Seismic Performance of Buildings in Hilly Regions with and Without Base Isolation and Cable Support System

V. S. Athira, S. Nair Minnu, and S. C. Mohan

Abstract The construction of buildings in hilly areas faces several challenges, such as slope stability, suitable building configuration, etc. The capacity of buildings on the sloping ground reduces as it has to accommodate different length columns in a single storey. These buildings possess both vertical and horizontal irregularities. The current study is an effort to comprehend the effect of seismic forces on the buildings in hilly regions and suitable protection systems. A comparative study of a fixed base, base-isolated, cabled-supported, and base-isolated building with cable support is carried out. The base isolator is designed according to the UBC-97 guidelines. Seismic analysis results show that the base isolator building outperformed other protection systems. Moreover, the base-isolated building with cable support also performed equally sound as base-isolated building. The reaction forces in the cables reduced the stiffness requirement of the isolator. On the other hand, the cabled building did not show any effect on the building.

Keywords Building in hilly regions · Base isolation · Cable support · Irregularity · Seismic analysis

1 Introduction

An earthquake is considered to be a major threat in the unrecorded and recorded human history [1]. An earthquake can be described as a result of a sudden movement of tectonic plates, which results in the release of energy. Its impact affects larger areas and is usually unpredictable, causing loss of life and property and poses problems to the communication systems, transport systems, etc., and results in social and financial weakening of the country. From previous earthquakes, it is confirmed that hilly areas are most vulnerable to earthquakes. Hilly regions are the toughest, and most exciting features to carry any developmental activities. Construction of buildings in hilly terrain is inhibited by their difficult terrain, steep inclines, complicated geological structure, climatic settings, and rich flora. In retort to these settings, various built

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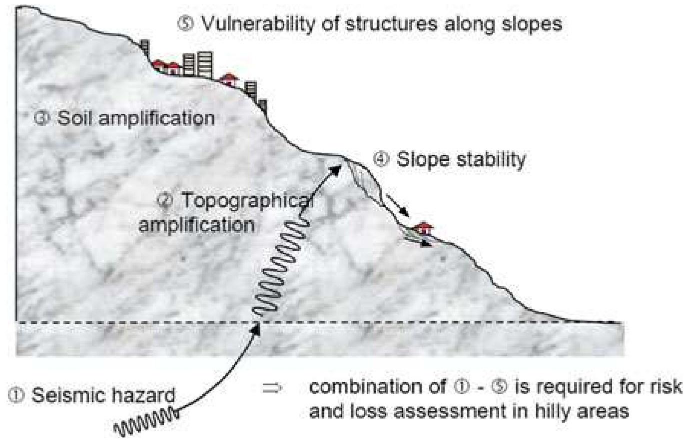


Fig. 1 Seismic safety issues associated with buildings on slopes [2]

form construction techniques and patterns of development have arisen in different hill regions of the country. Fast urbanisation has led to an increase in the population size of the hill towns and, at the same time, the development of hilly areas. Thus, there is an increased demand for the development of multi-story buildings on sloping ground. Lesser availability of plain ground also makes these construction activities on the sloping ground necessary. Buildings in hilly areas are different from those in plains. They possess vertical and horizontal irregularities and are torsionally coupled. As a result, those buildings built on slanted grounds are highly susceptible to earthquakes. These irregularities result in complex seismic behaviour, not anticipated by any of our current seismic codes. The buildings in hilly areas possess columns of different length in the ground storey due to the sloping nature of the ground. Wind load may also be considered critical when the upward slope exceeds 3°. Construction in hilly areas poses several challenges, as depicted in Fig. 1 such as topographic amplification of seismic ground motion due to the geometric features, slope failure hazard, and irregular configurations of buildings due to foundations at different levels, etc.

1.1 Current Scenario in Hilly Regions of India

The most serious concern for the engineering community during the planning and design of buildings in hill regions is their safety against natural hazards. Many vernacular practices like the Dajji wall, Kath-Kuni, Koti-banal, taaq, and wooden buildings have good responses during previous earthquakes (Fig. 2). However, current construction practices in hilly areas lack good seismic resistance and cause serious loss of human life and other precious resources. Therefore, conventional methods can be adopted with suitable modifications for the construction of better earthquake-resistant buildings in hilly areas. Materials like timber and thatch used in old-style buildings that are susceptible to fire and termite attacks can be replaced with more robust and fire-resistant materials like steel or aluminium.

Fig. 2 Vernacular practices in hilly areas [5]

1.2 Configurations of Buildings in Hilly Areas

Buildings in hilly areas possess exceptional structural configurations compared to normal buildings. Normally adopted configurations of buildings in hilly zones are shown in Fig. 3 [3]. In step-back buildings, successive floors step back towards

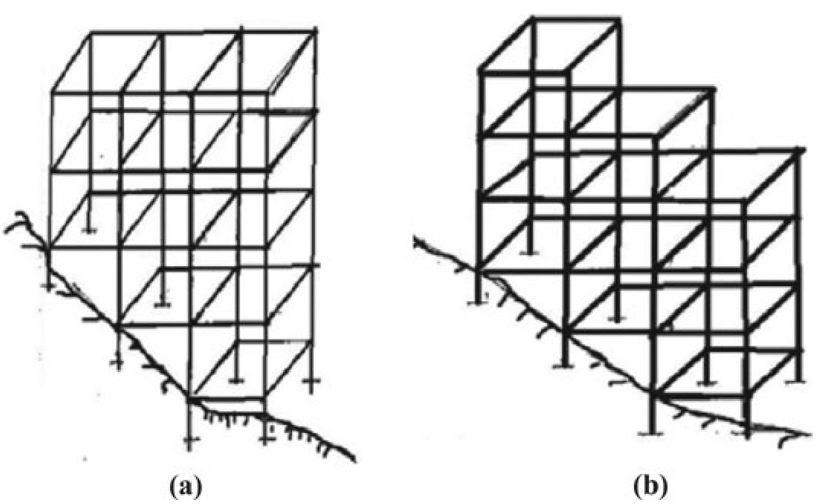


Fig. 3 **a** Step back building. **b** Set back and step back building [3]

the hill slope. Step back buildings have unequal column heights that cause stiffness variations in along-slope and cross-slope directions. Thus, even buildings with symmetric horizontal configurations are torsionally coupled and have high vulnerability to earthquakes. Considering the inefficiency of current construction practices adopted in hilly areas and the loss of life and resources, methods like base isolation, additional stiffness provision, etc. should be adopted to improve the performance of buildings in hilly areas during an earthquake. In this study, the effects of the provision of base isolation and the provision of cables for additional stiffness in buildings of hilly areas are studied.

1.3 Base Isolation

Base isolation is the most safest method that can be adopted in earthquake-prone areas [1]. The objective of a seismic isolation system is to separate a building from its foundation soil so that the building is least affected during an earthquake. Base isolations devices are usually provided to reduce stiffness in the horizontal direction. The basic idea behind base isolation is to shift the time-period of the building and avoids the resonance condition [4]. In an isolated base building, the base isolation device is placed between the superstructure and the foundation of the building. This enables to detach building from the ground; by doing so, the energy induced by an earthquake is not transmitted up through the building. The use of base isolation in a building reduces base shear and acceleration. It avoids seismic damage to the building. However, the use of base isolation is a challenge in hilly regions as isolators have to be designed for various levels according to the reaction force. Designing all the isolators with the highest force is not economical; hence a separate design is required for forces at different levels of foundation.

The following are three major requirements of a good seismic isolation system:

1. Sufficient horizontal flexibility to increase the time-period of the building.
2. Sufficient capacity to dissipate energy or damping to reduce the displacement.
3. Sufficient rigidity to the structure under service loading.

1.3.1 Lead-Rubber Bearing

Lead-rubber bearing (LRB), applied to buildings and bridge constructions, is a cost-effective way for seismic isolation. An LRB is composed of a ***laminated elastomeric bearing*** pad, top, and bottom sealing & connecting plates, and a lead plug which is inserted in the middle of the bearing. The lead core provides rigidity to the building under service loads, and this facilitates energy dissipation during major earthquakes. When subjected to minor earthquakes, the lead-rubber bearing provides lateral and vertical stiffness. The lateral stiffness is a result of the high elastic stiffness of the lead plug and the vertical rigidity.

The main advantage of lead-rubber bearing is that in a single compact unit, it provides rigidity at service load levels, flexibility at earthquake load levels and provide damping. The LRB possesses energy absorbing capacity through additional hysteretic damping through the yielding of the lead core, which helps in reducing lateral displacements of the isolator.

1.4 Cable Supports

Cables are tensile members which can be provided as beams and membranes or to assist beams, columns, other member types as stay wires or suspended members. The application of cables can be seen cranes, ships, towers, bridges, roofs, etc. In cable structures, ropes, strands, chains, etc., are provided as tensile members as main load-bearing elements and give support to other members, resist lateral forces. In this study, cables are provided along one side of the building with the longest columns. The cables are attached to the joints and assigned fixed supports at the other end (at 6 m away from the building). The idea behind the provision of cables was to study the effect of increasing the stiffness of superstructure.

2 Objectives and Methodology

The present study emphasises on the comparison of the seismic performance of a building in a hilly region with and without suitable earthquake protection systems. In addition to base isolation, cable support is assigned to the building and analysed with the following objectives:

- Study the behaviour of a building in the hilly region during an earthquake.
- Study the seismic response of the building when the base isolator is provided.
- Study the effect of providing cable support to the building under seismic activity.
- Study the effect of providing a combination of cable support and base isolation on the seismic performance of the building.

The software used for the study is ETABS. Dynamic analysis was carried out for the building. The building is modelled, and analysis was carried according to IS 1893: 2016 and IS 456: 2000. The building was subjected to Koyna ground motion. Lead core rubber bearing was designed according to UBC 97 code. The building is modelled as a five-storeyed set back building in seismic zone V. The building details are given in Table 1.

Table 1 Building details

Plan dimension	30 × 15 m
Beam	450 × 550 mm
Column	600 × 600 mm
Slab	125 mm thick
Storey height	3 m

3 Models Considered for Analysis

The study involves the analysis of four models: building with fixed base, base-isolated building, cable-supported building, and the one with cable support and base isolation. The plan view of the top floor of the models is shown in Fig. 4. The four models are shown in Figs. 5, 6, 7 and 8. The four models are titled as:

1. Model A—Building with a fixed base (Fig. 5).
2. Model B—Building with base isolation (Fig. 6)
3. Model C—Building with cable support. (Fig. 7).
4. Model D—Building with cable support and base isolation. (Fig. 8).

The fixed base building is analysed for static and seismic loads. From the reactions obtained base isolators for different levels are designed. For Model C, the building was given cable support. Steel cables of diameter 100 mm were provided. The reactions were determined, and the base isolator was designed for the same.

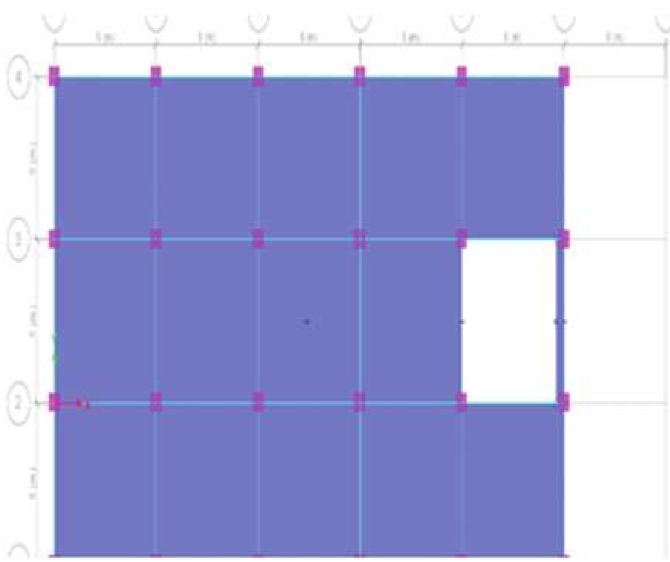


Fig. 4 Top floor plan view of the building

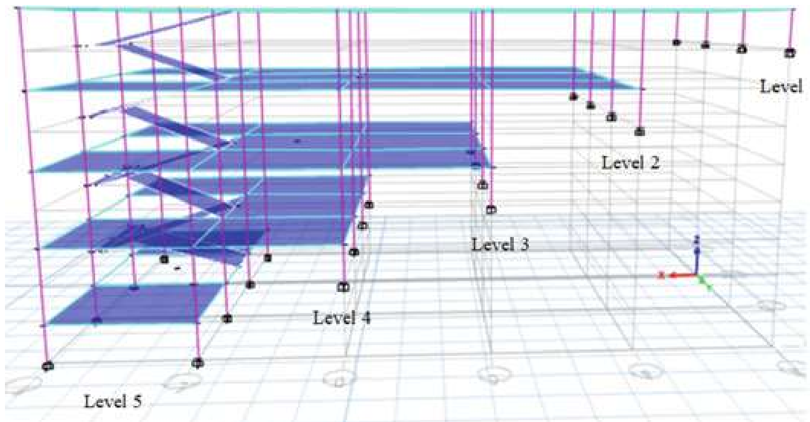


Fig. 5 3D view of Model A

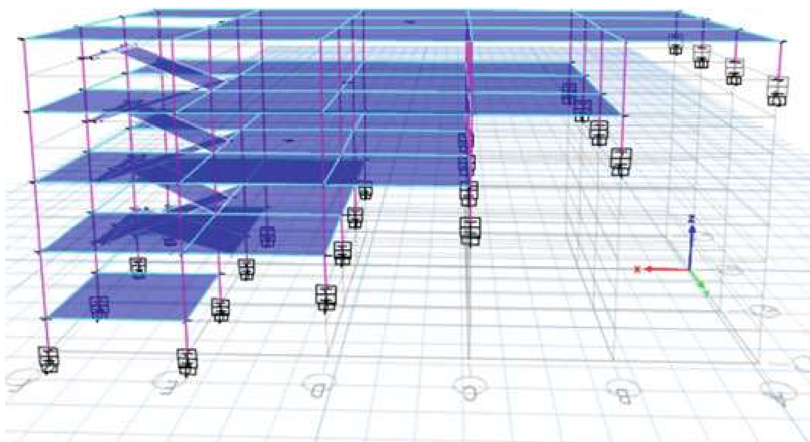


Fig. 6 3D view of Model B

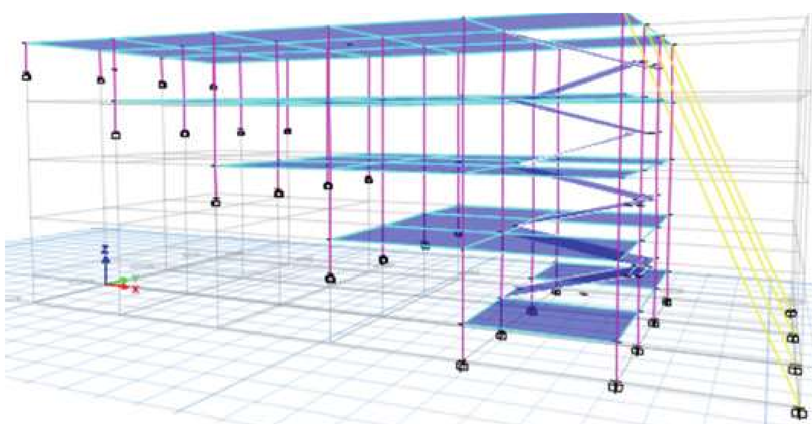


Fig. 7 3D view of Model C

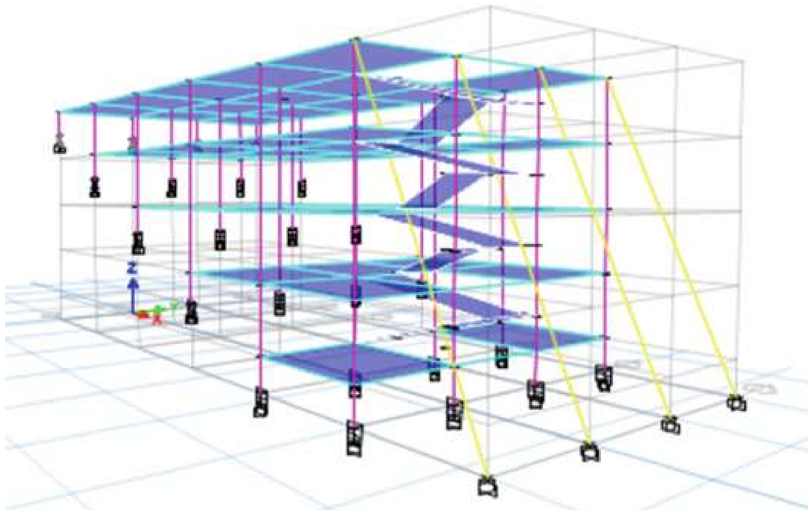


Fig. 8 3D view of Model D

3.1 Properties of Isolator

For building Model B and Model D, different isolators were designed according to the reactions in each storey level. Both base isolators are designed according to the UBC-97 guidelines. The properties of the two isolators are given in Table 2.

Table 2 Base isolator properties

Models	Levels	Maximum reaction (kN)	Horizontal stiffness (kN/m)	Vertical stiffness (kN/m)	Height of isolator (mm)
B	1	131.17	72.399	25750.05	540
	2	386.11	212.81	75691.8	475
	3	624.85	344.47	122516.8	450.4
	4	872.69	480.92	171048.65	442
	5	1126.96	621.13	220916.2	442.4
D	1	76.85	42.354	15064.15	577.6
	2	230.16	126.85	45118.25	500.8
	3	378.78	208.85	74281.86	475
	4	533.51	293.9	104558.5	458
	5	1124.59	619.88	2204709.5	442.4

4 Results and Discussions

4.1 Modal Analysis

The modal analysis was done first to get an idea of possible mode shapes of the buildings. The models were then studied under the response spectrum analysis technique to observe the response of both conventional and base-isolated buildings concerning time. Mode shapes are the deformation pattern of the building when vibrating at a particular natural frequency. The mode shapes of all the four models were analysed to study the behaviour of all the storeys in the fundamental mode. The fundamental mode in X-direction is opted for the study.

From Fig. 9a–d it can be seen that Model A and C behaved similarly. This can be due to the futility of the cable under seismic action. Models B and D behaved similarly, and the displacement was found to be higher for these models. The parameters considered for evaluating the building are time-period, storey acceleration, base shear, storey shear, overturning moment, storey displacement, and storey drift.

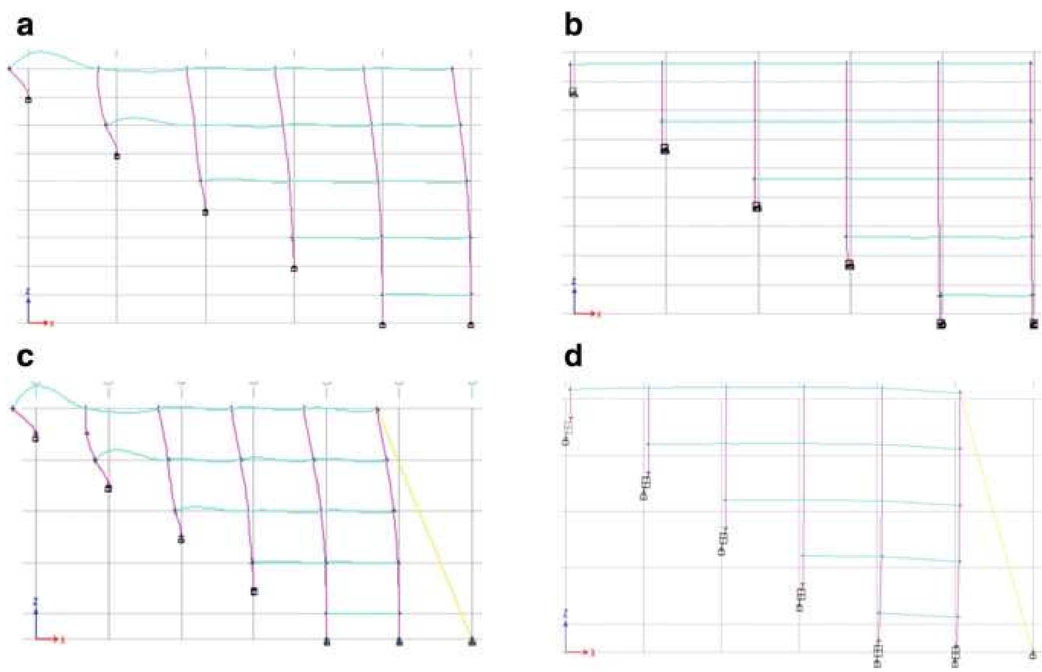


Fig. 9 **a** Fundamental mode shape of Model A**. b** Fundamental mode shape of Model B. **c** Fundamental mode shape of Model C. **d** Fundamental mode shape of Model D

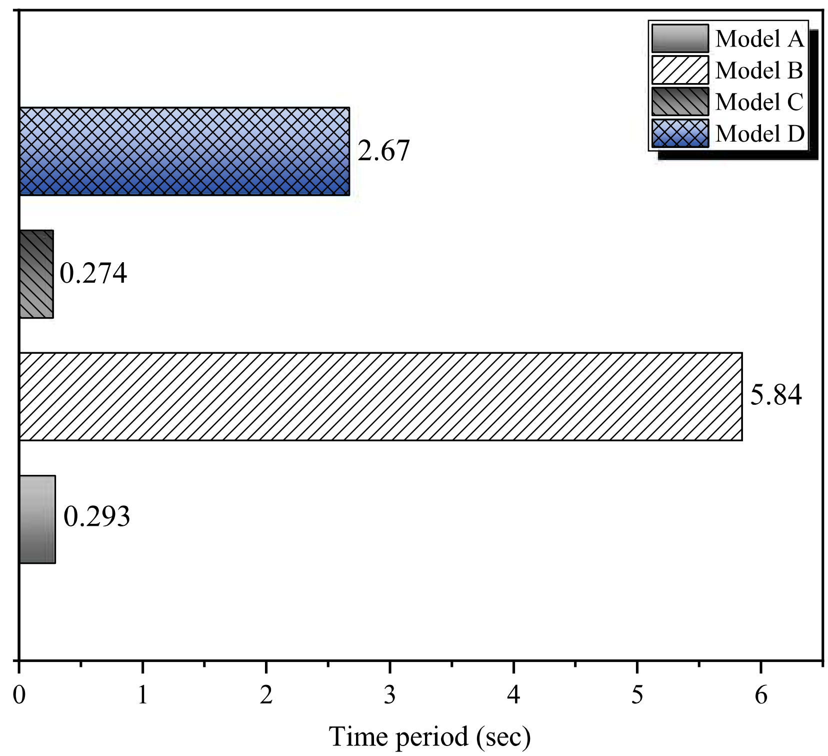


Fig. 10 Variation in time-period

4.2 Variation in Time-Period

This study demonstrated that the overall response was mainly affected by the incorporation of rubber bearings used as base isolators. The predominant time-period has been lengthened for the seismically isolated building as logically expected. Figure 10 shows the variation of the time-period in the fundamental mode. The base isolation (Model B) has increased the fundamental time-period of building to 5.8 s compared to that of 0.2 s for the fixed base building (Model A). The cabled building does not show much change in time-period, whereas Model D shows an increased fundamental time-period to 2.67 s; hence it is comparable with Model B. Base isolators make the building more flexible at the base and helps in less transfer of lateral forces at the time of an earthquake. Thus the time-period is found to be higher for base-isolated buildings.

4.3 Variation in Storey Acceleration

Figure 11 shows the variation of storey accelerations in different storey levels. They are indicators of inertia forces acting at different storey levels. As a general rule, the force acting on a building is directly proportional to its acceleration. Hence, the main

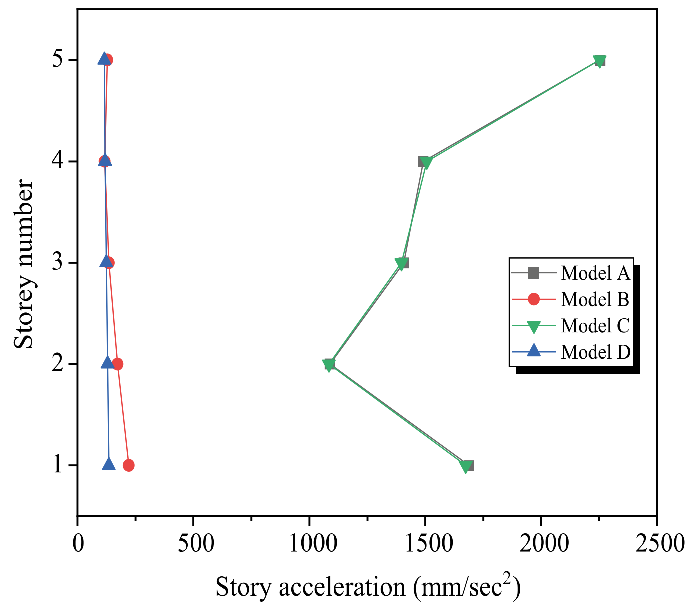


Fig. 11 Variation in storey acceleration

aim should be to reduce the acceleration to decrease the seismic forces on the building. According to the results obtained, a reduction in acceleration at storey levels by the use of isolators is observed. The accelerations are found to decrease significantly for Model D also. The cabled building is found to face the same accelerations as that of fixed building.

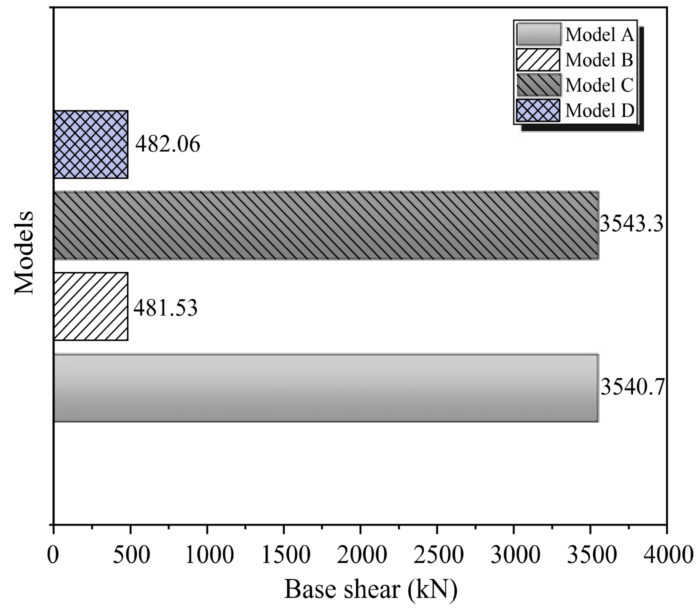
4.4 Variation in Base Shear

Base shear is the maximum lateral force acting at the base of the building during seismic activity. When a building is base-isolated, the maximum elastic forces are reduced due to the shift in time-period and energy dissipation by the isolator. Thus, a considerable reduction in base shear is witnessed in the base-isolated building. It is obvious from Fig. 12 that base shear is high for fixed and cabled buildings, whereas for Model B and D base shear has considerably reduced and are almost similar which shows the effectiveness of the isolator. The less stiff isolated building gave the same results as that of high stiff isolated buildings.

4.5 Variation in Storey Shear

Storey shear is the seismic force acting at different storeys. For the top storeys, Model, D performed better than all other models, as observed in Fig. 13. However, at the second and first storey, the results were reversed as storey shear was found to be more for Models B and D. The storey shear was found not to follow a uniform

Fig. 12 Variation in base shear



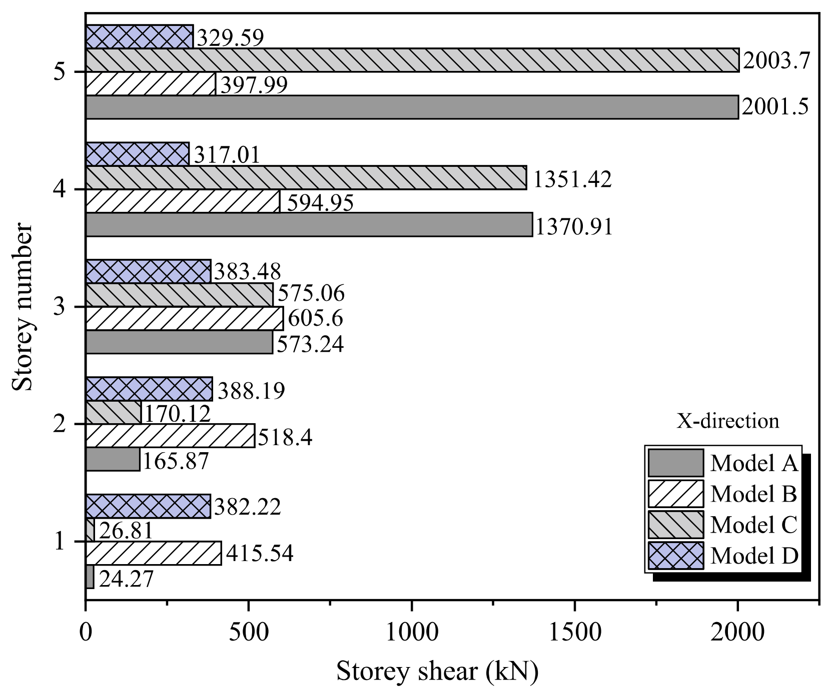


Fig. 13 Variation in storey shear

pattern of change with the storeys for the models studied. This might be due to the difference in the floor area for each storey.

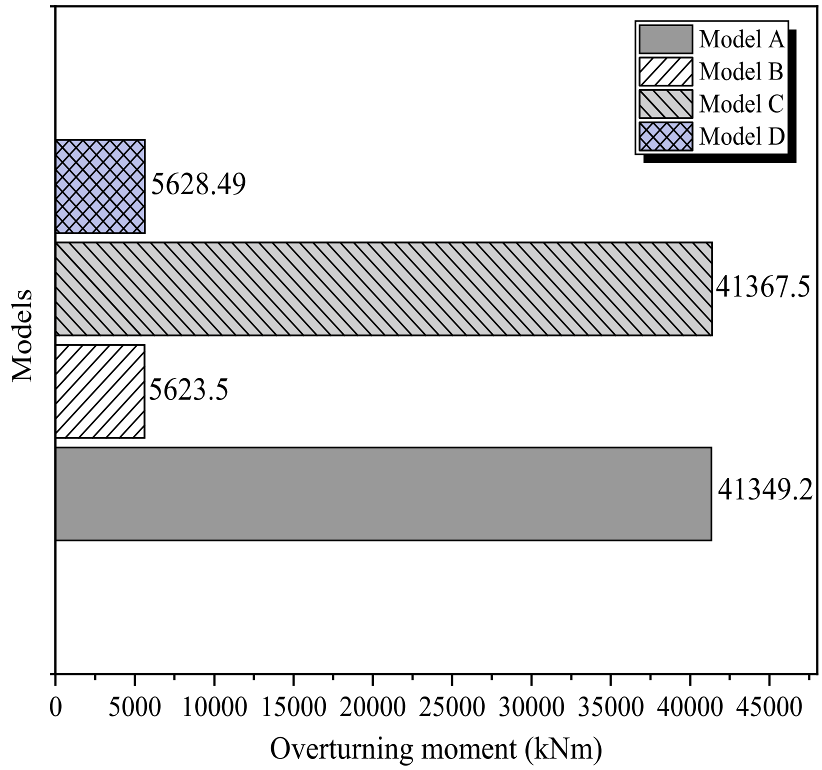


Fig. 14 Variation in overturning moments

4.6 Overturning Moments

The overturning moment is experienced by the structure when it is subjected to lateral forces such as wind force, seismic force, etc. The force causes lateral deflection of the structure in the direction of the force and hence leads to the formation of overturning moments. Stability of the structure considerably increases if the overturning moment is considered for analysis. From Fig. 14, it is evident that moments are considerably reduced for Models B and D. This is because less force is acting on the super building for isolated buildings; hence less moment is observed.

4.7 Variation in Storey Displacement

Storey displacement refers to the maximum total displacement experienced by the storey. Higher displacement of storeys creates uneasiness to the occupants (Fig. 15).

It was observed that Model A and C had similar displacements in all the storeys. The highest displacement was found for Model B in all the storeys, which reduced to 60% in Model D in all the storeys. This was because cables provided extra stiffness to the building, which reduced displacement. Model B had 90% more displacement than

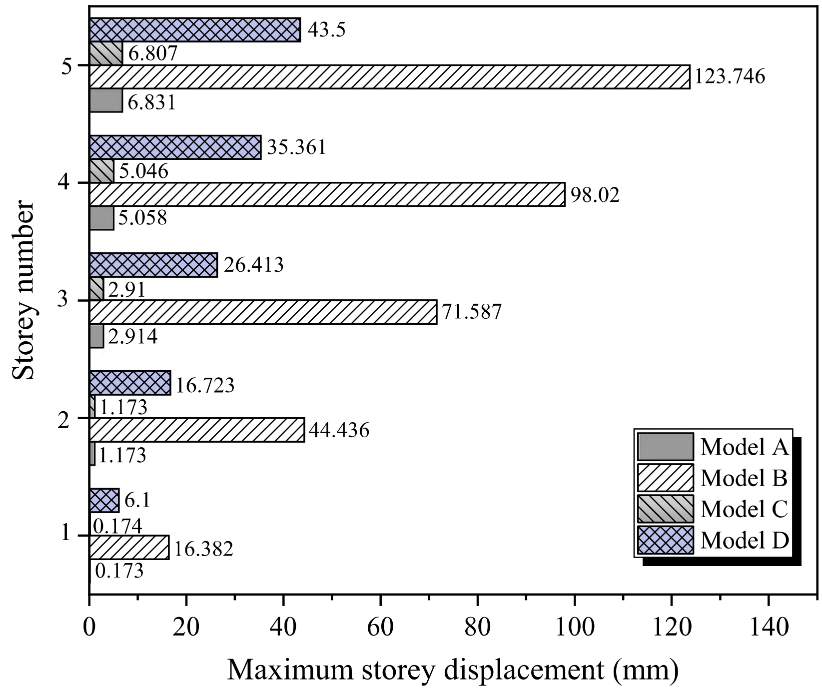


Fig. 15 Variation in storey displacement

Models A and C. Base-isolated buildings were found to have higher displacements as it is more flexible than fixed base building.

4.8 Variation in Storey Drift

It is observed that in the top storey drift is very less for Models C and D. It is evident that storey drift is high for base-isolated building (Model B) however, the presence of cable has reduced the storey drift to a very great extent (Model D). The effect of cables in reducing storey drift is found to decrease in the lower storeys; however, it was found to perform better than base-isolated building (Model B) (Fig. 16).

5 Conclusions

The study focused on a comprehensive analysis of seismic responses of a building in the hilly area. Earthquake protection systems used in the study were base isolation and cable supports. The primary focus of the study is to make base isolators economical by combining with cable support technique. The challenge was high as this had to be implemented in hilly terrain. By introducing cables to the base-isolated building, the stiffness of the building increases, thus reducing the demand of highly

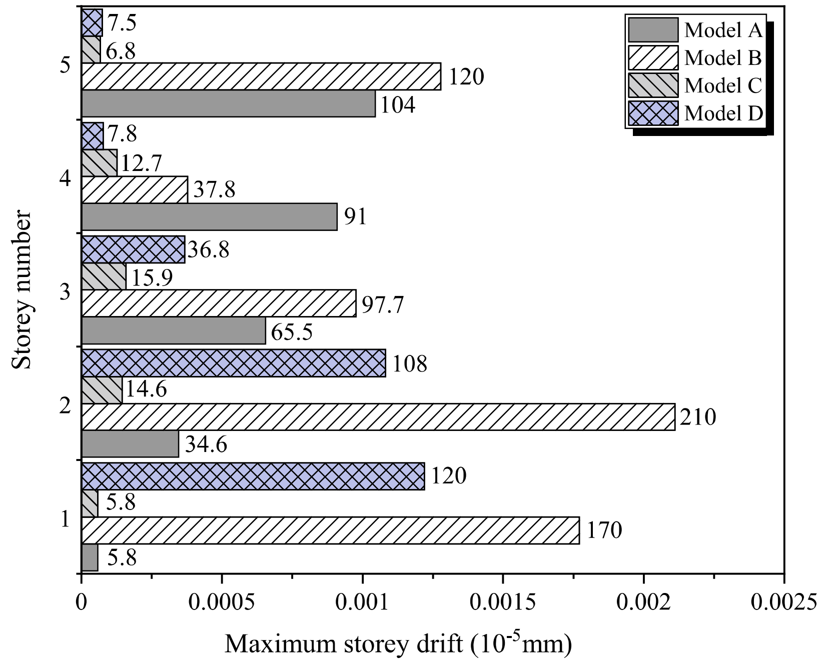


Fig. 16 Variation in storey drift

stiff base isolator. Therefore the cost of the base isolator can also be reduced considerably, making it available for the common people. Parameters such as time-period, storey accelerations, base shear, storey shear, overturning moments, storey displacements and storey drift in different models were considered for the comparative study. From the results obtained, it was found that the base-isolated building showed better seismic performance. In contrast, cable with base-isolated building gave comparable results as that of base-isolated building. It can be inferred that cables act as extra stiffness providers which reduce the reactions hence reducing the material and stiffness required for the isolator. It can be seen that the low stiffness isolator performs as good as the high stiffness isolator. On the other hand, only providing cables is not effective to reduce seismic demand on the building.

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