Earthquakes and Structures, *Vol. 14, No. 4 (2018) 305-312*
DOI: https://doi.org/10.12989/eas.2018.14.4.305

Fundamental periods of reinforced concrete building frames resting on sloping ground

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(Received November 2, 2017, Revised February 18, 2018, Accepted February 21, 2018)

Abstract. Significant research efforts were undertaken to evaluate seismic performance of vertically irregular buildings on flat ground. However, there is scarcity of study on seismic performance of buildings on hill slopes. The present study attempts to investigate seismic behaviour of reinforced concrete irregular stepback building frames with different configurations on sloping ground. Based on extensive regression study of free vibration results of four hundred seventeen frames with varying ground slope, number of story and span number, a modification is proposed to the code based empirical fundamental time period estimation formula. The modification to the fundamental time period estimation formula is a simplified function of ground slope and a newly introduced equivalent height parameter to reflect the effect of stiffness and mass irregularity. The derived empirical formula is successfully validated with various combinations of slope and framing configurations of buildings. The correlation between the predicted and the actual time period obtained from the free vibration analysis results are in good agreement. The various statistical parameters e.g., the root mean square error, coefficient of determination, standard average error generally used for validation of such regression equations also ensure the prediction capability of the proposed empirical relation with reasonable accuracy.

Keywords: reinforced concrete frame; sloping ground; fundamental time period; free vibration

1. Introduction

Due to scarcity of flat land, a large number of buildings in the hilly region are constructed on sloping ground. Furthermore, increasing trend of unplanned developments in the form of various irregular buildings is observed in various attractive tourist destinations in the hilly regions. The buildings on slopes are intrinsically more vulnerable due to their irregular structural configuration alone apart from the amplification of seismic ground motion due to the geometry of topographic features as well as earthquake-induced slope failure e.g., landslides, rock falls etc. Hence, they are susceptible to severe damage when affected by seismic ground motion. In fact, the various past earthquakes have revealed the susceptibility of buildings located near the edge of stretch of hills or sloping ground (Kumar and Paul 1999). Thus, seismic performance evaluations of such buildings are very crucial to ensure their safety during future earthquakes.

The structural configurations of buildings in hilly areas are largely irregular having foundation at different levels. The common geometric configurations of multi-storeyed reinforced concrete (RC) framed buildings on hill slopes are shown in Fig. 1. It may be noted that the foundation structure more or less follows the natural shape of the slope. The dynamic characteristics of such buildings are significantly different from the buildings resting on flat topography due to irregularity in both the horizontal and vertical directions. As a consequence, the centre of mass and centre of stiffness of a storey do not coincide.

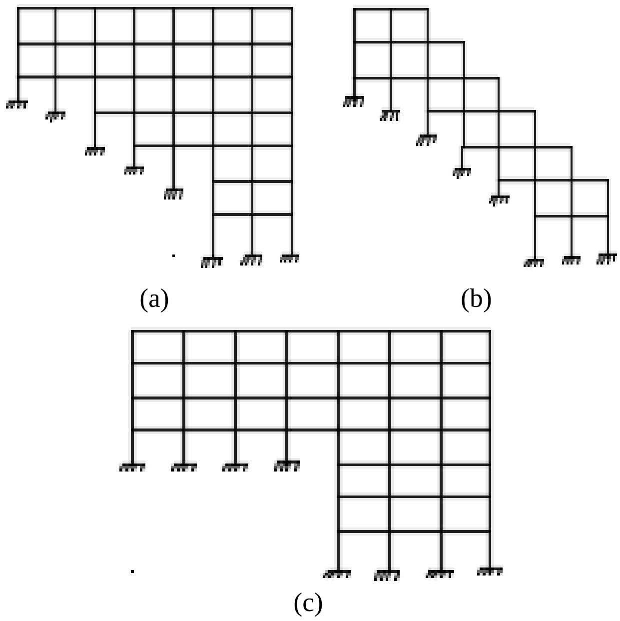

Fig. 1 Various configurations of building on slope frequently used on hill area: (a) stepback building type (b) setback stepback building type and (c) floors at two different levels

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ISSN: 2092-7614 (Print), 2092-7622 (Online)

Additionally, they also do not remain on a vertical line in different floors due the irregular variation of stiffness and mass in both vertical and horizontal directions. Thus, such buildings are subjected to significant torsional response. Furthermore, buildings on hill slope are characterized by unequal column heights depending on the site conditions resulting in considerable variation in stiffness of columns, particularly at ground storey. The short, stiff columns on uphill side attract much higher lateral forces and are prone to severe damage.

The early studies on vertical irregularity i.e., setback buildings dates back to 1970 reporting higher drift demand at the upper portion of the setback (Humar and Wright 1970). Subsequently, there are numbers studies on seismic performance of vertical irregular buildings which shows greater damage concentration near vicinity of the setback (Moehle and Alarcon 1986), greater ductility demand at the tower portion of the setback compare to the base portion (Aranda 1984), higher torsion in the tower portion of the setback (Khoure *et al.* 2005).However, there are limited studies on the definition and quantification of irregularity in setback building (Karavasilis *et al.*2008a, b), and estimation of fundamental period of setback buildings (Sarkar *et al.* 2010). Sarkar *et al.* (2016) studied the performance of setback buildings on flat ground based on pushover analysis. Hideo *et al.* (2011) noted that the distribution of longitudinal stress in setback building is largely nonlinear in the transverse direction. They presented an extended version of the rod theory which accounts for variation in the transverse direction as well as longitudinal stiffness distribution for structures with setback. Varadharajan *et al.* (2014) introduced an irregularity index for quantification of mass, stiffness and strength irregularity based on modal participation factor and also proposed an empirical relation for estimation of fundamental period of buildings with setback irregularity based on the results of dynamic analysis of different building frames. Georgoussis *et al.* (2015) proposed an approximate method for analysis of multi-story setback buildings based on an equivalent single story asymmetric modal system. Kenji (2016) presented a pushover based simplified approach to obtain the peak response of symmetric buildings with bidirectional setback. Recently, Panagiotis *et al.* (2017), Asteris *et al.* (2017) studied the effect of vertical geometric irregularities on the fundamental period of masonry infilled structures.

The studies on seismic performance of buildings as discussed above are to consider the effect of vertical irregularity of typical setback buildings on flat ground. But the studies on seismic performance of buildings on hill slopes are limited. Kumar and Paul (1998) presented three-dimensional models for seismic analyses of stepback and setback buildings to compare their performances. Detlof *et al.* (2003) studied various retrofitting strategies on hillside homes in Loss Angeles area. Birajdar and Nalawade (2004) studied the behaviour of RC frame building on sloping ground for different configurations like stepback buildings, setback buildings and setback stepback buildings and observed that stepback setback buildings are more suitable on sloping ground. Singh *et al.* (2012) carried out an analytical study using linear and nonlinear time history analysis of stepback RC frame buildings on slope and noted considerable amount of torsional effects under cross slope excitations. Vijayanarayanan *et al.* (2012) studied the performance of RC building along hill slope during 2011 Sikkim earthquake. Surana *et al.* (2015) performed seismic fragility analysis of stepback hill buildings by incremental dynamic analysis procedure and noted that the hill buildings designed as per the existing code provisions for buildings on flat topography exhibit a very high probability of incipient collapse. Vijayanarayanan *et al.* (2015) performed nonlinear analyses on typical buildings on steep hill slopes with different restraints at base of the columns and noted that buildings having small plan dimensions are most suitable for construction along steep hill slopes.

The studies on the seismic performance of buildings on sloping ground are mostly limited to the case studies and it is noted that the design codes have not given particular attention to the buildings on slope. The setback buildings are defined in various seismic design codes (e.g., IS 1893, ASCE 7) where dynamic structural analysis using three-dimensional model is recommended for major irregularity in stiffness and geometry. This general recommendation does not provide any particular attention to the building forms on slope grounds due to the scarcity of studies on buildings on slope. In this regard, it is important to note that most of the seismic design codes require the base shear obtained through dynamic analysis (and thereby, other response quantities) to be scaled up to the base shear corresponding to the fundamental period as per the code specified empirical formula stipulated in the design codes. Moreover, estimation of natural time period, a fundamental property of a building seems to be important at initial stage as many trials are required in order to decide the configurations and layout of the buildings at planning stage. The empirical equations recommended in the design codes, such as IS 1893, ASCE 7, Euro code 8 for estimation of fundamental period are applicable to regular buildings. The studies on height related empirical formula are enormous for regular building frames (Chopra and Goel 1997, 2000, Hatzigeorgiou and Kanapitsas 2013) infilled RC frames (Asteris *et al.* 2015a, b, 2016). Such studies on setback building frames are also notable (Sarkar *et al.* 2010, Varadharajan 2014, Asteris *et al.* 2017). But the applicability of these studies for estimation of fundamental period of buildings on slopes is not studied. Due to sloping ground, the foundation levels of buildings are different. The heights of the columns are not same and the distribution of mass, stiffness and strength are varied along the height. In such cases, the time period not only depends on the height of the building but also depends on the slope of the ground. The design codes are not clear about the definition of building height in such situation. But, there will be bay-wise variation of height of a building on slope. As a consequence, it becomes difficult to compute fundamental periods of such buildings based on empirical relations provided in various codes. Thus, it is important to study the performance of the code based empirical equation for estimation of fundamental period of buildings on slope which is of practical use for structural engineers for code-based design of structures.

The present study focuses on the seismic performance of RC building frames with different configurations on sloping

Table 1 The details of the building geometry on different sloping ground

Ground	7 Storey					6 Storey				
Slopes	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay
2.5°	●	●	●	●	●	●	●	●	●	●
5°	●	●	●	●	●	●	●	●	●	●
7.5°	●	●	●	●	●	●	●	●	●	●
10°	●	●	●	●	●	●	●	●	●	●
12.5°	●	●	●	●	●	●	●	●	●	●
15°	●	●	●	●	●	●	●	●	●	●
17.5°	●	●	●	●	●	●	●	●	●	●
20°	●	●	●	●	●	●	●	●	●	●
22.5°	●	●	●	●	●	●	●	●	●	●
25°	●	●	●	●	●	●	●	●	●	●
27.5°	●	●	●	●	●	●	●	●	●	●
30°	●	●	●	●	●	●	●	●	●	●
32.5°	●	●	●	●	●	●	●	●	●	●
35°	●	●	●	●	●	●	●	●	●	●
37.5°	●	●	●	●	●	●	●	●	●	●
40°	●	●	●	●	●	●	●	●	●	●
42.5°	●	●	●	●	●	●	●	●	●	●
45°	●	●	●	●	●		●	●	●	●
Ground	5 Storey					4 Storey				
Slopes	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay
2.5°	●	●	●	●	●	●	●	●	●	●
5°	●	●	●	●	●	●	●	●	●	●
7.5°	●	●	●	●	●	●	●	●	●	●
10°	●	●	●	●	●	●	●	●	●	●
12.5°	●	●	●	●	●	●	●	●	●	●
15°	●	●	●	●	●	●	●	●	●	●
17.5°	●	●	●	●	●	●	●	●	●	●
20°	●	●	●	●	●	●	●	●	●	●
22.5°	●	●	●	●	●	●	●	●	●	●
25°	●	●	●	●	●	●	●	●	●	●
27.5°	●	●	●	●	●	●	●	●	●	●
30°	●	●	●	●	●		●	●	●	●
32.5°	●	●	●	●	●			●	●	●
35°		●	●	●	●			●	●	●
37.5°		●	●	●	●				●	●
40°			●	●	●				●	●
42.5°			●	●	●				●	●
45°				●	●					●
Ground	3 Storey					2 Storey				
Slopes	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay	7 Bay	6 Bay	5 Bay	4 Bay	3 Bay
2.5°	●	●	●	●	●	●	●	●	●	●
5°	●	●	●	●	●	●	●	●	●	●
7.5°	●	●	●	●	●	●	●	●	●	●
10°	●	●	●	●	●	●	●	●	●	●
12.5°	●	●	●	●	●		●	●	●	●
15°	●	●	●	●	●			●	●	●
17.5°	●	●	●	●	●				●	●
20°	●	●	●	●	●					●
22.5°		●	●	●	●					●
25°			●	●	●					
27.5°				●	●					
30°				●	●					
32.5°				●	●					
35°					●					
37.5°					●					
40°										
45°										

ground to supplement preliminary analysis and design of irregular buildings on slopes. To be specific, a modification of the empirical time periods formula specified in the code for stepback type RC building frame reflecting the slope of the ground and framing configuration is investigated. Based on an extensive regression study of free vibration analysis results of four hundred seventeen frames with varying slopes, number of storeys and span numbers, a modification is proposed to the code-based empirical fundamental time period estimation formula. The modification proposed to the fundamental time period estimation formula is a simplified function of the ground slope and a newly introduced equivalent height parameter to reflect the effect of stiffness and mass irregularity along the vertical as well as horizontal direction. The derived empirical formula is successfully validated with various combinations of slope and framing configurations of buildings with reasonable accuracy.

2. Seismic performance of buildings on slopes

A rigorous parametric analysis is performed by considering four hundred seventeen RC frame buildings on slope to study the variation of seismic responses of all the buildings. In this study, two-dimensional idealization of the building frames is adopted. The building frames with varying number of stories and bays with different slopes as depicted in Table 1 are analysed. The ground floor height, other floor height and span length of all the building frames are kept same as 4.2 m, 3.5 m and 3 m, respectively. The minimum foundation depth of 1.75 m is maintained in the response analysis. The beam and column dimensions of buildings may affect the time period marginally compare to the length of beam and columns. Thus, for simplicity the beam and column dimensions are kept identical for all buildings in the parametric study. The rectangular beam section of 450 mm×350 mm and column dimension of 400 mm×400 mm, slab width of 150 mm is considered. The dead load applied on the structure is self-weight of the member. The live load for floor level, are 3 KN/m^2 and for roof level is 1.5 KN/m^2.

The bare frame buildings are modelled as plane frame in SAP2000 (2016) structural analysis software and are analysed using the seismic coefficient method and linear dynamic method as per IS1893 (2002). The seismic parameters corresponding to seismic zone V, medium soil type and importance factor of 1.0 are considered for the analysis. The response reduction factor for Special Moment Resisting Frame (SMRF) building is taken as 5 as per the Indian code (IS1893-2016). The SMRF buildings are designed and detailed to meet the ductile detailing requirements. The fundamental time period is obtained from free vibration analysis. For comparative study, the base shear, time period and roof displacement are extracted from the analysis of each frame configuration.

The variation of the time period with slope of ground for different bays and storey numbers are shown in Fig. 2. It can be seen that the time period of building reduces with increasing slope. The time periods of the buildings for all the slopes are consistently smaller than the time period of the corresponding regular buildings on flat ground. The

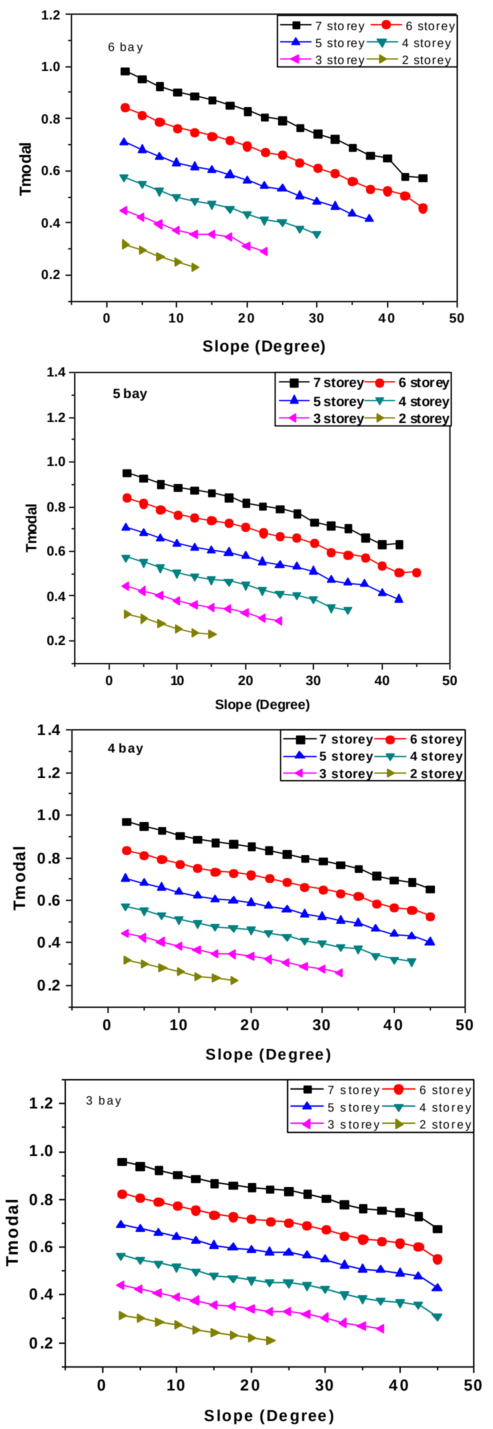

Fig. 2 The variation of the time period with slope of the building for different bays and storey numbers

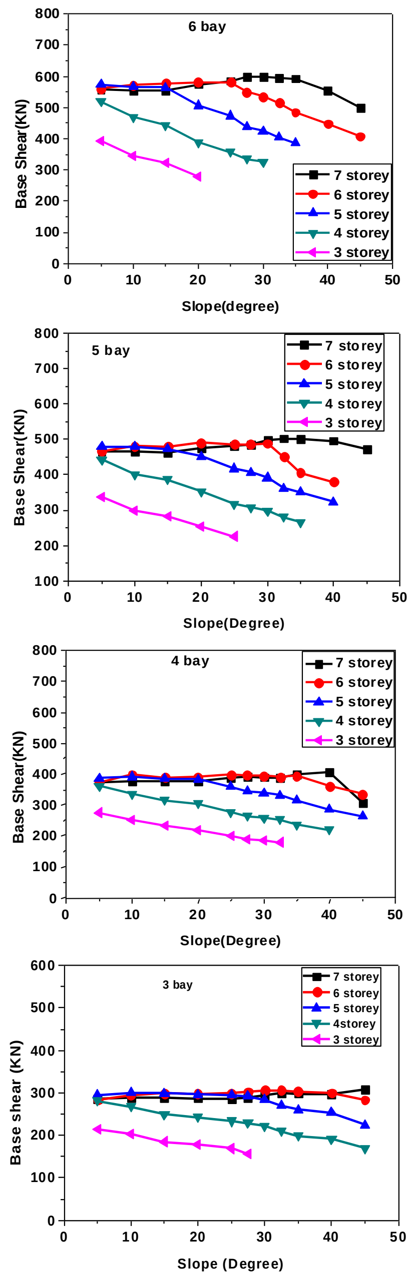

Fig. 3 The variation of the base shear with slope of the building for different bays and storey numbers

observations remain same for all the storeys and bays considered in the parametric study. The variations of the base shear and the maximum storey displacement with slope for different bay numbers and storey numbers of stepback buildings resting on sloping ground are shown in Fig. 3 and Fig. 4, respectively. It can be seen that the base shears of the buildings are reducing with increasing slope. This is due to the fact that the height of the building is not same in all the spans. Thereby, the effective height of the building is decreasing with the increasing ground slope.

3. Fundamental time period

The earthquake resistant design codes around the world provide a simple empirical formula for estimation of fundamental natural period of vibration (T) of building frames in terms of the overall height (h) of a building. For example, Indian code (IS 1893 2016) recommends the following formula for RC frame without infill

$$T = 0.075h^{0.75} \quad (1)$$

Where, h is the overall height of a building considered in the seismic coefficient method for calculating the design base shear and lateral force due to seismic effect on the building. Such empirical relations ignore the aspect of irregularity and fundamental period is a function of overall

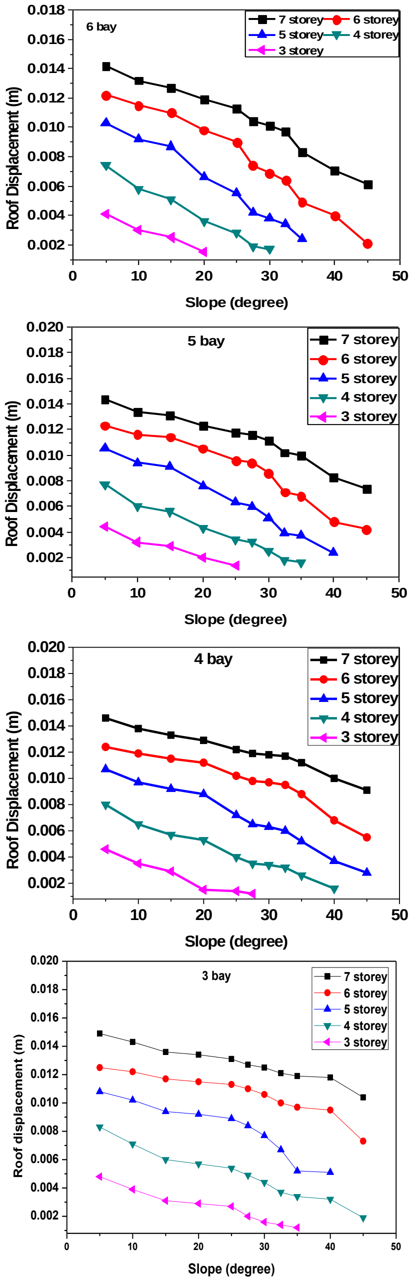

Fig. 4 The variation of the maximum displacement with slope of the building for different bays and storey numbers

building height only. However, building irregularities due to mass, stiffness and strength may change the fundamental period significantly. Therefore, such empirical relations recommended by design codes are inadequate in predicting fundamental periods for irregular buildings. In this regard, the studies on height related empirical formula for setback building frames are proposed in the literatures (Sarkar *et al.* 2010, Varadharajan 2014, Asteris *et al.* 2017). But, as mentioned earlier, these studies are limited to setback buildings on flat ground and may not be applicable for estimating fundamental time period of buildings on slope. An attempt is made in the present study to develop such relations for buildings on slopes typically observed in hilly regions.

The parametric studies of various frame configurations

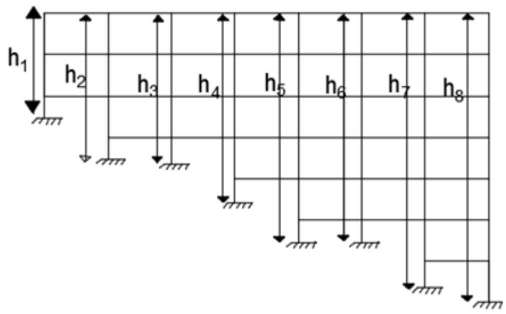

Fig. 5 A typical seven storey stepback building on slope and associated storey height

on sloping ground presented in the previous section clearly reveal that the actual time period of buildings on slope are of lesser values as compared to the estimated time period using code-based formula. In this regard, it is important to note that the height of the building is not same in all the bays of a building on hill slope. Hence, the time periods of buildings on sloping ground are not only dependent on the height of the building but also on the slope of the ground. In view of this, instead of usual definition of height used in the code-based relation which is ambiguous for such buildings, a parameter termed as equivalent height (h_{eqv}) of a building on hill slope as defined in Eq. (2) is introduced in the present study. Subsequently this parameter is used to develop the fundamental time period estimation relation

$$h_{eqv} = \frac{1}{n_b}\sum_{i=1}^{n_b} h_i \tag{2}$$

Where, h_i is the associated storey height of the i-th bay and n_b is the total number of bays in a building as explained in Fig. 5.

4. Regression analyses of time periods

The fundamental periods of all the building frames considered in the parametric study as described in the previous section are taken for regression analysis. The equivalent height of all the considered building frames are computed using Eq. (2). The regression analysis is performed for estimation of fundamental time period T in terms of equivalent height and slope. Based on the regression study, the following empirical relation is proposed for estimating the fundamental time period of stepback buildings on sloping ground

$$T = 0.042 h_{eqv}^{0.97} \theta^{-0.06} \tag{3}$$

However, this empirical formula is only applicable to two dimensional stepback buildings on sloping ground. For setback buildings on hill slopes, separate sets of analyses are required to develop empirical formula for estimating fundamental time period.

The correlation between the predicted and the actual time period as obtained from the free vibration analysis for all the frames considered for regression studies are plotted in Fig. 6 which shows a good correlation. However, the

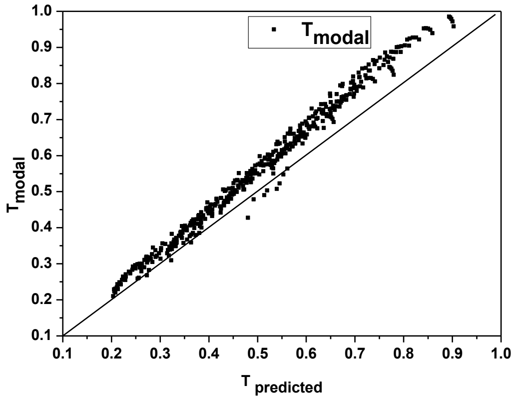

Fig. 6 The comparison of actual and predicted fundamental time periods

predicted time period obtained from the proposed modification formula are kept biased on the higher side as reflected in the plot for conservative estimate of base shear as is also done in most of the codes.

Further, the root mean square error (RMSE), the coefficient of determination (R^2) and the standard average error are computed to verify the predictability of the proposed formula. The expressions of the RMSE is

$$\mathrm{RMSE} = \sqrt{\frac{1}{m}\sum (T_i - \overline{T}_i)^2} \tag{4}$$

The coefficient of determination (R^2) defines as,

$$R^2 = 1 - \frac{\sum_1^m (T_i - \overline{T}_i)^2}{\sum_1^m (T_i - \overline{T})^2} \tag{5}$$

And the standard average error is given by

$$\varepsilon_m = \frac{\sum_1^m \left(100 \frac{|T_i - \overline{T}_i|}{T_i}\right)}{m} \tag{6}$$

Where, T_i is the actual time period, $\hat{T}_i$ is the predicted time period as obtained from the proposed formula for i-th considered frame, $\overline{T}$ is the mean value of the time period and m is the total numbers of frame considered for statistical study. The values of those parameters for all the building frames used in the regression study are as following: $RMSE$=0.067305, R^2= 0.8764217, ε_m=10.43% which clearly show good prediction capability of the proposed equation.

Further, to study the capability of the proposed empirical relation to estimate the fundamental time period, a comparative study is performed. For this, the same frames are considered but with slopes which were not considered in the regression analysis e.g., 4, 8, 12, 16, 20, 24 and different bay width i.e., 4.5 m instead of 3m considered for regression analysis. The time period obtained by the proposed formula and that of obtained from the free vibration analysis using SAP 2000 are compared in Fig. 7. Further, the statistical parameters given by Eqs. (4) to (6) for this 4.5 m bay frame are obtained as: RMSE=0.0686, R^2=0.8476, ε_m=9.56%.

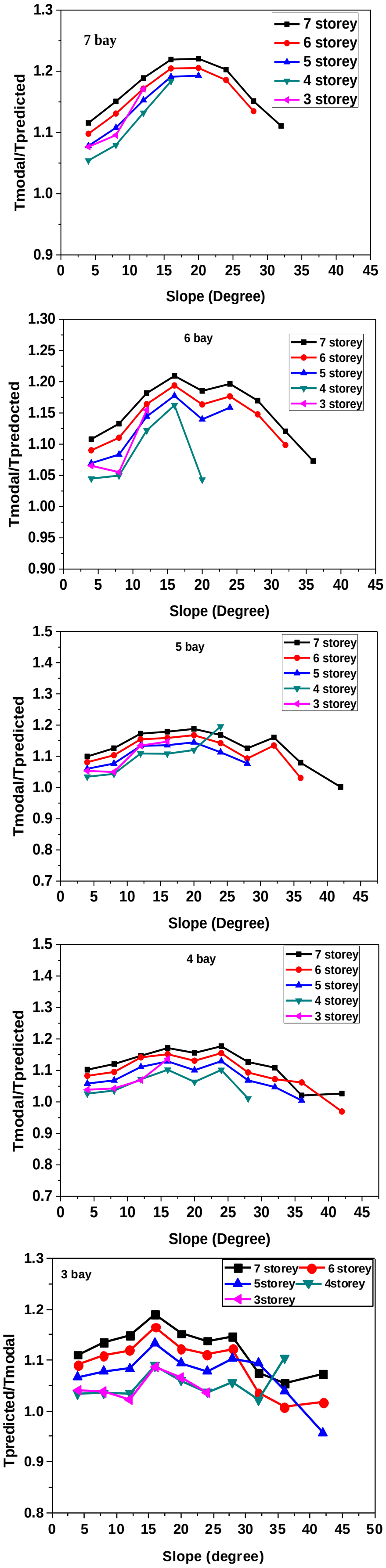

Fig. 7 The comparison of time period obtained by the proposed formula and from free vibration analysis

Table 2 The comparison of time periods obtained by using the proposed formula and from free vibration analysis

Building Configuration		Ground Slope				
		5°	10°	15°	20°	25°
6 storey 7 bay (5 m, 3 m×4 m)	Modal	0.7271	0.6849	0.6611	0.6270	0.6080
	Proposed	0.7788	0.7296	0.6826	0.6160	0.5630
5 storey 7 bay (5 m, 3 m×4 m)	Modal	0.6447	0.5962	0.5507	0.4850	0.4360
	Proposed	0.5884	0.5330	0.4810	0.4370	0.4090
3 storey 7 bay (5 m, 3 m×4 m)	Modal	0.3830	0.3350			
	Proposed	0.3530	0.3050			

The time period obtained by the proposed formula and the time period obtained from the free vibration analysis are further compared in Table 2 for various storey and bay numbers with different bay dimension. The observation on prediction capability remains same as earlier.

The prediction capability of the proposed empirical equation can be readily noted from the results presented. It may be noted that the fundamental time periods predicted by the proposed formula are mostly on the lower side as compared to the time period obtained from the free vibration analysis. In this regard, it is of worth noting that the code proposes conservative time period estimation relation so that it will be marginally on the lower side. This will result in a base shear higher than the actual base shear obtained from dynamic analysis. Thus, the design will be on the safer side. The calibrated formula proposed in the present study also follows the similar principle of keeping the predicted time period conservatively on the higher side.

5. Conclusions

A modification of code based empirical expression to estimate fundamental periods of building frames resting on sloping ground is proposed in the current study to supplement the preliminary analysis and design of irregular buildings on slopes. The modified relation is obtained based on extensive regression analysis of free vibration results of several stepback frames with varying slopes, storey numbers and bay numbers. The detailed parametric study shows that the fundamental time period of building frames reduces with increasing ground slope. Following the observation of parametric study, the modification to predict the fundamental time period is proposed as a simplified function of ground slope and a newly introduced equivalent height parameter to reflect the effect of stiffness and mass irregularity along the vertical as well as horizontal direction. The developed empirical expression is capable of estimating fundamental time periods of the stepback building frames on sloping ground with reasonable accuracy. The correlation between the predicted and actual time period obtained from the free vibration analysis are in good agreement considering the fact that the prediction formula is conservatively kept biased for marginally higher prediction of the time period. The various statistical parameters e.g. root mean square error, coefficient of determination and standard average error generally used for validation of such regression equations also confirm the predictability of the empirical equation. The observations are same with slopes and bay width which were not considered in the regression analysis indicating the capability of the empirical relation proposed. The modified code based empirical expression for fundamental period is developed in the present study for stepback buildings with two-dimensional idealization. However, this study can be readily extended to three dimensional stepback buildings, setback buildings and setback stepback buildings on hill slopes. The nonlinear seismic performances of such buildings are expected to be different than similar building types on flat ground and needs to explore further to understand the behaviour of buildings on hill slope at various performance levels.

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