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Response Reduction Factor of Reinforced Concrete Buildings on Sloping Ground

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Abstract
Due to rapid urbanization and scarcity of land, the construction of building on sloping ground is increasing in recent times. Step back building and Step back setback building are two configuration of buildings which are commonly built on sloping ground. Since Nepal lies in seismically active region, such vertically irregular buildings are vulnerable to earthquake. Seismic performance such as base shear, time period, top story displacement, interstory drift of step back building, step back setback building and regular building are evaluated using linear static analysis and response spectrum analysis. From the analysis it is found that the step back setback building has less base shear and less time period than step back building which results in less displacement. Non-linear static analysis is used to determine overstrength factor, ductility factor and response reduction factor of step back building, step back setback building and regular building. It is found that building configuration play an important role in overstrength factor, ductility factor and response reduction factor.

Keywords
Step back building, Step back setback building, Overstrength factor, Ductility factor, Response reduction factor

1. Introduction

Nepal lies in the boundary of two tectonic plates. Collision of Indian plate and Eurasian plate has formed Himalayas. Large strain energy stored on such region and sudden release of energy in the form of earthquake makes Nepal seismically active region. The structures built in such regions are very vulnerable to earthquakes. The recent 2015 Gorkha earthquake has caused damage to many infrastructures and many people lost their life. Loss of life was not due to earthquakes but due to the damage of weak structures caused by earthquakes. The construction of reinforced concrete buildings in Nepal has been increasing post Gorkha earthquake. There is increasing trend in building construction on sloping ground due to various reasons like consumer's need, constraint in spaces, high value of land, aesthetic appearance. In buildings on sloping ground, the distribution of mass and stiffness varies along horizontal and vertical plane so that the center of mass and center of stiffness does not coincide resulting in the torsional stresses[1]. As building having regular geometry, adequate lateral strength, stiffness and ductility performs better during earthquakes[2], buildings on sloping ground which are asymmetrical horizontally and vertically have suffered serious damages during past earthquakes[3].

Building Configuration: Depending upon the bays arrangement there are two types of configurations of buildings on sloping grounds:

1. Step back type of configuration:
   In this building arrangement, the upper part of structure remain in same horizontal plane but lower part of the structure maintain slope of terrain.
2. Step back setback type of configuration:
   In this building arrangement, the upper part of structure are arranged in stepping pattern and lower part of the structure maintain slope of terrain[4].

2. Response reduction factor

Most of the design codes of structures are based on linear elastic force system. The effect of nonlinear behavior of the structure is incorporated in design by the use of response reduction factor. Response reduction factor is the ratio of maximum seismic forces experience by structure if it were to remain entirely elastic under specified ground motion to seismic forces which it has been designed to withstand. According to ATC 19[5], the response modification factor(R) is defined as the product of three parameters that influence seismic response of the structure. Mathematically it is expressed as

$$R = \Omega * R\mu * R_R \tag{1}$$

where Ω is strength factor, $R\mu$ is ductility factor and R_R is redundancy factor.

2.1 Overstrength factor

Overstrength is the presence of strength in addition to design strength of structure due to which structure yields at higher loads than design loads. It is due to the difference between actual and design material strength, load factors and multiple load cases, serviceability limit state provisions, minimum reinforcement and member sizes exceeding design requirements, strength of non-structural components[6] etc. Overstrength factor (Ω) is given as

$$\Omega = \frac{V_y}{V_d} \tag{2}$$

where V_y is strength at first significant yield and V_d is design strength.

2.2 Ductility factor

Ductility refers to the ability of the structure to undergo large inelastic deformations and dissipate large amount of energy without collapse. Ductility factor is a measure of non-linear response of structure and is governed by displacement ductility(μ). The displacement ductility is given as

$$\mu = \frac{\Delta u}{\Delta y} \tag{3}$$

where Δu is ultimate displacement and Δy is yield displacement. Miranda and Bertero[7] considered 124 recorded ground motions on rock, alluvium soil sites, soft soil sites. Strength reduction factor was calculated for different soil and equations were proposed to determine ductility factor for different soil sites. The relationship proposed by Miranda and Bertero[7] have been used in this study to calculate the ductility factor (Rμ).

$$R\mu = \frac{\mu - 1}{\phi} + 1 \tag{4}$$

$$\phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T} e^{-2(\ln(T) - 0.2)^2} \tag{5}$$

where μ is displacement ductility, T is period of structure.

2.3 Redundancy factor

ATC 19[5], defines redundancy as structures with multiple vertical lines of framing that can withstand forces and prevent structure from immediate collapse. From past researches, the value of redundancy factor is considered as one in this study[8].

3. Case Study of Buildings

In this study building on plain ground: regular building and buildings on sloping ground: step back building, step back setback building of three, four and five story are considered. All model buildings have 3 bays in each orthogonal direction with 4m bay length and 3m story height. Step back building and Step back setback building are modeled on 37 degree slope and are provided with basement wall.

Table 1: Structural elements dimension

No. of story	Column dimension(mm)	Beam dimension(mm)
3	350*350	230*300
4	400*400	230*400
5	450*450	300*450

Table 2: Material properties and Design Parameters

Importance factor	1
Soil type	Type D very soft soil
Concrete grade	M25
Reinforcement grade	HYSD500
Slab thickness	125mm
Basement wall thickness	200mm
Live load	2KN/m2 on floors 1.5KN/m2 on roof
Floor finish	1.2 KN/m2
External wall load	13.49KN/m 10.12KN/m with openings
Internal wall load	7.64KN/m 6.49KN/m with openings
Lateral load	NBC105:2020[9]

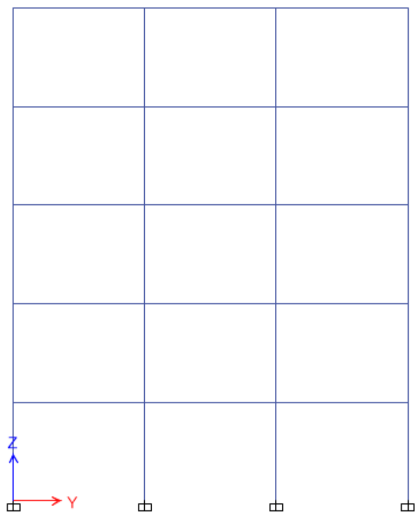

Figure 1: Regular building

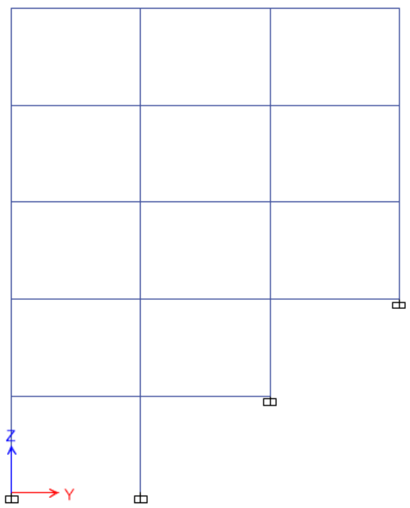

Figure 2: Step back building

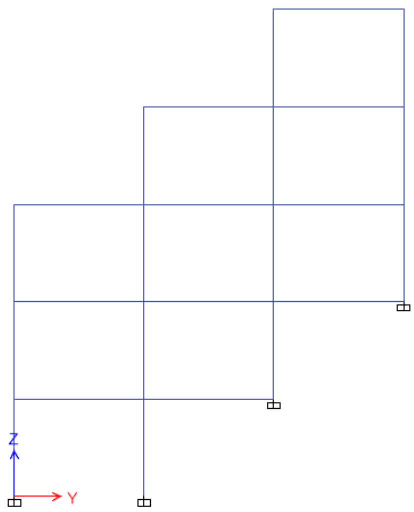

Figure 3: Step back setback building

4. Methodology

Structural modeling of Regular building, Step back building and Step back setback building are modeled and analyzed by equivalent static method and response spectrum method using ETABSv16.2. The structural members are checked and designed in accordance with NBC105:2020[9] code. Seismic response of buildings such as base shear, time period, top story displacement and interstory drift are determined. Pushover analysis is carried out considering both material and geometric non linearities. Material non linearity is considered using default hinges whereas geometric non linearity is considered using P-Delta effect in structural elements. P-M2-M3 hinges is applied in column whereas M3 hinges is applied in beam. Pushover curve which is Base shear vs displacement curve is obtained from pushover analysis. Bilinear idealization of thus obtained pushover curve is carried out based on FEMA356:2000[10]. The yield displacement, ultimate displacement and yield base shear are obtained from bilinear idealized curve which are used to calculate overstrength factor, ductility factor and response reduction factor.

5. Results and Discussion

5.1 Base shear

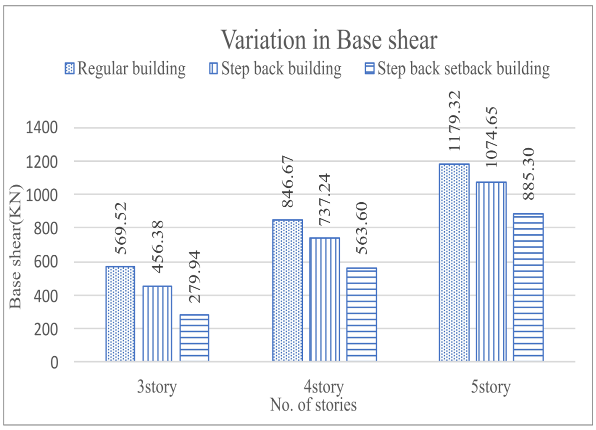

Figure 4: Variation in Base shear

As ground slope angle increases seismic weight of the structure decreases which results in less base shear in buildings on sloping ground in comparison to regular building. Among step back building and step back setback building, base shear of step back building is higher than step back setback building.

5.2 Time period

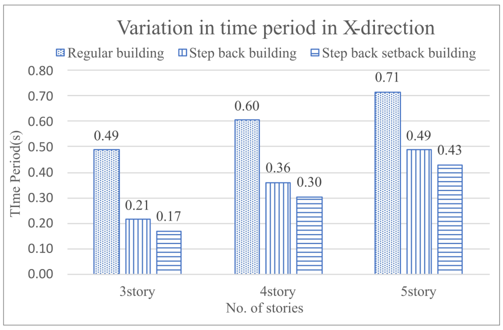

Figure 5: Variation in time period in X-direction (across slope)

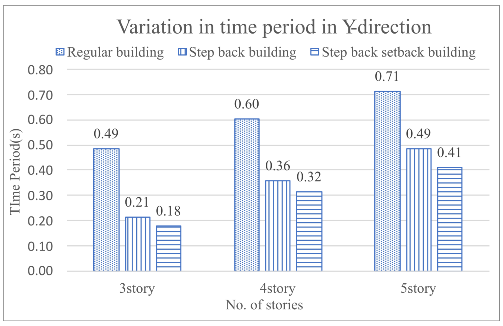

Figure 6: Variation in time period in Y-direction (along slope)

In buildings on sloping ground, building height is considered from top ground level. As empirical time period is directly proportional to height of building, time period of buildings on sloping ground is less than regular building which shows that regular building in plain ground is flexible than buildings on sloping ground. From the chart it is obtained that the time period of step back building is more than step back setback building making step back building more flexible.

5.3 Top story displacement

In regular building in plain ground, base shear and time period is high due to which building becomes flexible causing high displacement. As slope angle increases column height decrease due to curtailment of columns towards the slope which results in increased stiffness due to which displacement decreases in buildings on sloping ground. Among step back building and step back setback building, the top story displacement of step back setback building is lower than step back building due to low base shear and time period.

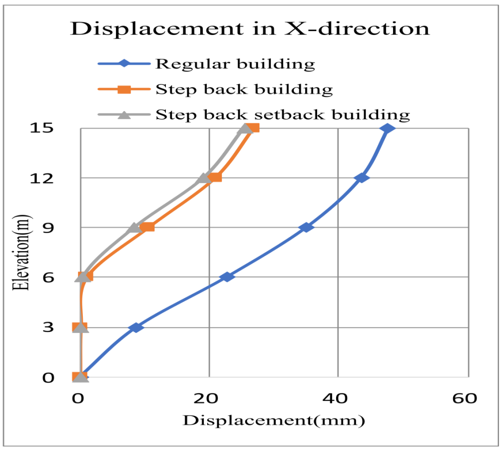

Figure 7: Displacement of 5story buildings in X-direction (across slope)

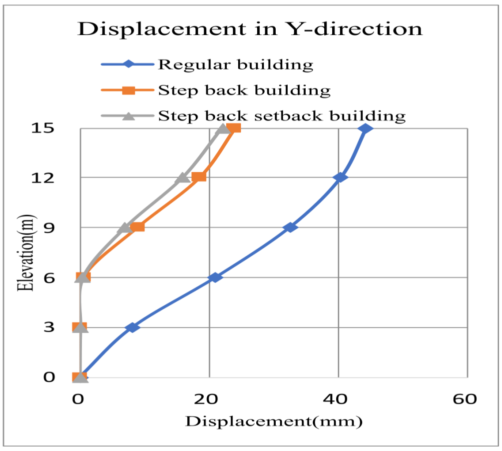

Figure 8: Displacement of 5story buildings in Y-direction (along slope)

5.4 Interstory drift

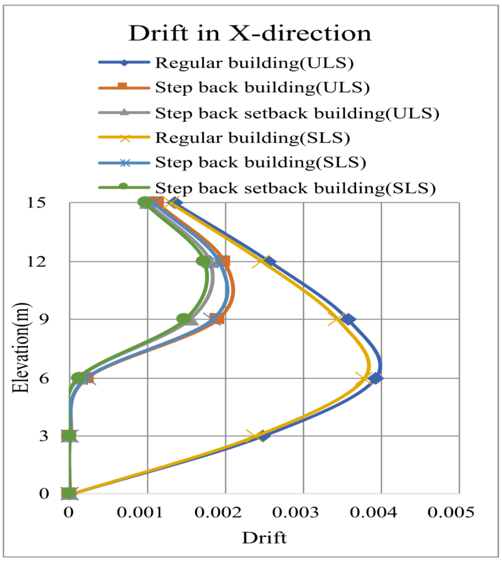

Figure 9: Story drift of 5story buildings in X-direction (across slope)

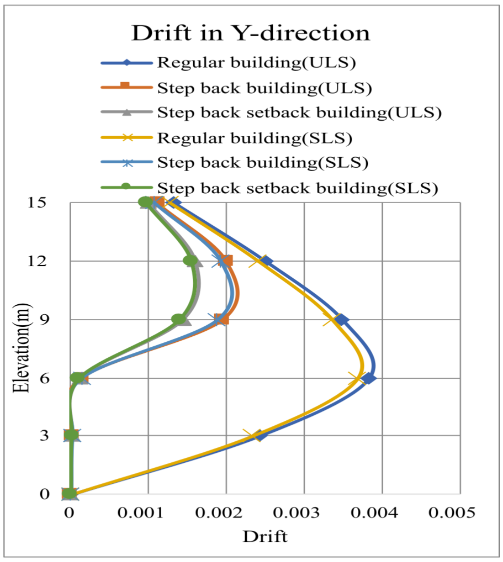

Figure 10: Story drift of 5story buildings in Y-direction (along slope)

The inter-story drift for different buildings is shown in the above figures. The obtained interstory drifts are less than the allowable value permitted by NBC105:2020 for ultimate and serviceability limit state. From the graph it is seen that regular building has maximum drift. In comparison to step back building, the interstory drift is less in step back setback building.

5.5 Maximum forces in column

Table 3: Maximum forces in column for 5story buildings

Type of building	Axial Force (KN)	Shear Force (KN)	Bending Moment (KNm)	Torsion (KNm)
Regular building	240.94	101.91	210.64	9.83
Step back building	155.72	98.89	210.84	11.25
Step back setback building	125.13	105.57	212.31	17.65

Axial force is higher in regular building than step back building and step back setback building. Due to high stiffness, columns of buildings on sloping ground attracts high shear force and bending moment and suffer severe damage during earthquake . However, shear force and bending moment are decreased due to the presence of basement wall. Torsion in column in step back building and step back setback building is higher than that of regular building.

5.6 Comparison of Pushover curves

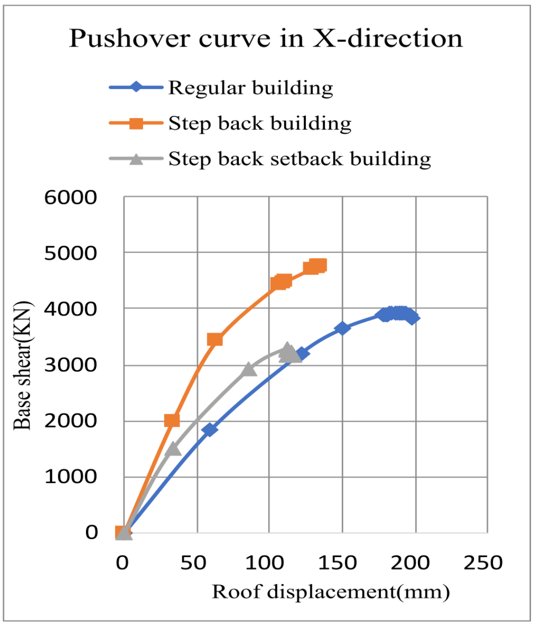

Figure 11: Comparison of pushover curves of 5story buildings in X-direction (across slope)

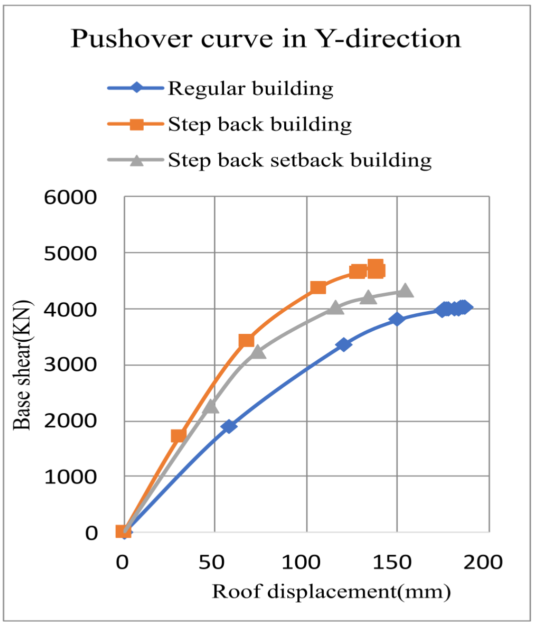

Figure 12: Comparison of pushover curves of 5story buildings in Y-direction (along slope)

The stiffness of step back building and step back setback building is higher than regular building in both directions due to presence of basement wall and curtailment of length of column due to sloping ground.

The ultimate displacement of regular building is higher than both step back and step back setback building. From the pushover curves, it is observed that ultimate base shear of step back building is higher due to uneven length of column caused by sloping ground which is reduced in step back setback building.

5.7 Overstrength factor

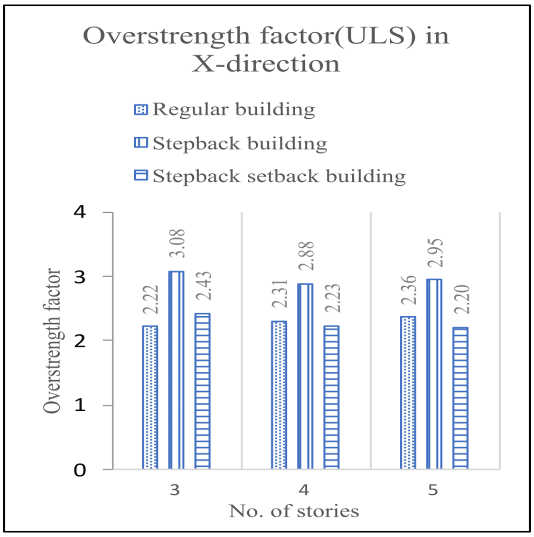

Figure 13: Overstrength factor in X-direction (across slope)

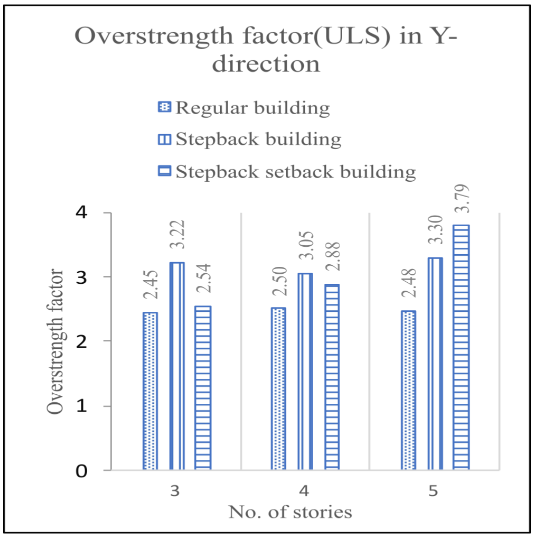

Figure 14: Overstrength factor in Y-direction (along slope)

Due to curtailment of columns at sloping ground, buildings on sloping ground have higher stiffness than regular building. Due to high stiffness in step back building, it yields at higher base shear than regular building. Thus step back building has high yield base shear and low design base shear than regular building which results in high overstrength factor.

As compared to step back building, step back setback building has less number of columns in upper portion of the structure which reduces mass and stiffness of the structure. The reduction in mass decreases seismic weight of structure resulting in less design base shear than step back building whereas due to less stiffness the yield base shear of step back setback building is lower which results in less overstrength factor except for 5story in Y-direction. It is due to higher rate of increase in design base shear than yield base shear.

As number of story increases in X-direction (across the slope), yield base shear and design base shear increases at similar rate in all building models so there is slight variation in overstrength factor in regular building, step back building and step back setback building except step back setback building in Y-direction (along the slope). This is due to yield base shear increase at higher rate than design base shear which increases overstrength factor significantly.

5.8 Ductility factor

Ductility factor is a function of displacement ductility and time period whereas displacement ductility is a measure of inelastic deformation. Displacement ductility of step back setback building and step back building is higher than regular building in most cases. However for different building configuration, ductility factor does not show any specific pattern. Ductility factor of regular building and step back building is similar for 3story but ductility factor of regular building is higher than step back building for 4story and 5story in X-direction due to varying displacement ductility whereas ductility factor of step back setback building is higher than step back building by for 3story, 4story and 5story in X-direction due to higher displacement ductility in step back setback building. Ductility factor of regular building is lower for 3story and then higher than step back building for 4story and 5story in Y-direction whereas ductility factor of step back building is lower for 3story and slightly changes with step back setback building for 4story and 5story in Y-direction due to varying displacement ductility. From the chart, ductility factor varies significantly in X-direction whereas it varies slightly in Y-direction due to building configuration.

As number of stories increases, the ductility factor has slight variation in regular building, step back building and step back setback building except ductility factor decreases in step back building and step back setback building for 3story to 4story in X-direction and step back setback building in Y-direction for 3story to 4story due to decrease in displacement ductility.

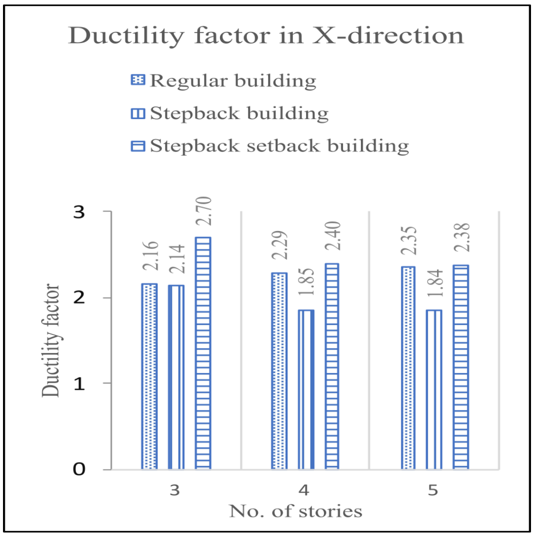

Figure 15: Ductility factor in X-direction (across slope)

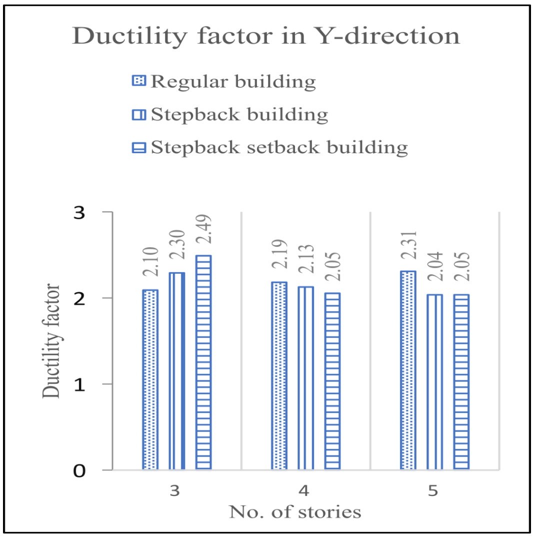

Figure 16: Ductility factor in Y-direction (along slope)

5.9 Response reduction factor

Response reduction factor is determined from the evaluated overstrength factor and ductility factor for all buildings. In X-direction response reduction factor of step back building is higher in 3story than that of regular building. It is due to high overstrength factor in step back building. Response reduction factor of step back building has less variation to that of step back setback building for all stories. In Y-direction response reduction factor of step back building is higher than that of regular building for 3story, 4story and 5story due to high contribution of overstrength factor whereas response reduction factor of step back building is higher for 3story and 4story due to high overstrength factor and then lower for 5story due to less overstrength factor than that of step back setback building.

As number of stories increases, response reduction factor increases in regular building but decreases in step back building and step back setback building for 3story to 4story due to ductility factor whereas there is no significant variation in all buildings for 4story to 5story in X-direction. In Y-direction there is no significant variation in response reduction factor except in step back building for 3stoy to 4story due to both overstrength and ductility factor and in step back setback building for 4story to 5story due to high overstrength factor.

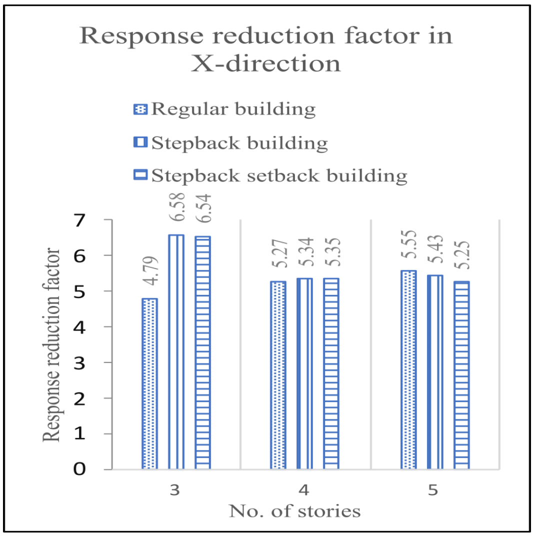

Figure 17: Response reduction factor in X-direction (across slope)

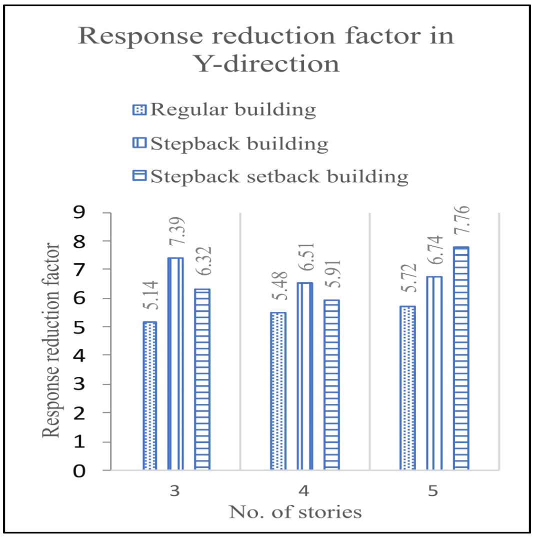

Figure 18: Response reduction factor in Y-direction (along slope)

6. Conclusion

In this study, seismic performance and response reduction factor of regular building, step back building and step back setback building are evaluated using linear static analysis, response spectrum analysis and non-linear pushover analysis. Following are the major conclusions drawn:

- The overstrength factor for all considered building models are found to be higher whereas ductility factor are found to be lower than the specified values in NBC105:2020[9]. The value of response reduction factor for considered building model ranges from 4.79 to 7.76.
- The overstrength factor, ductility and response reduction factor varies significantly due to building configuration.
- The base shear and time period of step back setback building is less which results in less top story displacement, interstory drift than step back building and is suitable on sloping ground.

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