focused on performance study and seismic evaluation of RC building on sloping ground. They studied the behaviour of RC frame on sloping ground with the presence of shear wall with different positions at centre and at corner and given the performance of structures with shear wall on sloping ground. A parametric study was carried out on eight storey building which includes a bare frame, building with shear wall at centre and at corner position located in seismic zone III. To give comparison they considered models on plane ground. All buildings consist of 5 bays in both directions. Seismic analysis has been done using linear static, Response spectrum analysis and evaluated using pushover analysis. Based on Equivalent static analysis, they found that the buildings with shear wall at centre and at corner have 41.4%, 61.5% respectively less displacement and based on Response spectrum analysis, these buildings have 23.6%, 38.1% less displacement as compared to the bare frame model on sloping ground. From which they conclude: as the buildings resting on sloping ground has higher displacement, the presence of shear wall reduces the lateral displacement considerably. Performance point determined from pushover analysis is the point at which the capacity of structure is exactly equal to the demand made on the structure by the seismic load. Based on state of structures at performance point, they observed that the spectral displacement of building on hill slopes have 114%-179% higher than building model on plain ground in longitudinal direction and also the plastic hinge formation is more in bare frame model, building with presence of shear wall on sloping ground when compared to the building on plain ground, which proves that the buildings on hill slopes are more vulnerable than other buildings. Hence, they conclude that the performance of buildings on hill slopes suggests an increased vulnerability of the structure with formation of column hinges at base level and beam hinges at each story level at performance point. Previous papers have not considered the presence of shear wall to study the seismic behaviour of hill slope buildings.

Prashant D and Jagadish Kori G [5] (2013) studied seismic response of one way slope RC frame building with soft storey. In this paper study is focused on the behaviour of buildings situated on sloping ground with and without infill wall, the influence of infill wall on buildings situated on sloping ground is presented. Non linear static pushover analysis is carried out on 10 storey buildings which include bare frame without infill wall and other model with infill wall including a soft storey building on sloping ground. All buildings consist of 5 bays along slope direction situated at a slope of 27 degree with the horizontal, located in seismic zone III. Building frame system considered is SMRF. They observed that the time period of bare frame model is found to be 1.975 sec which is almost 96-135% more than other models with presence of infill wall. Thus they conclude, this higher value of natural period in bare frame compared to infill frame ultimately results in underestimation of design base shear in bare frame model on sloping ground. The abrupt changes in the slope profile indicates stiffness irregularity, they observed that the displacement in bare frame model is found to be more because of reduced stiffness compared to other models with infill wall. They found that the base shear of infill models is almost 250% more compared to bare frame. It is concluded that the formation of plastic hinges is more in bare frame model and soft storey building compared to fully infilled fames. In this paper study is concentrated on variation of stiffness due to presence of infill wall and soft storey on sloping ground.

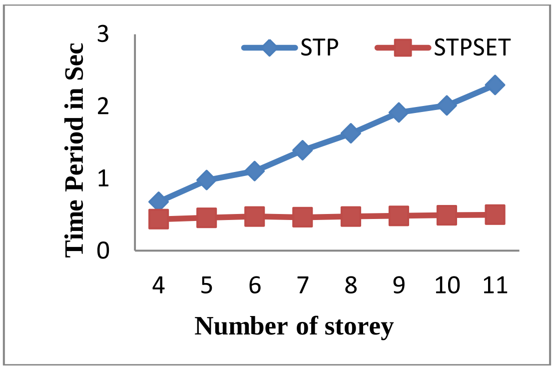
Rayyan-Ul Hassan and H.S.Vidyadhara [6] (2013) carried out seismic analysis of earthquake resistance multi-storey multi bay RC frame. They studied the seismic behaviour of bare frame model, building with first soft storey (infill wall in upper storeys) with presence of both infill and shear wall at corner position for which they used 4 bay twelve storey building situated at a slope of 1:1/3 located in seismic zone V. These buildings have been analysed using Equivalent static, Response spectrum and Pushover analysis. Based on Equivalent analysis results they noted that their is reduction in displacement of models with infill and shear wall at corners with respect to bare frame model by almost 79.15% and 89.27% respectively in longitudinal direction and from Response spectrum analysis which are almost 50.95% and 73.97% respectively. Hence they conclude that the presence of brick infill and shear wall reduces lateral displacement considerably. It is observed that there is increased base shear in building with shear wall when compared to bare frame model, as shown in Figure 6 (a). As per IS 1893 part (1) 2002 code, the permissible inter storey drift is limited to 0.004 times the storey height. In this study they found that all buildings considered are within permissible drifts, however the inter storey drifts of bare frame model on sloping ground found to be relatively higher compared to buildings with infill wall and shear wall, as shown in Figure 6 (b). From pushover analysis, it is observed that the spectral displacement and

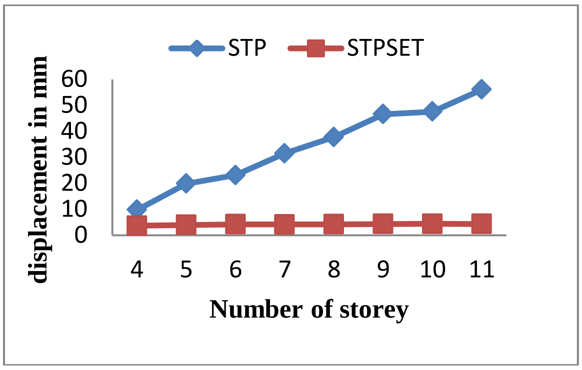
Roof displacement of bare frame is higher than building with shear wall at corner. Thus they conclude that the presence of infill wall and shear wall influences the overall behaviour of structures when subjected to lateral forces by effectively reducing large joint displacements found in bare frame, which was also concluded in study done by Mohammad Umar Farooque patel and Prashant D etal.

Jitendra Babu et al [7] (2012) carried out pushover analysis of various symmetric and asymmetric structures constructed on plain as well as sloping ground subjected to various kinds of loads. They considered various structures in plan symmetry and also asymmetry with different in bay sizes in mutual direction. On sloping ground they considered a 4 storey building in which they have taken one storey above ground level which is situated at a slope of 30 degree with the horizontal. They found that the short column lies in the severity level beyond collapse prevention (CP) from pushover analysis, they obtained displacement and base shear for asymmetric sloping ground as $104X10^{-3}$ m and 2.77×10^{3} kN respectively. Based on results they developed pushover curves with displacement on X-axis and Base shear on Y-axis and have given comparison between various cases they considered. They observed that the Base shear resisted for maximum displacement up to failure limit by symmetric structure is 70% and by asymmetric sloped building is 24% more than base shear resisted by asymmetric building on plain ground. They conclude that the structure with vertical irregularity is more critical than a structure with plain irregularity.

Ravikumar C. M et al [8] (2012) focused on the study of seismic performance of irregular configurations of RC buildings in which they studied vertical irregularities of buildings such as geometric irregularity and buildings resting on sloping for which two types of configurations were considered as buildings resting on sloped ground in X-direction and buildings resting on sloped ground in Y-direction. All buildings consist of 5 bays in X-direction and 4 bays in Y-direction with 3 storey located in severe zone V. The performance of these buildings was studied by linear analysis using code IS 1893 (part-1) 2002 and Nonlinear analysis using ATC 40. They observed that the vulnerability of sloping ground buildings was found to be remarkable which attracts large force to deform moderately. Base shear of building on hill slope was found to be 6019.2 kN, which was around 25-55% more than other buildings and also displacement was found to be 83.4 mm which was moderately higher than other buildings. They found that the performance goal was not achieved of sloping ground buildings in X-direction and in Y-directions this was achieved after collapse point. Thus they conclude that the buildings resting on sloping ground are more vulnerable to earthquake than the buildings resting on plain ground.

Halkude et al [9] (2013) focused on seismic analysis of buildings resting on sloping ground with varying number of bays and hill slopes. They studied the variation of time period, base shear and top storey displacement with respect to variation in number of bays along slope direction and hill slope angle. To study the seismic behaviour they considered different configurations, as step back building which are in the range of 4 to 11 storey and consist of varying bays of 3 to 6 in X-direction .They have not studied the seismic behaviour by varying bays along Y-direction, thus they considered one bay along Y-direction, situated at varying slopes of 16.32°, 21.58°, 26.56° and 31.50° with the horizontal located in seismic zone III .It is observed that, in all configurations, base shear increases with increase in number of storey , increases with increase in number of bay and decreases from lower angle to higher angle of slope as shown in figure 7 (a), Figure 7 (b) and Figure 7 (c), when compared between different configurations, base shear of step back building is found to be higher than step set back building. They observed that the time period increases with increase in number of storey in all configurations, in step back building time period increases with increase in number of bays, which is a reverse case in step back set back building in which time period decreases with increase in number of bay and in all configurations time period decreases with increase in hill slope showing minor change in time period as shown in Figure 7 (d). In all configurations it is observed that the top story displacement increases with increase in number of storey, displacement is nearly alike for 3 bay and 4 bay, But, it decreases considerably from 4 to 5 bay and further increases for 6 bay, as shown in figure 7 (e), with respective to hill slope, they found that the top storey displacement decreases with increase in hill slope showing lower value for higher slope .Thus they conclude that the step back frames produce higher base shear, higher value of time period and higher value of top storey displacement as compared to step back set back frames. Also they conclude that greater no of bays are observed to be better under seismic excitation, as number of bays increase time period and displacement decreases.





(a) (b)

Fig 3: (a) Variation of Time period (b) Variation of Displacement

Note: STP=Step back building; STEPSET = Step back set back building

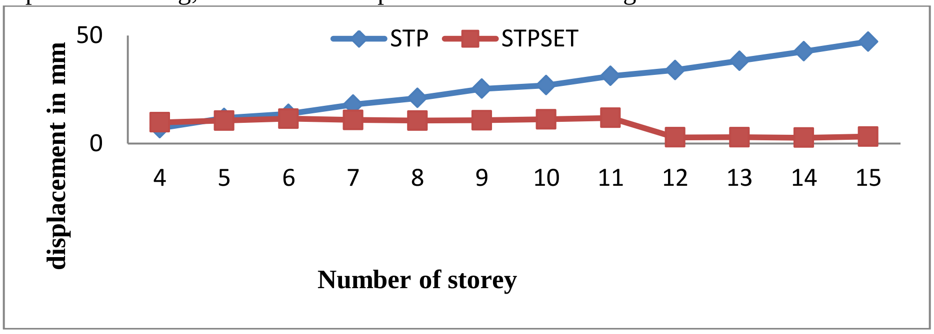


Fig 4: Variation of Displacement

Note: STP=Step back building; STEPSET = Step back set back building

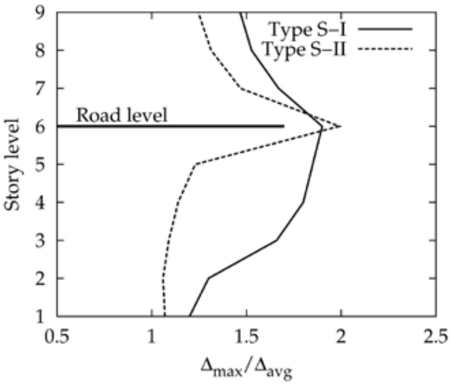
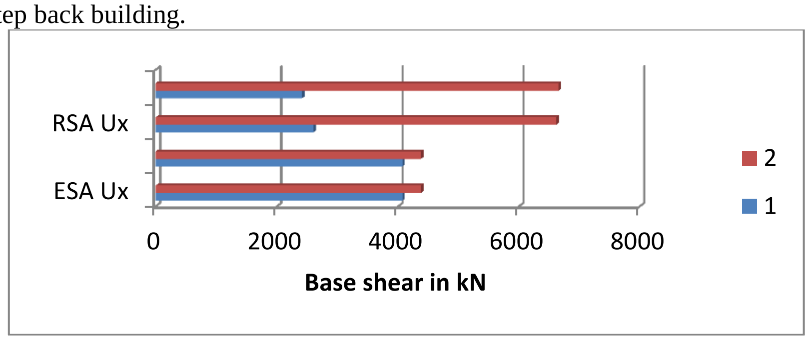
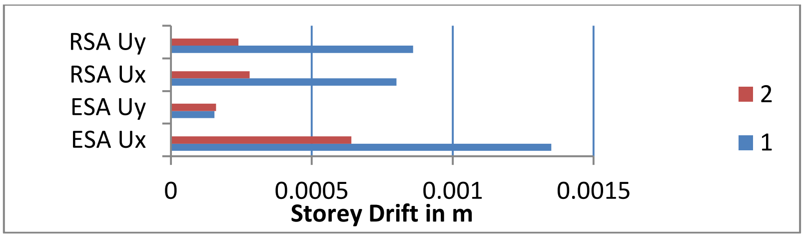


Fig 5: Variation of $\Delta_{max}/\Delta_{avg}$ along height in hill building configurations and due to seismic excitation in cross-slope direction.

Note: Type S-I=Step back building.



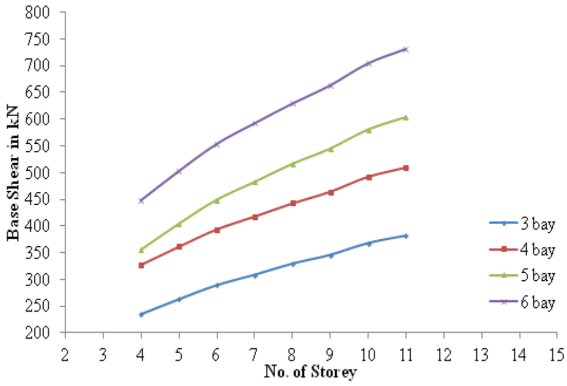
(a)



(b)

Fig 6: (a) Variation of base shear (b) Variation of Storey drift

Note: 1=Bare Frame building on sloping ground: 2=Building with Shear wall



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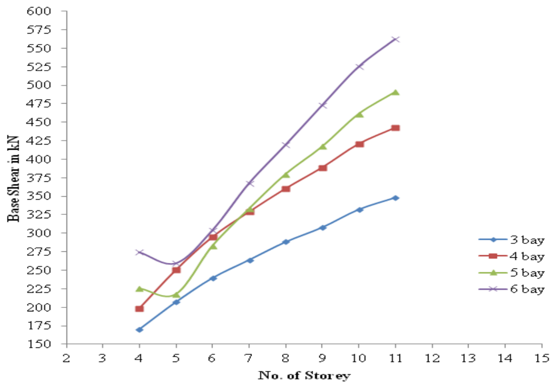

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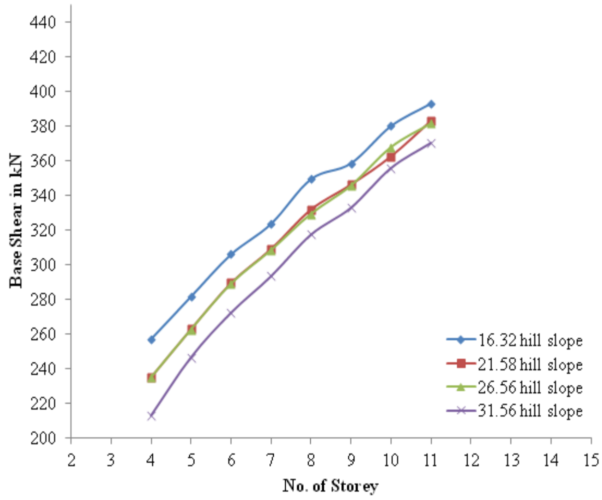

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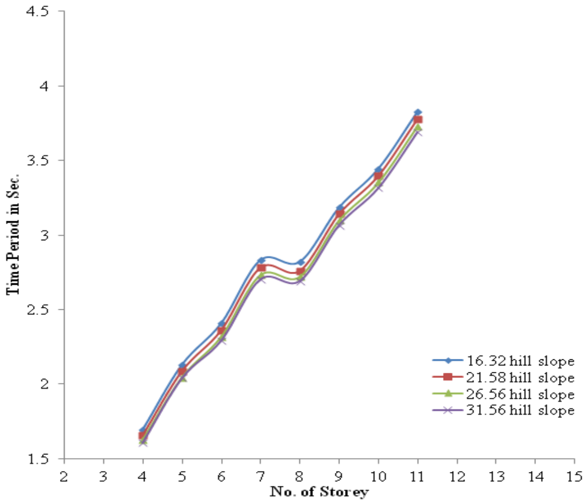
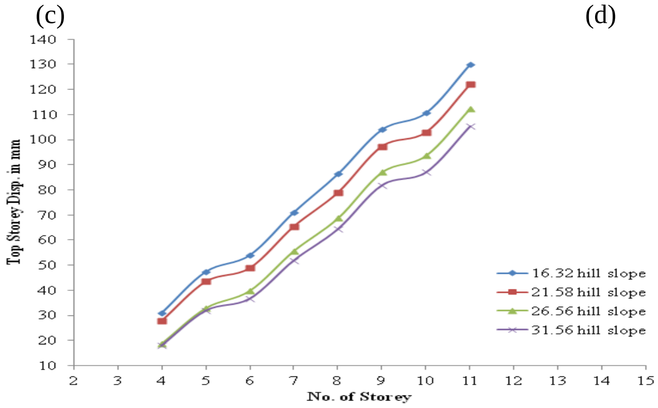


(d)



(e)

Fig 7 (a) Variation of base shear for step back frame with respective to number of bays, (b) Variation of base shear for step back set back frame, (c) Variation of base shear for step back frame with respective to hill slope, (d) Variation of time period for step back frame with respective to number of bays, (e) Variation of top storey displacement for step back frame with respective to hill slope.

During the course of this Review, it is observed that very few researchers have studied the seismic behaviour of buildings situated on varying slopes and varying number of bays along slope direction .Some researchers have suggested suitable building configuration on sloping ground. Some researchers have studied the seismic behaviour of hill slope buildings by considering infill wall (soft storey) and Shear wall. A tabular summary of fundamental time period, Base shear and displacement given by various researchers is presented in Table 2.

III. Conclusions

From the above discussion following conclusions can be made.
1. Step back buildings produce higher base shear, higher value of time period, higher value of top storey displacement compared to step back set back building. During seismic excitation Step back building could prove more vulnerable than other configuration of buildings.
2. It is observed that, short columns attracts more forces and are worst affected during seismic excitation. From design point of view, special attention should be given to the size (strength), orientation (stiffness) and ductility demand of short column.
3. The hill slope buildings are subjected to significant torsional effects, due to uneven distribution of shear force in the various frames of building suggest development of torsional moment, which is found to be higher in step back building.
4. Many researchers suggested as step back set back buildings may be favoured on sloping ground.
5. From the study it is concluded that the presence of infill wall and shear wall influences the behaviour of structure by reducing storey displacement and storey drifts considerably, but may increase the base shear, hence special attention should be given in design to reduce base shear.
6. It is concluded that the greater number of bays are found to be better under seismic condition, as the number of bays increases, time period and top storey displacement decreases in hill slope buildings.

l No	References	Type of building	Time period In sec	Base shear In kN	Displacement In mm	Remarks
1	B.G. Birajdar and S.S Nalawade (2004)	STP 4 to STP 11	0.6782-2.2972	134-358	9.75-56.05	Step back 4 to 11 storey
		STPSET 4 to STPSET 11	0.437-0.499	86-103	3.61-4.28	Step back set back 4 to 11 storey
2	S.M. Nagargoje and K.S. Sable (2012)	STP 4 to STP 15	-	398-290.25	7.27-47.07	Step back 4 to 15 storey
		STPSET 4 to STPSET 15	-	341.32-414.84	9.75-3.21	Step back set back 4 to 15 storey
3	Mohammed Umar Farooque patel et al (2014)	8-storey	-	3111.72	13.10	Bare frame
		8-storey	-	7536.2	10	Building with shear wall at centre
		8-storey	-	13920.42	8.10	Building with shear wall at corner
4	Prashant D and Dr Jagadish Kori G (2013)	10-storey	1.975	6289.029	352.8	Bare Frame
		10-storey	0.834	29034.46	117.6	Building with Infill
5	Rayyan-Ul-Hassan Siddiqui and H.S.vidhyadhar (2013)	12-Storey	-	2601.1	211	Bare Frame
		12-Storey	-	6508.9	103	Building with Infill(soft storey)
		12-Storey	-	6617.8	55	Building with Infill and Shear wall at corner

Table 2**:** Summary of fundamental time period, Base shear and displacement given by various researchers

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