A Study on the Seismic Performance of Square and L-Shaped Buildings Resting on Various Angles of Hill Slopes

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Abstract

Due to the rapidly increasing population integrated with the problem of lack of availability of flat lands on hilly areas, the practice of constructing buildings on sloping grounds is increasing. This research aims to analyze the similarities and differences in the performance of L-shaped and square plan buildings resting on sloping grounds that are subjected to earthquake induced lateral forces. In order to achieve the objective, we modeled a total of 14 buildings, seven of which are of square plan, and remaining are L-shaped. The buildings are placed at hill slope angles ranging from 0 to 30 degrees. These buildings are analyzed using Response Spectrum Method in a structural analysis software called ETABS. A comparative analysis of the seismic parameters such as time period, base shear, modal mass participation and displacement is made for all L-shaped and square plan buildings and presented in the paper.

Keywords : ETABS, hill slope, irregular, L-shaped, response spectrum method

I. INTRODUCTION

Earthquake is a natural hazard, which has been occurring for millions of years and will continue to do so in the future. During an earthquake, the seismic waves propagate away from the source via crust to the ground surface which shakes the earth surface. It may last for a few seconds to a few minutes. Earthquakes are unpredictable and the ground may move in any possible direction making it one of the most horrific and devastating phenomena on earth. The ground motion during an earthquake induces lateral forces on a standing structure. Buildings are severely impacted by lateral movements, that is, earthquakes which disturb the stability of buildings and can result in their collapse. Earthquakes of a large magnitude occur rarely, therefore, there is a tendency of constructing buildings keeping in mind only the gravity load and not paying adequate attention to earthquake design criteria. Consequently, buildings undergo huge damage when struck upon by major earthquakes because of their inability to withstand lateral forces. Moreover, if buildings are constructed on hill slopes, then there is more threat. Past studies have shown that the configuration irregularity poses a major threat to a building and hence, are consequently, damaged under strong ground motions.

Hilly areas do not have adequate amount of plain ground. What aggravates the problem is that with the rapid increase in population, the demand for flat land in hilly areas has also increased. However, due to lack of plain land, residential, commercial, industrial buildings in hilly regions must be constructed on sloping grounds to meet the needs of the increasing population. Furthermore, formation of plain grounds by excavation is quite

Manuscript Received : November 21, 2020 ; Revised : April 24, 2021 ; Accepted : May 15, 2021. Date of Publication : June 5, 2021.
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DOI : https://doi.org/10.17010/ijce/2021/v4i1/160807

expensive and sometimes unfeasible. Cutting of hill slopes for the formation of plain land might also destruct the natural habitat of various flora and fauna. Additionally, hillside construction practice is gaining popularity from the perspective of tourism as well because hillsides are loved by people for beauty and pleasant climates. However, the houses constructed on steep slopes pose structural and construction problems. Even though all buildings are vulnerable to earthquakes, the buildings having irregularity are more vulnerable. The construction of buildings on hill slopes is very different from those constructed on plain surface. The buildings constructed on hill slopes are very irregular. Such structures are highly vulnerable to earthquakes and may result in loss of millions of lives and properties. Even if we consider a building having a plan of square configuration, due to the slope variation, there is variation in the heights of columns. Thus, the variation in heights of columns results in the variation of stiffness. This ultimately causes the stiffer columns to attract larger lateral forces. The buildings undergo torsion due to the unsymmetrical nature of these buildings making it very susceptible to collapse during earthquakes.

Many researchers have made an attempt to understand the response of buildings during seismic events. Baral and Yajdani [1] studied the seismic response of 10 story buildings with different position of shear walls on a flat slope. They concluded that positioning of shear wall at the center of a ten storey building was most effective in improving the performance of buildings during an earthquake. Paudel and Adhikari [2] studied the effect of masonry infills on seismic performance of RC frame buildings and concluded that the better collapse performance of fully-in filled frames is associated with the larger strength and energy dissipation of the system, associated with the added walls. Khanal and Chaulagain [3] studied the seismic elastic performance of L-shaped building frames through plan irregularities. They concluded that the present building codes were insufficient to account for the irregularities. Other researchers have made attempts to understand the response of buildings on hill slopes. Kumar and Paul [4] developed a method of dynamic analysis of buildings on hill slope by transformation of mass and stiffness about an arbitrary axis. Daniel and Sivakamasundari [5] carried out an analytical study to analyze the seismic behavior of step back configuration of hill building and compared it with that of a regular building on flat ground. Mohammad, Baqi, and Arif [6] highlighted the seismic performance of RC buildings on hill slopes. They modelled a total of 18 structures of two different configurations. namely, (a) Step back buildings; (b) Step back set back buildings, and carried out seismic analysis using ETABS by Response Spectrum Method. They concluded that step back set back buildings performed better than step back buildings when subjected to seismic loads. Ghosh and Debbarma [7] highlighted the effect of slope angle variation on buildings constructed on hill slopes by considering soil structure interaction. Dangi and Akhtar [8] carried out a research on the seismic analysis of a Reinforced Concrete (RC) building on sloping ground with shear walls at various positions. They concluded that a significant improvement is observed in seismic performance of a building on sloping ground by providing shear walls with different configurations because the lateral displacement and member forces reduce considerably in a building due to the provision of shear walls.

Although the aforementioned researches have provided a better view of structural behavior of buildings on hill slopes, there has not been much research about the performance of L-shaped buildings in comparison to buildings with square plan with variation in hill slope angles. If we look from the architectural point of view, irregular buildings are appreciated for aesthetics and beauty. However, from a civil engineer's point of view, irregular buildings are highly criticized. Nevertheless, we cannot say no building with L-shaped plan will be constructed on hill slopes. On buildings with L-shaped configuration, re-entrant corners are formed and thus these corners cause stress concentrations. Hence, in our analysis we have incorporated L-shaped buildings resting on hill slopes of varying angles and evaluated their seismic performance. Such structures have variation in mass and stiffness along vertical and horizontal planes due to which the center of mass and center of stiffness do not coincide and thus, causes torsional moments. Hence, this paper has been written to anticipate the seismic performance of buildings on hill slope at various angles: 0, 5, 10, 15, 20, 25, and 30 degrees. Special case of L-shaped plans has also been looked upon in this paper.

The major objectives of this paper are as follows :

- To analyze 3-D buildings having square shaped and L-shaped plans at various hill slope angles: 0, 5, 10, 15, 20, 25, and 30 degrees.

- To investigate and compare seismic performance of L-shaped and square shaped buildings.

Building Configurations :

IS 1893:2016 states that for a building to perform well in an earthquake, a building should possess four main attributes, namely simple and regular configuration, adequate lateral strength, stiffness, and ductility. Buildings having simple regular geometry, uniformly distributed mass, and stiffness in plan as well as in elevation, suffer much less damage than buildings with irregular configuration. To study the effect of irregularities, we have considered buildings with two different plans :

(1) Square plan

(2) L- shaped plan

A total of 14 buildings (5 storeys) have been modeled and all of the buildings have columns of dimension 450*450 mm, beams of dimensions 450*300 mm and slabs of dimension 125 mm. The outer walls are 230 mm thick and the inner walls are 115 mm thick. The parapet wall is of height 1m and thickness 115 mm. All the floors have height of 3 m. The number of bays along X and Y directions are four each. The distance between two columns is 4 m.

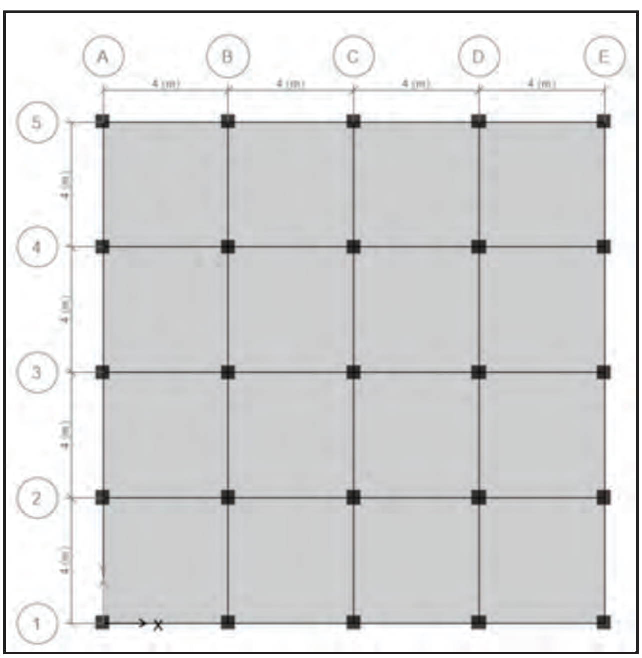

Fig. 1. Plan of Building (Square)

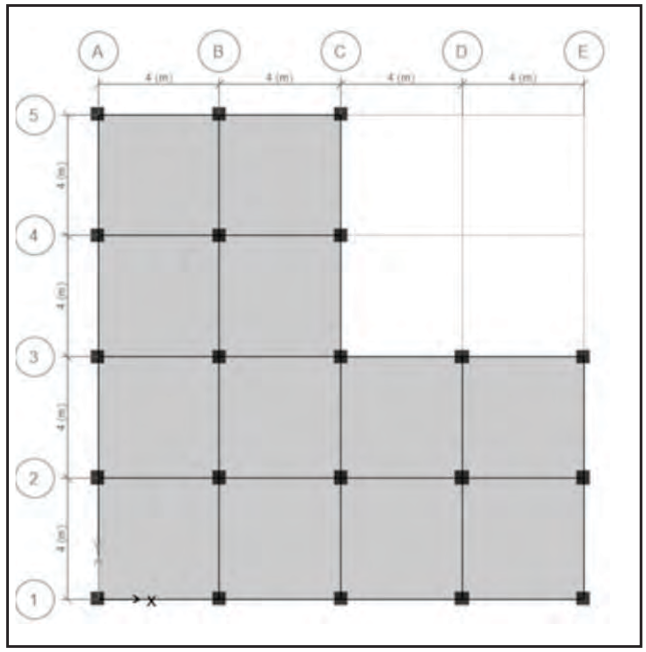

Fig. 2. Plan of Building (L-shaped)

Seismic Parameters and Loads

For all of the above considered buildings we have used concrete of grade M25, and reinforcement bars of Fe415.The live load 1.5 kN/m^2 is used for roof and for other floors 2.5 kN/m^2.

Note : As per IS 1893:2016 clause 7.3.2, the roof live load is considered to be 0 during earthquake and for other floors 25% during earthquakes. The floor finish load used is 1 kN/m^2 KN/m^2. The wall loads are :

- 13.8 kN/m applied on outer beams
- 6.9 kN/m applied on inner beams
- 2.3 kN/m for parapet

The building is modelled following the guidelines of IS 1893:2016 in ETABS v17. Adhering to the guidelines in IS *1893:2016 Part I*, the seismic analysis has been done with the following considerations: medium soil sites (type II); importance factor is equal to 1.0; seismic zone factor (z) for the zone (v), z = 0.36 ; building damping ratio = 5%.

II. METHOD OF ANALYSIS

Linear Dynamic Method

To get a realistic picture of behavior of buildings on hills slope, we have carried out 3-D modeling of structures and subjected them to seismic loads. For our analysis we have used the Response Spectrum Analysis Method (*as per IS 1893:2016 Part I Clause 7.7*). In Response Spectrum Method, the response in different

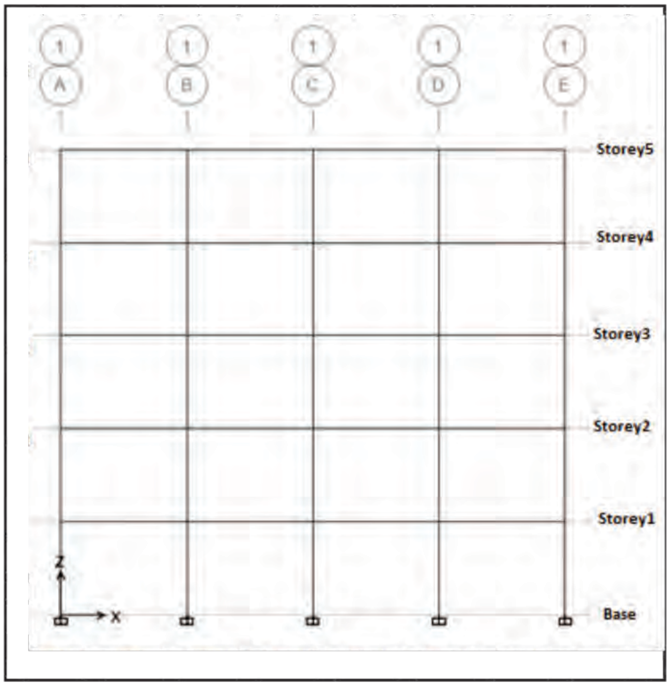

Fig. 3. Elevation Along Grid 1 of MS0 & ML0

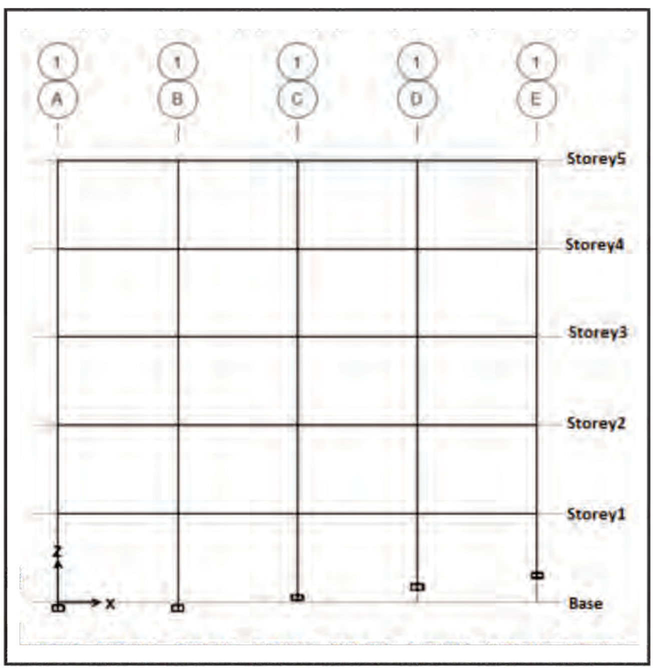

Fig. 4. Elevation Along Grid 1 of MS5 & ML5

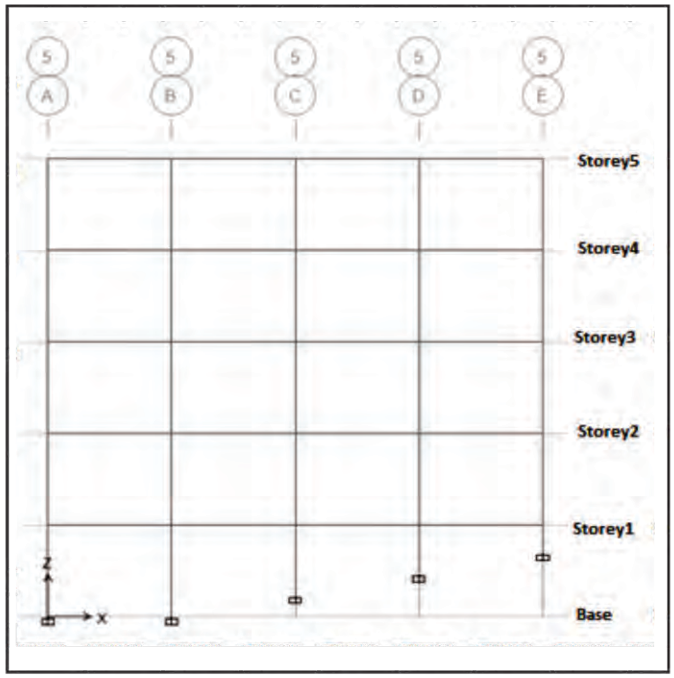

Fig. 5. Elevation Along Grid 1 of MS10 & ML10

modes of vibration are combined at different levels. It is a dynamic analysis. The software that we have used is ETABS. ETABS stands for Extended Three Dimensional Analysis of Building System and is very popular for its specialization in structural analysis of lateral forces. It is a widely used software for the analysis of buildings, high rise buildings to be more specific. It uses the Finite Element Method (FEM) for analysis. All 14 models have been analyzed for earthquake loads by adopting dynamic analysis, that is, Response Spectrum Analysis. Load combination as per IS 1893 (2016) Part I has been used.

III. ANALYSIS AND INTERPRETATION OF RESULTS

The results obtained after Response Spectrum analysis are presented next.

A. Fundamental Time Period

According to IS 1893:2016 Part 1, the empirical formula for time period is given by $0.075H^{0.75}$ [9]. According to this formula, the time period is dependent only on the height (H) of the building and no other parameter. The values obtained by this formula for various heights of our buildings (as per Fig. 5 of IS 1893(Part 1):2016)) range

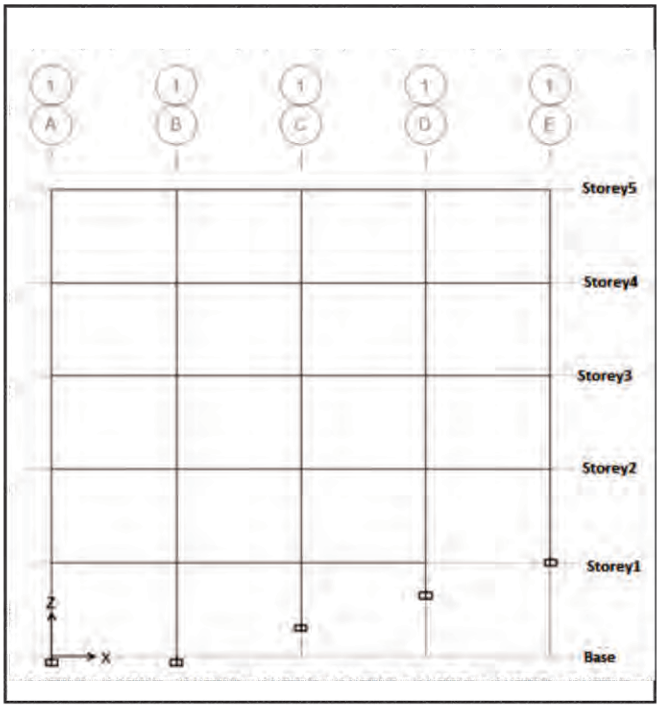

Fig. 6. Elevation Along Grid 1 of MS15 & ML15

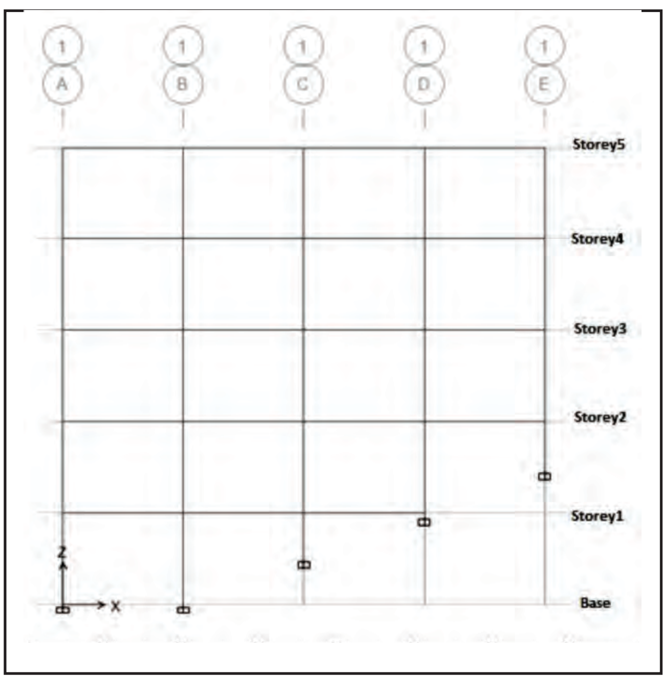

Fig. 7. Elevation Along Grid 1 of MS20 & ML20

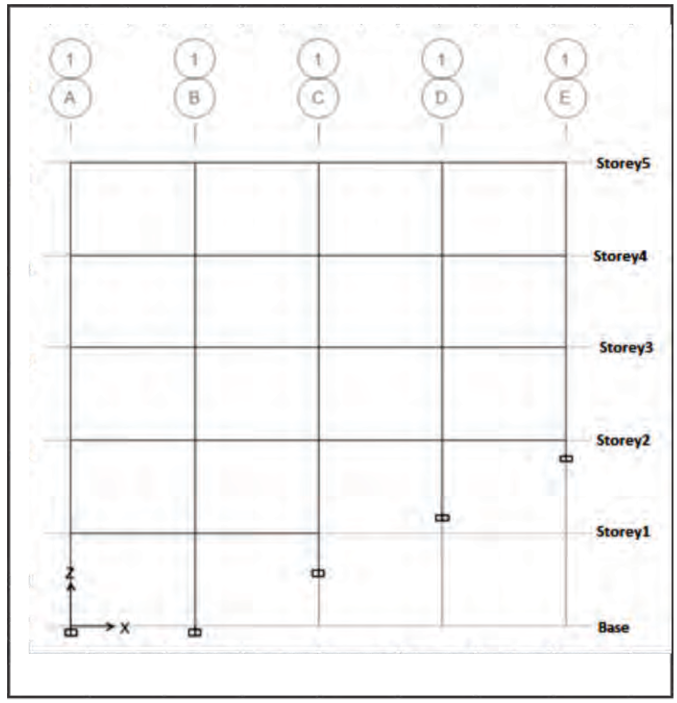

Fig. 8. Elevation Along Grid 1 of MS25 & ML25

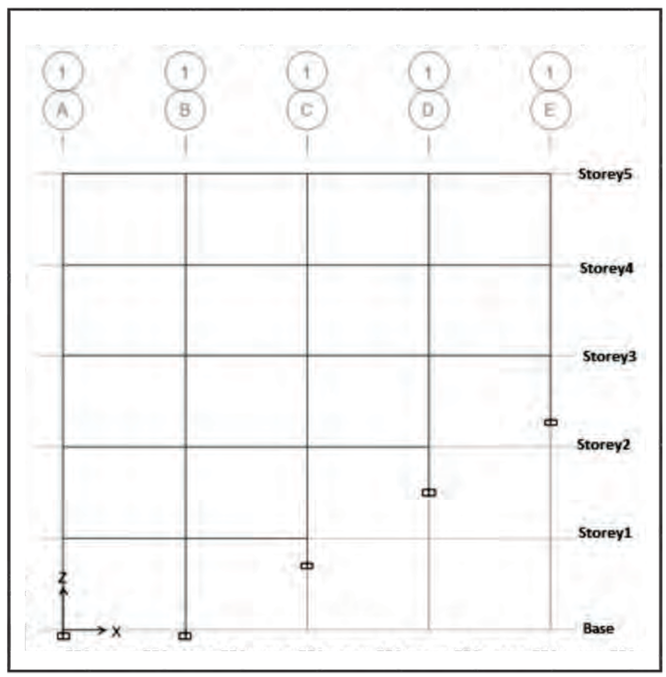

Fig. 9. Elevation Along Grid 1 of MS30 & ML30

from 0.36 to 0.57 sec as shown in Table II. However, the time period that we have obtained in our analysis – range 0.446 sec to 0.664 sec is higher than that obtained by the empirical formula. The values obtained from the analysis are higher than those obtained by empirical relations by approximately 10% to 43%. This shows that the code should consider other factors as well while calculating time period. Factors like slope angle and plan configurations must be taken into account.

TABLE I.
DESCRIPTION OF MODELS

S. No.	Name of Model	Description of the Model
1	MS0	Square Plan model in 0° slope
2	MS5	Square Plan model in 5° slope
3	MS10	Square Plan model in 10° slope
4	MS15	Square Plan model in 15° slope
5	MS20	Square Plan model in 20° slope
6	MS25	Square Plan model in 25° slope
7	MS30	Square Plan model in 30° slope
8	ML0	L-shaped model in 0° slope
9	ML5	L-shaped model in 5° slope
10	ML10	L-shaped model in 10° slope
11	ML15	L-shaped model in 15° slope
12	ML20	L-shaped model in 20° slope
13	ML25	L-shaped model in 25° slope
14	ML30	L-shaped model in 30° slope

TABLE II.
TIME PERIOD

	TIME PERIOD	
Model	From Model (sec)	From Empirical Formula (sec)
MS0	0.664	0.571
MS5	0.635	0.539
MS10	0.593	0.510
MS15	0.571	0.477
MS20	0.508	0.440
MS25	0.417	0.402
MS30	0.441	0.356
ML0	0.664	0.571
ML5	0.641	0.539
ML10	0.617	0.510
ML15	0.599	0.477
Ml20	0.53	0.440
Ml25	0.456	0.402
ML30	0.505	0.356

(I) Buildings with Square Plan

Fig. 10 shows that with the increase in slope the fundamental time period of the model is reduced. The decrease in time period is due to the fact that with the increase in slope, intermediate columns are introduced. The decrease in column length increases the stiffness of the building and hence, the time period decreases. However, at 30 degree slope, there is a slight increase in the time period compared to that of building at 25 degrees. The slight increase in time period is due to the cumulative effect of mass and stiffness which caused the buildings on 30 degree slope to be more flexible and thus, the reduced time period. The pattern of time period in our study is similar to that obtained by Ghosh and Debbarma [7] in their study.

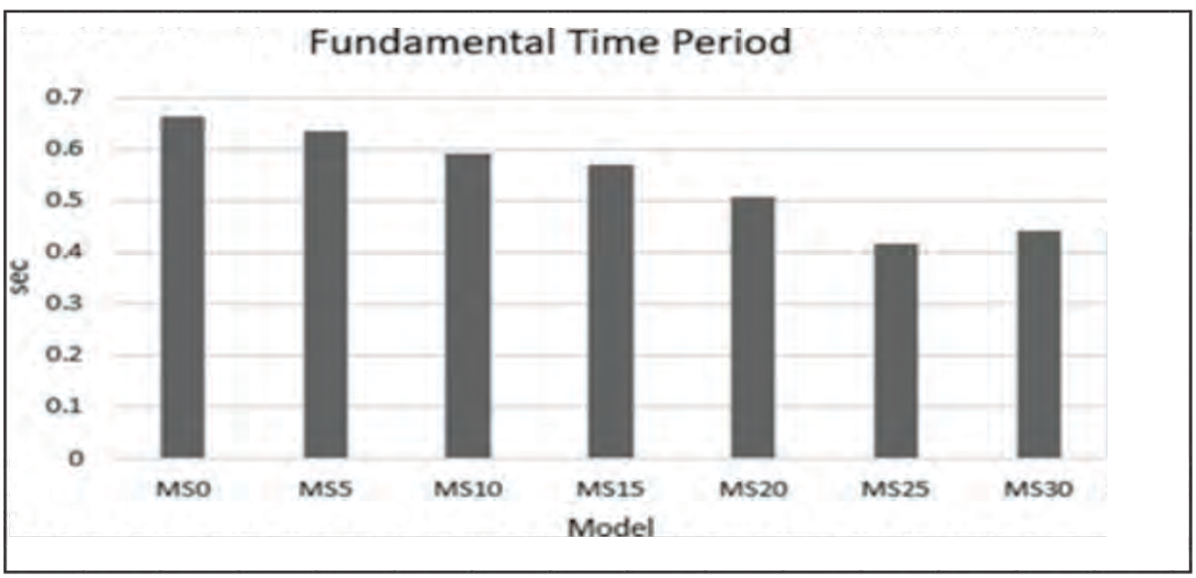

Fig. 10. Fundamental Time Period for Buildings with Square Plan

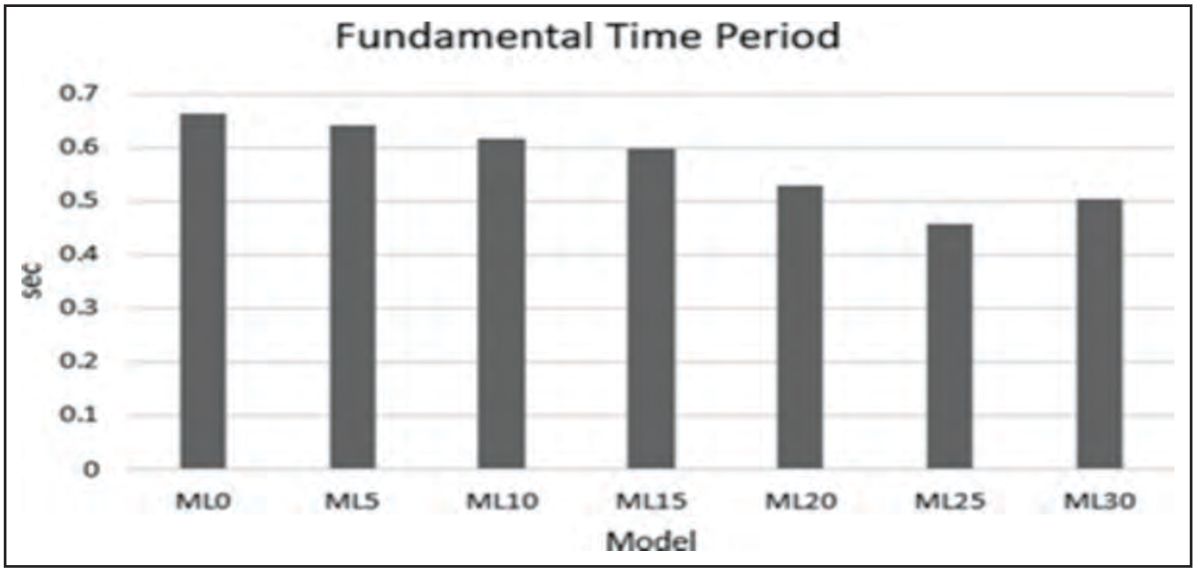

Fig. 11. Fundamental Time Period for Buildings with L-Shaped Plan

(*ii) Buildings with L-shaped plan*

A similar result to that of buildings with square shaped plan has been obtained for L-shaped buildings. In L-shaped buildings as well, the pattern of time period is similar to that of buildings of square shaped plans at various angles of slopes. The time period like that of square building has increased slightly at 30 degree slope.

B. MODAL MASS PARTICIPATION RATIO

Clause 7.7.5.2 of IS 1893 (2016) states that the number of modes to be used in the analysis for earthquake shaking should be such that the sum total of modal masses of these modes is atleast 90% of the total seismic mass[9].

(I) Buildings with Square Plan

For buildings on slope, in our analysis, the number of modes required to achieve 90% modal mass participation varied from 5 modes to 14 modes. With the increase in slope angle, the number of modes required also increased. For building at 0-degree slope, only 5 modes are enough. At 30 degrees, however, 13 modes were required.

(ii) Buildings with L-shaped Plan

From our analysis of L-shaped buildings, the number of modes required to achieve 90% modal mass participation varied from 5 to 14. With the increase in slope, the number of modes required for 90% modal mass participation also increased. At 0-degree slope, only five modes were required. However, at 30 degrees, 14 modes were required.

C. DISPLACEMENT

(I) Buildings with Square Plan

For buildings with square plan, at 0 degree there was no bidirectional displacement for unidirectional force. However, with the increase in slope, bidirectional displacement occurred for unidirectional force. The reason for this is the irregularity. With the increase in slope, the building irregularity increased and hence, bidirectional displacement occurred for unidirectional force. From our analysis we found that along the direction of slope, that is, X-direction, the displacements due to force along the same direction increases with the increase in storey and decreases with the decrease in slope. The result corresponds to the result obtained by Ghosh and Debbarma[7]. However, along the Y-direction, the displacement increased with the increase in storey but did not take a constant decreasing or increasing trend with the increase in slope. At storey 5, the maximum displacement was shown by MS15 and the minimum displacement was shown by MS25. The displacement is higher along the Y-

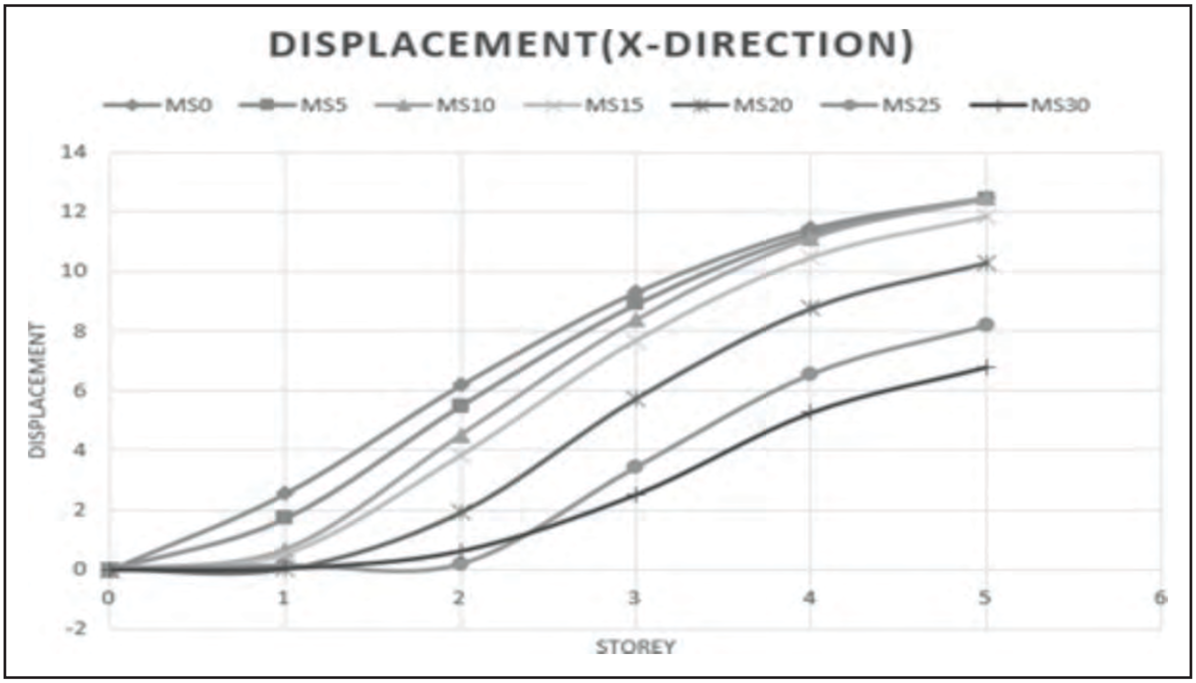

Fig. 12. Displacement Along X-direction for Square Shaped Buildings

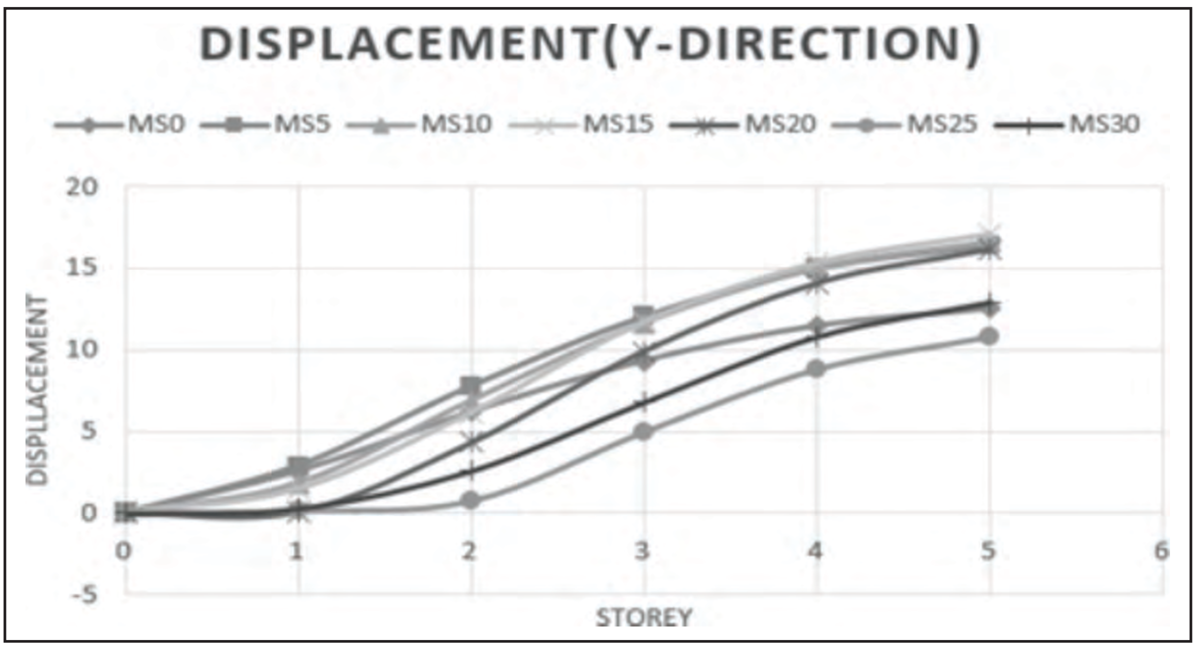

Fig. 13. Displacement Along Y-direction for Square Shaped Buildings

direction than along the X-direction, that is, displacement is lesser along the direction of change in slope compared to that along the perpendicular direction of change in slope.

(ii) Buildings with L-shaped Plan

For buildings with L-shaped plan, it is seen that bidirectional displacement for unidirectional force is obtained even at 0 degree. This is because of the

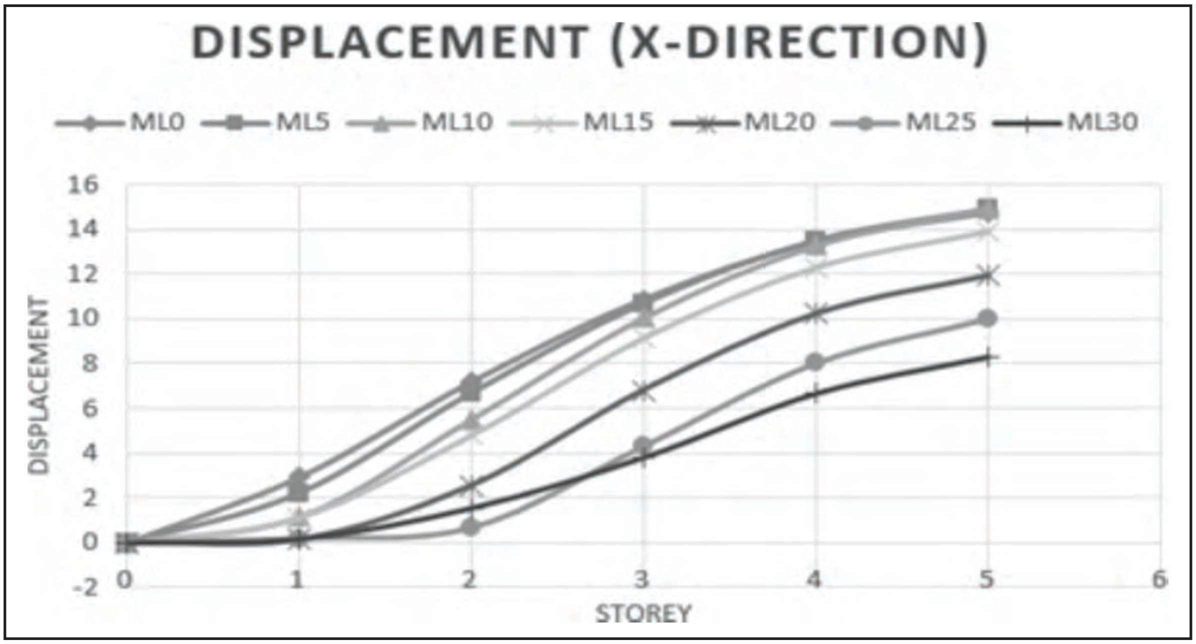

Fig. 14. Displacement Along X-direction for L- shaped Building

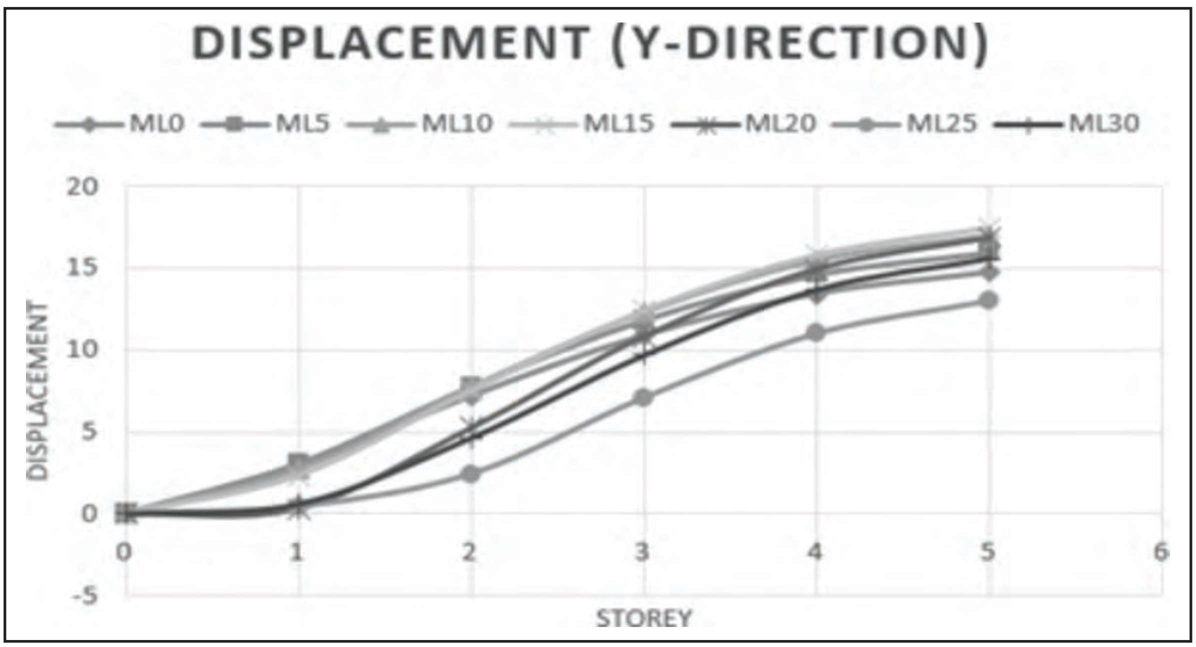

Fig. 15. Displacement Along Y-direction for L- Shaped Building

configuration of the building, that is, irregular buildings even at 0 degree undergo bidirectional displacement for unidirectional moment. The amount of displacement, like in squared shaped building, is higher along Y-direction than that along X-direction. The pattern of displacement is similar for L-shaped buildings and square shape buildings along both the directions.

L-shaped buildings have lesser mass, but due to their plan irregularity, they have higher values of displacement as compared to square shaped buildings at the same angle of slope.

D. BASE SHEAR

(I) Buildings with Square Plan

From Fig. 16 and 17, we can see that the base shear is higher for all the buildings on slope in comparison to that on the flat ground. This holds true for base shear along both the directions, that is, X-direction and Y-directions. Along X-direction for some of the buildings there is a drop in base shear for certain slope angles. This could be due to the fact that as we increase the slope, there is decrease in floor area and change in column heights which ultimately reduced the base shear. For example, at slope 25 and 30 degree there is decrease in base shear than that at 20 degrees. At 25 degrees there is reduction in floor area and at 30 degrees there is further decrease in floor area. Hence the reason for the decrease could be the decrease in floor area. Overall, the pattern of base shear along both X-direction and Y-direction is similar.

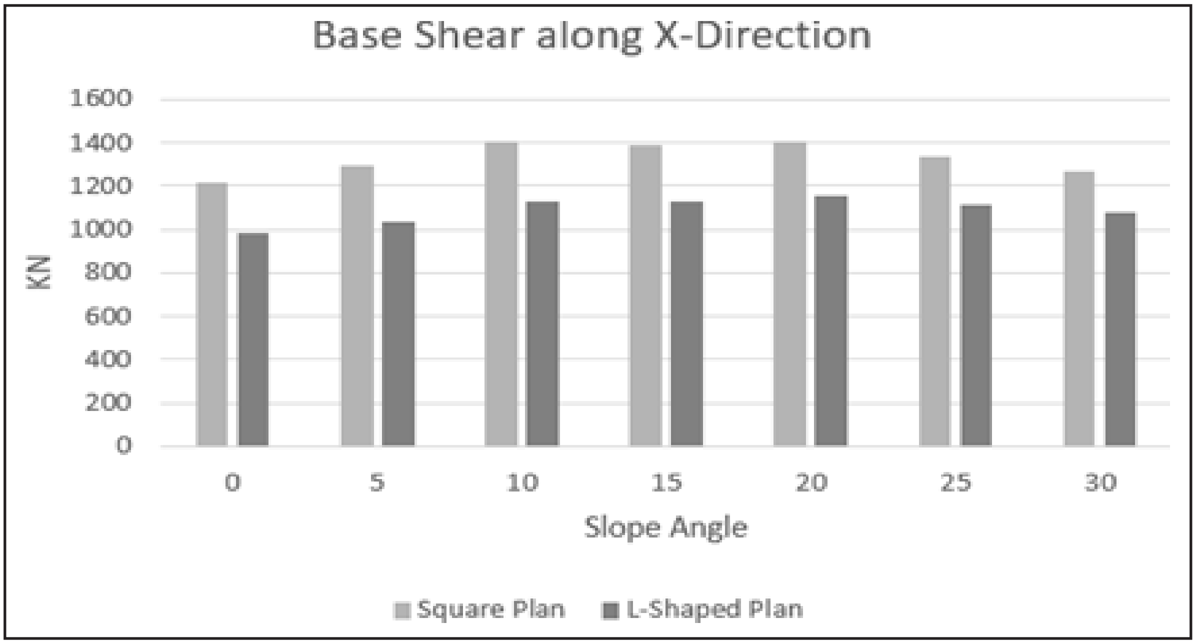

Fig. 16. Base Shear Slong X-direction

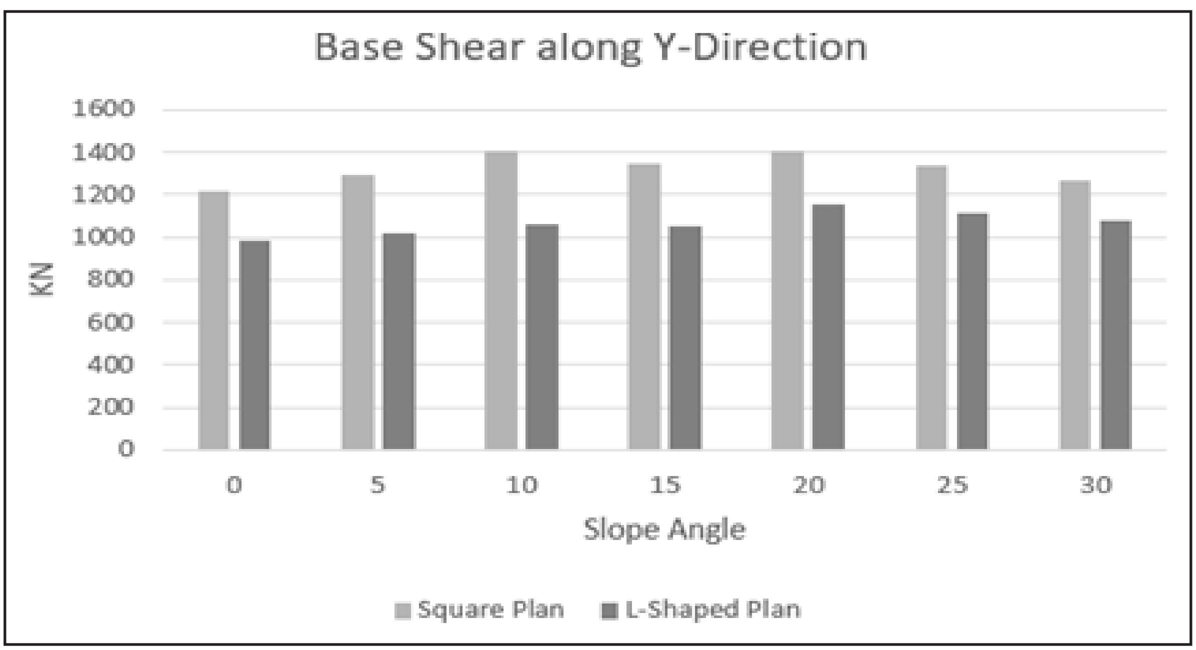

Fig. 17. Base Shear Along Y-direction

(ii) Buildings with L-shaped Plan

From Fig. 16 and Fig. 17, we can see that the base shear is greater for buildings on slope in comparison to the building on plain surface, that is, 0 degree. Along both the directions, the pattern of base shear for L-shaped buildings is similar to that of square shaped buildings due to the change in slope angle.

IV. RECOMMENDATIONS

- IS codes should incorporate additional factors like slope angles and irregular shapes for the time period.
- Further research can be done with different number of storeys for the verification of this research.
- Since the buildings constructed on hill slopes have intermediate columns on some slopes, special care must be given in such cases as stiffness becomes greater in such cases.
- For buildings on hill slopes with square shaped or L-shaped plans, it is recommended that both the architects and structural engineers work closely from early stages of construction.

V. LIMITATIONS OF THE STUDY

- The stability of slopes has not been considered in the present study, that is, analysis with the consideration of geotechnical aspect has not been done in this paper.
- Our paper does not cover the soil structure interaction.
- Our paper fails to cover the study based on hill slopes along both X and Y directions.

VI. CONCLUSION

Our study discusses the effect of slope angle on buildings of 5 storey with storey height 3 m each and compares the response of buildings with square plan and L-Shaped plans. A total of 14 buildings were considered at slopes 0, 5, 10, 15, 20, 25, and 30 degrees. All the buildings were analyzed by response spectrum method and the results obtained were expressed in terms of time period, modal mass participation ratio, displacements, and base shears.

The performance of square shaped and L-shaped building was found to be quite similar in terms of time period, displacements, and base shear. At 0 degree slope both the buildings have the same time period, that is, the effect of building plan on time period at 0 degree was not significant. At other angle of slopes there were changes in the value of time period but the overall pattern of change was similar for both types of buildings. The pattern of base shear and displacement was also similar for L-shaped and square shaped buildings. However, for modal mass participation ratio, even though the range of number of modes required was same, the pattern was quite different. For square plan buildings the number of modes required to achieve 90% modal mass participation decreased at 30 degrees. However, for L-shaped buildings the number of modes required was same as that required at 25 degrees. Hence, we can conclude that plan irregularity has some effect on the modal mass participating ratio.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHORS' CONTRIBUTION

All the authors have contributed equally to the work.

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