Effect of Base Isolation on the Seismic Performance of Hill Buildings

Zaid Mohammad, Ahmed Bilal, and Abdul Baqi

Abstract RC buildings constructed on hill slopes pose complex structural behaviour as compared to conventional buildings resting on a plain ground. The hill buildings come under the category of irregular buildings, which are asymmetric in elevation as well as plan at different floor levels, due to which the centre of gravity and stiffness at subsequent floor levels always vary and cause additional torsional moments in the buildings. Further, the length of the columns in hill buildings also varies pertaining to steep slopes, resulting in variation of lateral stiffness in all columns. Moreover, the base isolation systems have shown a profound effect to reduce the seismic vibrations in the buildings. Thus, in this study, the influence of a commonly used base isolation system, i.e. Laminated Lead Rubber Bearing (LLRB) on the seismic performance of two hill building configurations, viz. stepback and setback-stepback, was investigated. All the configurations have been modelled using a finite element software, and examined by Response Spectrum analysis and Non-linear Static Pushover analysis. The dynamic parameters obtained from the numerical study were discussed as variations in storey shear, base shear, time period, drift, maximum top storey displacement values and plastic hinge development pattern in the building structure. finally, the vulnerability and suitability of the different configurations against seismic excitations were compared.

Keywords Hill buildings · Push-over analysis · Base isolation · Laminated lead rubber bearing

1 Introduction

The population growth has led to an increase in infrastructural development in hilly areas. Due to the scarcity of plain ground in hills, the construction of RC buildings

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has to be carried out on steep sloping grounds. Thus, the buildings constructed on hill slopes show different dynamic behaviour as compared to those resting on the levelled ground under seismic forces [1]. The stepback configuration is generally preferred for the buildings on the steep slopes, however, a setback-stepback configuration is also common. Buildings resting on hill slopes have unsymmetrical structural configuration due to which the centre of mass and centre of stiffness varies along various floors and impart twisting moment in structural members, in addition to the lateral loads, when subjected to earthquake loads. Further, due to the short column effect in hill buildings, the shorter column on the uphill side has higher stiffness and attracts much more forces as compared to that of the column on the downhill side. Hence, it is found to be more vulnerable to damage under earthquake loads [2].

Previous studies have shown that a base isolation system is the most effective control measure for reducing the earthquake vibrations induced in the structural systems [3–5]. In conventional earthquake-resistant design of RC structures, the capacity of the structure is increased to provide the seismic demand through adequate reinforcement and ductility. Whereas, in a base isolation system, the dynamic properties of the building are modified in such a way that the shear demand for which the building has to be designed is reduced. In this technique, some flexible system is introduced between the foundation system and the column base of the structure, which increases the damping as well as the horizontal flexibility of the building. The fundamental time period of the RC structures is generally found in the range of the predominant period of the earthquake ground motions which causes a high dynamic amplification effect [6, 7]. Thus, the time period of the building can be increased beyond 2.0 s using base isolation, which significantly brings down the seismic demand [3]. The most common type of base isolator is the laminated lead rubber bearing isolator, as it is found to be very effective in reducing the high accelerations or the high-frequency motions. These are characterized by low horizontal stiffness to isolate the horizontal vibrations and high vertical stiffness [8, 9].

The state-of-the-art studies carried out so far, emphasized the structural behaviour of hill buildings and frame-infill interaction in normal buildings constructed on the plain ground [1, 2, 10–16]. But none of the studies were conducted on the behaviour of hill buildings with base isolation systems under earthquake loads. Moreover, IS 1893 (Part 1) has recommended to carry out three-dimensional dynamic analysis for the buildings with geometrical, mass and stiffness irregularity to ascertain the true response of buildings subjected to lateral loads [17]. Also, the inelastic behaviour of hill buildings should be analysed in order to get the true response of the structure. Thus, the present study explores the influence of a commonly used base isolation system, i.e. Laminated Lead Rubber Bearing (LLRB) on the seismic performance of two hill building configurations, viz. stepback and setback-stepback. All the configurations were modelled using a finite element software, and examined by employing Response Spectrum analysis and Non-linear Static Pushover analysis. The seismic parameters obtained from the numerical study were discussed as variations in storey shear, base shear, time period, drift, maximum top storey displacement values and plastic hinge development pattern in the building structure. Finally, the vulnerability and suitability of the different configurations against seismic excitations were compared.

2 Materials and Methods

The present study investigates the structural behaviour of two different types of buildings resting on an inclined terrain, viz. stepback and setback-stepback, under seismic loads. The influence of laminated lead rubber bearing (LLRB) base isolation system on the seismic performance of the considered configurations was analysed. The Response Spectrum and Non-linear Static Pushover methods were employed to ascertain the seismic response of building configurations. The obtained seismic parameters from the analyses were compared as variation in the values of the fundamental time period, lateral drift, lateral shear at foundation level and plastic hinge development pattern in along as well as across hill slope direction. The elasticity modulus and Poisson's ratio of concrete material are taken as 25,000 N/mm^2 and 0.2, respectively. The concrete mix and reinforcement steel grade were assumed as M25 and Fe500, respectively. For seismic analysis, rigid frame diaphragm is considered in the floor systems and support conditions are assumed to be fixed at foundation level. Due to accidental eccentricity, the torsional effects have been considered in the analysis in accordance with IS 1893 (Part 1): 2016. For non-linear analysis, plastic hinges were allocated at the ends of all the frame elements in all the models. The load application was considered to be displacement control in pushover analysis. When the load was incrementally increased, structure members may start to yield and lead to failure. The members experience changes in stiffness sequentially and demonstrate various stages as shown in Fig. 1, viz. immediate occupancy, life safety and collapse prevention levels [18].

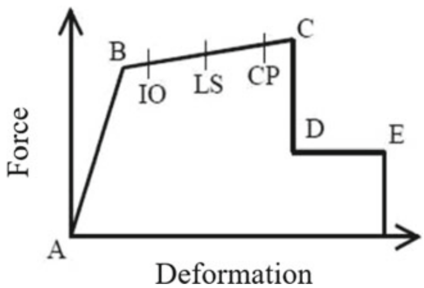


Fig. 1 Force versus deformation curve for plastic hinge at different stages

Table 1 Parameters considered in different building configurations [11]

Geometric parameters	Seismic parameters
Thickness of slab = 0.150 m	Zone = V
Height of each storey = 3.5 m	I = 1.5
Depth of foundation = 1.75 m	R = 5
Column size = 0.23 m × 0.50 m	Soil condition = II (i.e. medium)
Beam size = 0.23 m × 0.50 m	Live load = 3 kN/m^2

2.1 Building Configuration

Four different models of stepback and setback-stepback building configurations with and without base isolator systems were analysed. The buildings were modelled with 4 bays in along as well as across slope directions. The length of each bay in along and across the slope in all the models was taken as 7 and 5 m, respectively. The inclination of the ground was assumed to be 27° with the horizontal [11].

The load due to the masonry infills has been considered at the periphery of the building frames. The various parameters considered in the analysis of different building configurations are mentioned in Table 1.

2.2 Design of Base Isolation System

For the design of an effective base isolation system, the main requirements are: (a) capability to carry vertical loads, (b) sufficiently low stiffness in the horizontal direction which can increase the time period of the building to the required value, (c) large vertical stiffness so that the amplification in the vertical direction can be minimized, (d) sufficient damping to prevent excessive isolation level displacements, and (e) initial stiffness to prevent movement due to small vibrations [19]. While designing a base-isolated building, the following steps are followed [3]:

(i) Base isolators were designed based on the vertical load coming on them for the specified zone and soil type.
(ii) Base isolated building was designed to achieve the desired criteria.
(iii) Finally, the design was checked using non-linear dynamic analysis.

The base isolators were designed using the relationships given by Datta [3]

$$K_{eff} = \frac{W}{g}\frac{4\pi^2}{T_b^2} \tag{1}$$

where K_{eff} is the effective stiffness of the base isolator, W is the maximum vertical load under any column for the load case ‘$1.2DL + 1.6LL_o$’ (where LL_o reduced live load) [19], T_b is the isolated time period, '$T_b = nT$', (where n may be taken as 3 to 4), T represents the time period for building having a fixed base.

$$A_r = W/p \tag{2}$$

$$T_r = GA_r/K_d \tag{3}$$

$$A_{pb} = F/\sigma_{pb} \tag{4}$$

where T_r is the thickness of one rubber layer, G is the modulus of rigidity of rubber, G varies from 0.69 to 0.86 MPa for the range of strain specified for rubber bearing, i.e. $\gamma = 100 - 150\%$ [6], A_r represents the area of rubber layer, F is the characteristic strength calculated while determining the bilinear curve properties of the base isolator, σ_{pb} is the yield shear strength of the lead. σ_{pb} has a value of 8–10 MPa [4].

In order to account for sufficient over strength, peak design earthquake forces are used directly to design isolation system and substructure, that is, the R factor is taken as unity for designing the isolation system and the substructure. For the design of superstructure, the response reduction factor, R_I is kept lesser than that of fixed base building. As per FEMA P751 (2009) [20], R_I is taken as three-eighth of the R factor considered for the fixed base structure. For superstructure, R_I is considered as 2. For substructure, R_I is considered as 1. In IBC 2006, 1605.2.1 [21], three load cases, are available for the design of isolators.

In this paper, hill buildings with two configurations, viz. stepback and setback-stepback have been analysed. Base isolators were designed for both the buildings and the responses were compared with the buildings having fixed supports (see Fig. 2). In order to keep the design economical, base isolators were not provided beneath all the columns. Base isolators were provided at supports that were at higher levels from the base supports as shown in Fig. 3 and were subjected to higher shear forces under earthquake.

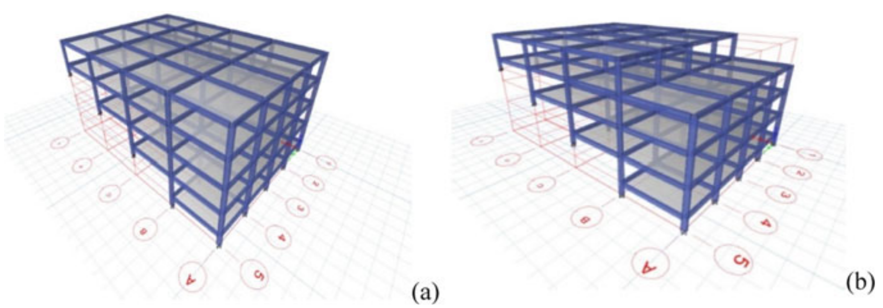


Fig. 2 Different hill building configurations: **a** Stepback building and **b** Setback-stepback building

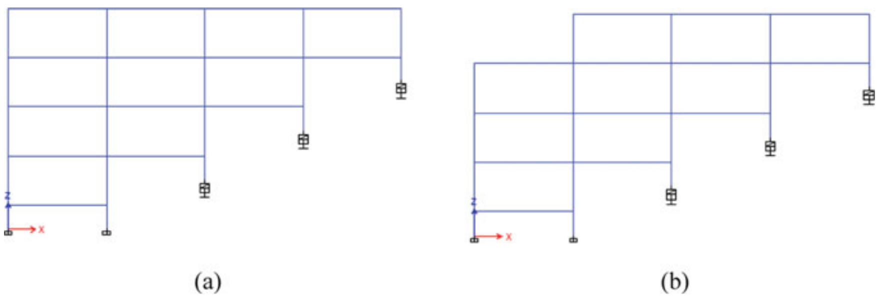


Fig. 3 Hill building configurations with a base isolator in **a** Stepback building and **b** Setback-stepback building

Initially, the buildings were analysed using the response spectrum method where input spectrum was taken from IS 1893:2016 [17]. The vertical load at each column was evaluated and the base isolator was designed individually. For example, while designing the base isolator under an interior column for setback-stepback configuration, the values of effective stiffness, design displacement and energy dissipation per cycle have been calculated as $K_{eff} = 2112$ kN/m, $\Delta_d = 0.213$ m, *and* $W_d = 82.56$ kNm, respectively, from Eq. 1, for zone V and damping coefficient $\xi_{eff} = 0.15$. Final values of parameters of the backbone curve of the base isolator have been obtained after iterations (Tables 2 and 3). Furthermore, the geometric properties have been calculated from Eqs. 2–4 as shown in Tables 4 and 5 [19]. Four sets of base isolators were designed for each building. Lumped plasticity approach was adopted for modelling non-linearity in the beams and columns. Hinges were defined as per FEMA 356 [18]. M3 hinges were provided for beams and P-M2-M3 hinges were provided for columns.

Table 2 Bilinear properties of the isolators used in stepback building

Isolator id	R (kN)	K_{eff} (kN/m)	F_y (kN)	K_u (kN/m)	K_d (kN/m)
RUB2000	2000	1222	70	9236	924
RUB1500	1500	964	55	7292	729
RUB1000	1000	643	37	4861	486
RUB650	650	418	24	3159	315

Table 3 Bilinear properties of the isolators used in setback-stepback building

Isolator id	R (kN)	K_{eff} (kN/m)	F_y (kN)	K_u (kN/m)	K_d (kN/m)
RUB2800	2800	1801	104	13,611	1361
RUB2000	2000	1222	70	9236	924
RUB1300	1300	836	48	6319	632
RUB850	850	546	31	4139	414

Table 4 Geometric properties of the base isolators used in stepback building

Geometric properties (in mm)	RUB2000	RUB1500	RUB1000	RUB650
Bearing diameter	600	550	450	35
Diameter of lead core	95	85	70	60
Thickness of each rubber layer	13	13	13	12
Layers of rubber	18	20	20	15
Thickness of the plates	3	3	3	3
Thickness of end plates	25	25	25	25
Bearing height	338	370	370	275

Table 5 Geometric properties of the base isolators used in setback-stepback building

Geometric properties (in mm)	RUB2800	RUB2000	RUB1300	RUB850
Bearing diameter	720	600	500	400
Diameter of lead core	100	95	75	65
Thickness of each rubber layer	13	13	13	13
Layers of rubber	18	18	18	18
Thickness of the plates	3	3	3	3
Thickness of end plates	25	25	25	25
Bearing height	338	338	338	338

3 Results and Discussion

The hill building configurations with fixed support and base isolator systems were analysed for the seismic loads in along as well as across slope directions including the effect of accidental eccentricity as per code provisions [17]. The three-dimensional models were analysed using the Response spectrum method and Push-over method of analysis. The results obtained from the analysis were discussed in terms of the fundamental time period, total base shear, lateral shear force at foundation and plastic hinge patterns in structural members, and compared within the considered configurations.

The dynamic properties obtained from the numerical analyses have been described in Table 6. It can be clearly observed that the base isolator system has significantly

Table 6 Seismic response of different building configurations

Building type	Support type	FTP by RSA (sec)		Base shear (kN)	
		Along	Across	Along	Across
Stepback	Fixed	0.718	0.417	2986	2258
	Base isolated	1.675	1.217	1521	884
Setback-stepback	Fixed	0.894	0.580	2502	1603
	Base isolated	2.165	1.613	989	638

influenced the seismic performance of both stepback and setback-stepback configurations. In the case of stepback buildings, the fundamental time period (FTP) in along slope direction was found to be increased by 133.3% with the introduction of a base isolator system in place of fixed isolated supports. The variation in FTP was found to be 191.8% in across slope direction. Similarly, base-isolated setback-stepback buildings exhibited a 142.1 and 178.1% increase in the FTP in along and across slope direction, respectively, as compared with that of fixed supported building.

There was a prominent decrease in the total base shear was observed in building configurations with base isolation in along as well as across slope directions, which indicates the less shear demand attracted by the structural members of base-isolated buildings as compared with those of fixed support systems. The base shear values were found to be reduced to 50.9 and 38.6% in along and across slope directions, respectively, after the base isolation system was introduced in the stepback building. Also, the base shear values in the base-isolated setback-stepback configuration were found to be decreased to 39.5 and 39.8% in along and across slope directions, respectively. Moreover, it can be ascertained that the setback-stepback buildings attract less base shear than the setback configuration of the hill buildings, thus proved to be less prone to earthquake forces.

Figures 4 and 5 describe the lateral shear force distribution in an interior frame of hill building configurations. It was observed that the building with fixed support

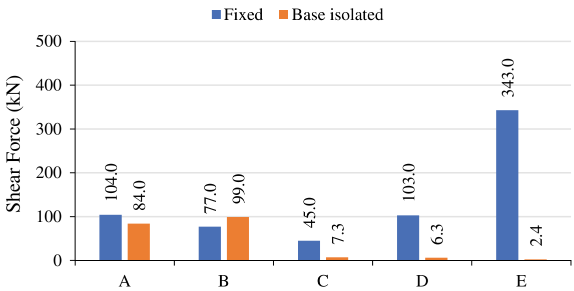
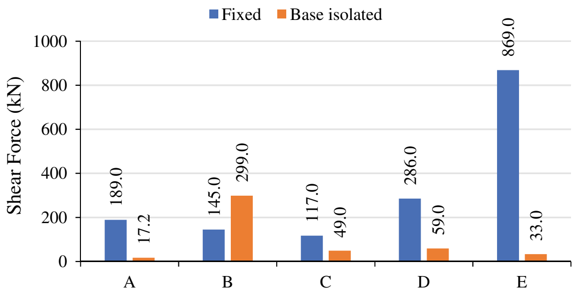


Fig. 4 Shear force distribution in columns at foundation level in stepback building in along slope direction

Fig. 5 Shear force distribution in columns at foundation level in setback-stepback in along slope direction



systems tends to attract higher shear forces in columns at upper storey level pertaining to higher lateral stiffness and short overall length. However, after the introduction of base isolators at columns C, D, and E, a significant reduction in the base shear values could be observed, especially at uppermost storey level at location E. Thus, it can be concluded that the introduction of base isolation systems in hill building configurations reduces the lateral shear demand in the structural members with higher lateral stiffness. A subsequent decrease in the values of base shear at C and D levels was also observed. However, the columns at frame A and B were remained fixed to reduce the lateral drift in the building structure.

The building configurations were also analysed using non-linear static pushover analysis after designing the reinforced concrete frames for assessing the seismic response of the structure. The plastic hinge pattern in structural members of different hill building configurations with and without base isolators was ascertained and compared in along as well as across hill slope directions at intermediate, upper and lower storey levels (see Figs. 6 and 7). The colour coding of the hinge represents the deformation and performance behaviour at various load levels. In the case of stepback configurations with fixed support systems, the plastic hinge was first formed in columns of the topmost storey due to high storey shear, also, complete yielding of foundation at upper hill frame was observed. However, after the introduction of base isolators, the formation of hinges could be observed in beams followed by the columns in lower storeys. Thus, a significant decrease in the shear demand in columns with high lateral stiffness was observed. Further, the performance of the building in across hill slope was observed to be significantly increased with the use of base isolators. It can be observed that the columns at uphill and downhill side have yielded prior to beams, while the base-isolated model displayed hinge formations in safe levels in only beam members. Moreover, due to less seismic weight, the setback-stepback configuration performed better and exhibited minimal yielding in fixed support condition, whereas, none of the frame members in base-isolated configuration displayed yielding at any location, showing the effectiveness of base isolation systems in the performance of hill building configurations.

4 Conclusion

In this study, the seismic behaviour of two different hill building configurations with fixed and base-isolated support systems was investigated. The three-dimensional models were analysed using the Response spectrum method and Push-over method. The dynamic properties of the hill buildings were evaluated and compared. It was observed that the fundamental time period of both stepback and setback-stepback buildings was increased significantly with the introduction of base isolators at the foundations. A prominent reduction in base shear value in along as well across hill slope direction was observed in both configurations. Further, in the case of step-back building with fixed support systems, the plastic hinges were first formed in the columns of topmost storey due to high storey shear, also, complete yielding

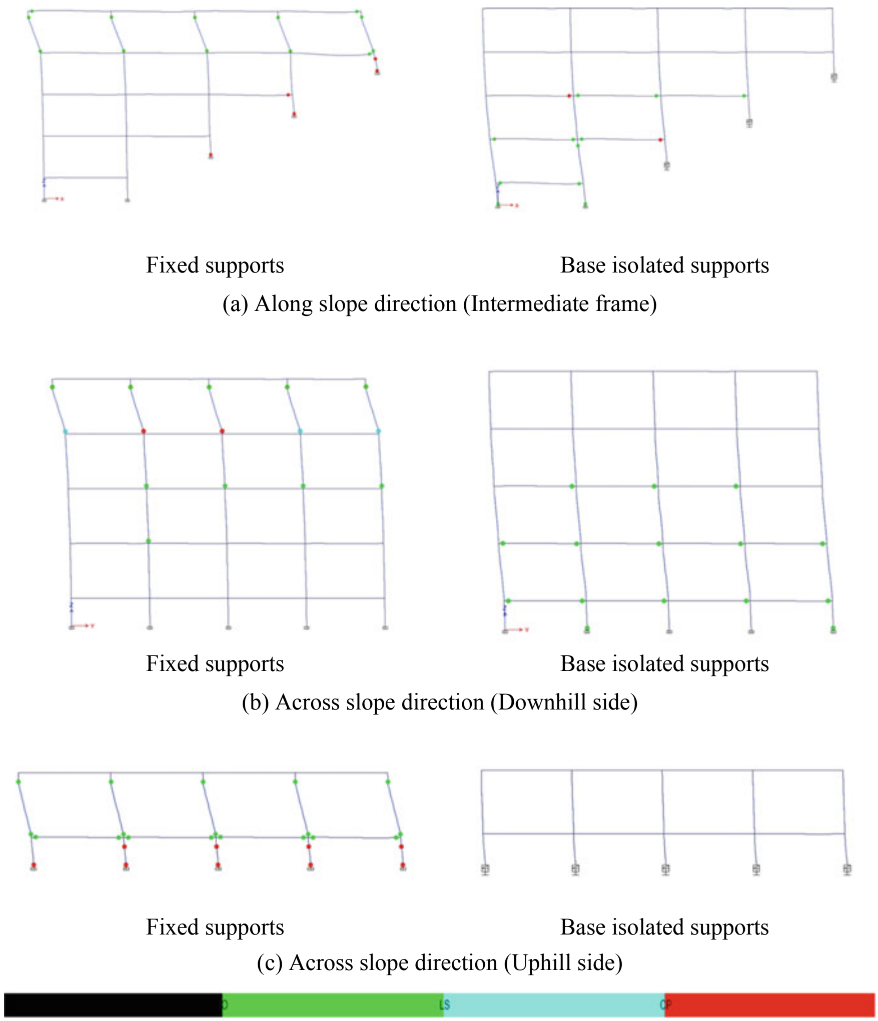


Fig. 6 Plastic hinge formation pattern in stepback building

of the foundations at upper hill frame was observed. However, after the introduction of base isolators, the formation of hinges could be observed in beams followed by the columns in lower storeys only. Moreover, due to less seismic weight, the setback-stepback configuration performed better and exhibited minimal yielding in fixed support condition, whereas, none of the members in base-isolated configuration displayed yielding at any location, showing the effectiveness of base isolation systems. Thus, it can be concluded that the introduction of base isolation systems in hill building configurations reduces the lateral shear demand in the structural members with high lateral stiffness. Additionally, it could be ascertained that the

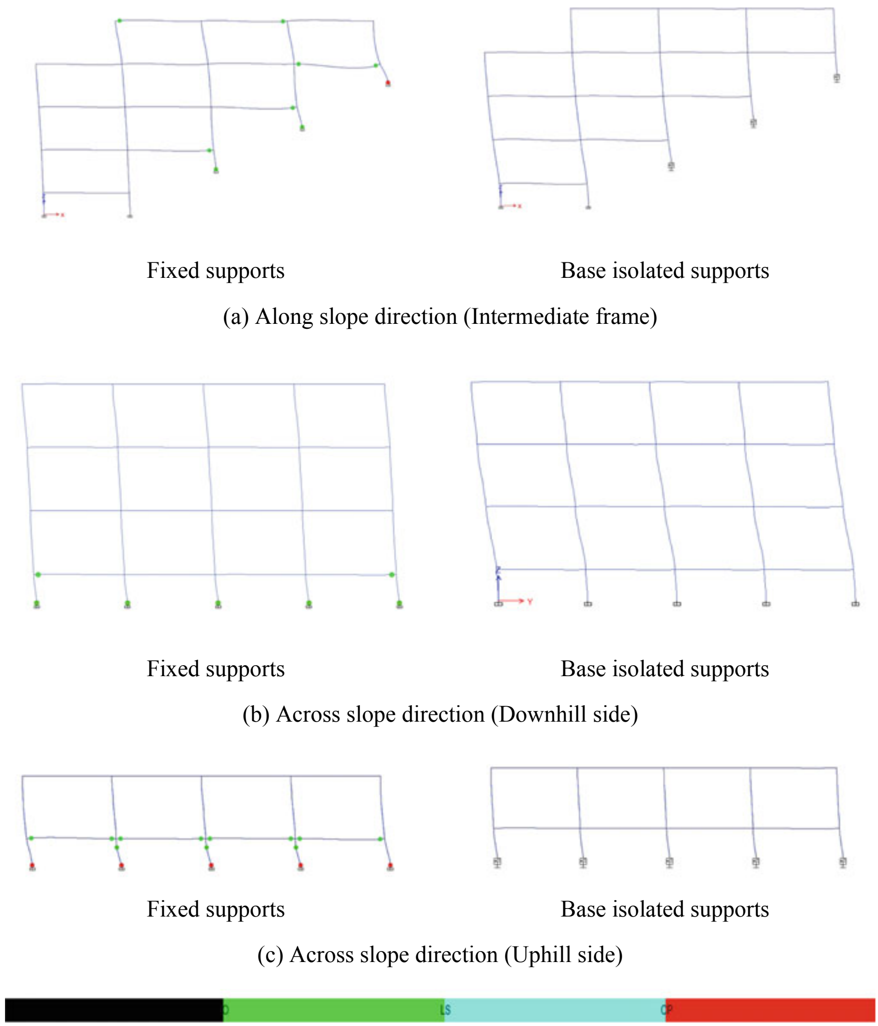


Fig. 7 Plastic hinge formation pattern in setback-stepback building

setback-stepback buildings attract less base shear than the setback configuration of the hill buildings, thus proved to be less prone to earthquake forces.

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