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Equations to evaluate fundamental period of vibration of buildings in seismic analysis

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Abstract. In this study effects of various parameters like a number of bays, the stiffness of the structure along with the height of the structure was examined. The fundamental period of vibration *T* of the building is an important parameter for evaluation of seismic base shear. Empirical equations which are given in the Indian seismic code for the calculation of the fundamental period of a framed structure, primarily as a function of height, and do not consider the effect of number of bays and stiffness of the structure. Building periods predicted by these expressions are widely used in practice, although it has been observed that there is scope for further improvement in these equations since the height alone is inadequate to explain the period variability. The aim of this study is to find the effects of a number of bays in both the directions, the stiffness of the structure and propose a new period equation which incorporates a number of bays, plan area, stiffness along with the height of the structure.

Keywords: number of bay; dynamic analysis; period of vibration; stiffness; plan area

1. Introduction

Estimation of seismic base shear requires the fundamental period of vibration *T* of the building. However, for the building configuration adopted and the construction material chosen, it is not always possible to exactly determine from theoretical considerations, that is, through detailed dynamic analysis. Hence, empirical formulae obtained through the experimentally observed behavior of buildings are utilized Panzera *et al.* (2013), Jiazeng *et al*. (2013) and Olivera and Navarro (2013). The stiffness contribution of many non-structural elements, such as in-fill masonry panels Vance (1995), Anil and Atlin (2007) also considered in deriving period formula in different countries. For this reason, the empirical expression for *T* may be specific to each country. The approximate fundamental period of vibration (*T*) in the sec of a moment resisting frames building without brick infill panels may be estimated by the empirical expression given in Indian seismic code IS1893 (Part1): 2016**.**

$$T = 0.075h^{0.75} \quad \text{for reinforced concrete(RC) frame buildings} \tag{1}$$

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$$T = 0.075h^{0.85} \quad \text{for steel buildings} \tag{2}$$

$$T = 0.09h/\sqrt{d} \qquad \text{for all other buildings} \tag{3}$$

where h is the height of the building and d is the base width of the building along the direction of the earthquake under consideration.

The period of vibration of a building depends on the stiffness and mass along its height. Therefore, any structural or nonstructural element with rigidity/mass or both has an effect on the fundamental period of the building. The behavior of any structure under dynamic forces depends upon the dynamic characteristics of structures, which are controlled by both their mass and stiffness properties; in addition, the performance of structures also depends on the number of bays in either direction along with the plan area of the building.

Recent Indian seismic design code IS1893 (Part1): 2016 allows the estimation of T by any of the following methods:

Experimental observations on similar buildings (which almost never happens in practice)

- Any rational method of analysis (referring to dynamic analysis), or
- Using the empirical expressions prescribed in the code IS1893 (Part1): 2016.

The fundamental period can be evaluated using simplified Eqs. 1- 3 found in codes, which are based on earthquake recordings in existing buildings, laboratory tests, numerical or analytical computations. These technical codes provide expressions which depend on basic parameters such as building height or number of stories. Building periods predicted by these expressions are widely used in practice, although it has been pointed out by Khan and Ekramul (2006) and Verderame et al. (2009) that there is scope for further improvement in these equations since the height alone is inadequate to explain the period variability. It is also known that the period of a reinforced concrete (RC) frame structure differs depending on whether the longitudinal or transverse direction of the structure is considered.

The aim of this study is to propose new period equations which incorporate the effect of a number of bays, the stiffness of the structure and plan area of the building along with the height of the building.

2. Literature study

Since the predicted fundamental period is used to obtain the expected seismic load affecting the structure, a precise estimation of it is important for the safety of the applied procedure in the design steps and consequently in the future performance of the structure after it is constructed. The fundamental period of vibration required for the simplified design of RC structures has been calculated for many years using a simplified formula relating the period to the height of the building.

Gerardo *et al.* (2009) have pointed out that height alone seems inadequate to explain period variability and the results of their study suggest that global parameter (e.g., plan area) should be added in simplified relationships for rapid period evaluation. Therefore, an expression which includes also the plan area is considered in the following equations.

$$T = \alpha H^{\beta} S^{\gamma} \tag{4}$$

where S is the product of the two principal plan dimensions of the building L_x and L_y.

Hadzima *et al*. (2012) proposed seven different equations in their study to determine more accurate expressions to calculate the fundamental period. In addition to the number of floors, the author has considered following additional parameters:

- The number of bays parallel to the considered direction;
- The ratio between the number of bays in the longitudinal and transversal directions;
- The product between the number of bays in the longitudinal and transversal directions.

Following are the expressions proposed to evaluate period of vibration

$$T = C_{1.}N^{C2} \tag{5}$$

$$T = C_1.N^{C2}.B^{C3} \tag{6}$$

$$T = C_1.N^{C2} + C_{3.}B^{C4} \tag{7}$$

$$T = C_1 N^{C2}\{\frac{Bx}{By}\}^{kc3} \tag{8}$$

$$T = C_1 N^{C2}.(B_{x.}B_y)^{C3} \tag{9}$$

$$T = C_1 N^{C2} + C_3(B_{x.}B_y)^{C4} \tag{10}$$

$$= C_1 N^{C2} + C_3\{\frac{Bx}{By}\}^{kc4} \tag{11}$$

where N is the number of storeys, B is the number of bays of the building parallel to the considered direction, B_x is the number of bays in the longitudinal direction, B_y is the number of bays in the transversal direction, k is a constant which has a value of 1 when the period in the longitudinal direction is to be determined and a value of -1 when the period in the transversal direction is to be determined and C_1, C_2, $C_{3,}$ and C_4 are (unknown) parameters that need to be determined. The parameters of the expressions are determined by performing nonlinear regression analysis.

Kwon and Kim (2010) present an extensive review of the evolution of the code equations from the 1970s to 2010. In addition, the authors conducted a quantitative comparison of the measured fundamental period and estimated fundamental periods calculated from the code equations. It was found that when looking at buildings between 6 and 8 stories, the difference between the code approximation and the measured period is relatively large. This leads the authors to conclude that further refinement to these equations is needed depending on building heights without actually suggesting any improvement.

Further, in the literature survey, it is observed that Applied Technology Council (1978), Goel and Chopra (1997) Gong *et al*. (2011), Guler *et al.* (2008), Megdy (2014), Hong and Hwoang (2000) have proposed the fundamental period of vibration in the form of

$$T = C_1 H^{C_2} \tag{12}$$

Similarly, some of the authors Navaroo *et al*. (2007), Crowley and Pinho (2006), Gallipoli *et al.* (2010), Michel *et al*. (2010), Ingle (1997) proposed expression of the form

$$T = C_1 H \tag{13}$$

$$T = C_1 N \tag{14}$$

Where the values of C_1 and C_2 derived by regression analysis.

3. Parameters for analysis

Various RC frame buildings were analyzed using computerized solution with the following assumption mentioned in Tables 1-3 and general arrangement of beams and columns are depicted in Fig. 1.

In this study dynamic analysis was performed on total 120 building configurations. Various parameters for the analysis are mentioned in Tables 1-3 and Fig. 1 and earthquake parameters were considered as per the provisions of the Indian seismic code for earthquake Zone III. Computer software STAAD Pro-V8i is used to analyze the building models.

Table 1 Building configuration

Type of structure	Multistory rigid jointed plane frames
No of storey	GF to G+12, G+16, and G+20
Floor height	3.6 m
Base Dimension	30.0 m×30.0 m
No of Grids	2×6, 3×6,4 ×6, 5×6, and 6×6

Table 2 Materials

The Materials used	Concrete M-25 and Reinforcement Fe-415.
Type of soil	Type -II, Medium soil as per IS1893 (Part1): 2016
Ec	$5000\sqrt{f_{ck}}$ N/ mm^2
F_{cr}	$0.7\sqrt{f_{ck}}$ N/ mm^2

Table 3 Structural details

Size of columns		1.0×1.0 m, 0.75×0.75 m, 0.6×0.6 m, 0.5×0.5 m., 0.4×0.4 m, & 0.3×0.3 m
Thickness of slab		150 mm
Walls-	(a) External	200 mm
	(b) Internal	100 mm
Imposed load **(IS-875-1987 Part1-2)**		4.00 kN/m^2
Floor finish		1.00 kN/m^2
Waterproofing		2.500 kN/m^2
Specific wt. of RCC		25.00 kN/m^3

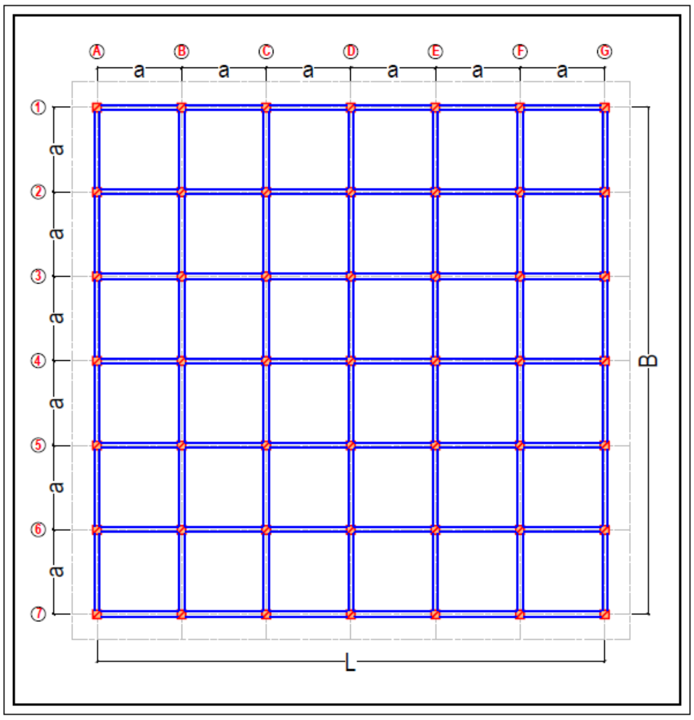

Fig. 1 Typical Plan with 6×6 grid

4. Proposed equations

Table 4 shows the value of the fundamental period of vibration for 60 various building configurations having a grid length of 4 m, 5 m & 6 m. For each grid length various values for the fundamental period are tabulated for column sizes 1000×1000 mm to 500×500 mm. Table 4 shows that, for a 2×6 grid, the values of the period of vibration comes out to be 4.46 sec for column size 1000×1000 mm and 3.73 sec for 500×500 whereas, for 6×6 grid size building, the period of vibration observed to be 4.46 sec and 6.04 sec for column size 1000×1000 mm and 500×500 mm respectively. Similar results are also tabulated in succeeding columns of the table for column sizes 750×750 mm, 600×600 mm, and 500×500 mm. Values so obtained are compared with the square shaped building, i.e., 6×6 grid, which is considered as a base case for comparing the results, it can be observed that the rectangular shaped buildings observed to be having a greater period of vibration as compared to square shaped buildings and period of vibration of the rectangular building having 19.39% higher as compared to the square shaped building, for the same building as in Table 4. The period of vibration observed to be increasing as the column sizes are reduced.

On the basis of analysis performed on 60 square/rectangular shaped buildings, it is observed that, evaluation of the period of vibration of buildings, depends upon the base dimensions, number of grids and stiffness of the structure, and the contribution of the same should also be incorporated in the formula to evaluate the fundamental time period of the building in seismic analysis.

Table 4 Fundamental Period of Vibration (sec) for 4 m, 5 m, and 6 m Grid Length

Column Size (mm)												
	1000×1000			750×750			600×600			500×500		
	Grid Length (m)			Grid Length (m)			Grid Length (m)			Grid Length (m)		
	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0	4.0	5.0	6.0
2×6	4.5	5.1	5.9	4.8	5.4	6.2	5.3	5.9	6.8	6.0	6.7	7.5
3×6	4.1	4.8	5.7	4.3	5.1	6.0	4.8	5.5	6.4	5.4	6.2	7.1
4×6	3.9	4.7	5.6	4.1	4.9	5.8	4.5	5.3	6.3	5.0	5.9	6.9
5×6	3.8	4.6	5.5	3.9	4.8	5.8	4.3	5.2	6.2	4.8	5.8	6.8
6×6	3.7	4.6	5.5	3.8	4.7	5.7	4.2	5.1	6.1	4.7	5.7	6.8

Table 5 Values of Time Period (sec) 10 Bays (Base Dimension 30.0×30.0 m)

S. No.	Number of Storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	1.6	2.1	3.2
2	G+10	39.6	1.5	1.9	2.9
3	G+9	36	1.3	1.7	2.6
4	G+8	32.4	1.2	1.5	2.4
5	G+7	28.8	1.1	1.4	2.1
6	G+6	25.2	0.9	1.2	1.9
7	G+5	21.6	0.8	1.0	1.6
8	G+4	18	0.7	0.9	1.3
9	G+3	14.4	0.5	0.7	1.1
10	G+2	10.8	0.4	0.5	0.8
11	G+1	7.2	0.3	0.4	0.6
12	GF	3.6	0.2	0.2	0.3

To develop the period formula, another 180 building configurations were analyzed, besides height of the building, parameters like a number of bays, bay width, plan area of the building, stiffness of the structure are considered as variables. Results obtained in the dynamic analysis are tabulated in Tables 5-10. Further 96 results are tabulated in Tables 11-14 with 6 bays in both the directions.

Table 6 Values of Time Period (sec) 9 bays (Base Dimension 30.0×30.0 m)

S. No.	Number of Storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	1.7	2.2	3.3
2	G+10	39.6	1.6	2.0	3.0
3	G+9	36	1.4	1.8	2.8
4	G+8	32.4	1.2	1.6	2.4
5	G+7	28.8	1.1	1.4	2.2
6	G+6	25.2	1.0	1.3	1.9
7	G+5	21.6	0.8	1.1	1.7
8	G+4	18	0.7	0.9	1.4
9	G+3	14.4	0.6	0.7	1.1
10	G+2	10.8	0.4	0.6	0.9
11	G+1	7.2	0.3	0.4	0.6
12	GF	3.6	0.1	0.1	0.2

Table 7 Values of Time Period (sec) 8 bays (Base Dimension 30.0×30.0 m)

S. No.	Number of Storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	2.0	2.6	3.9
2	G+10	39.6	1.8	2.2	3.4
3	G+9	36	1.6	2.0	3.1
4	G+8	32.4	1.4	1.8	2.8
5	G+7	28.8	1.3	1.6	2.5
6	G+6	25.2	1.2	1.4	2.2
7	G+5	21.6	1.0	1.3	2.0
8	G+4	18	0.8	1.0	1.6
9	G+3	14.4	0.7	0.8	1.3
10	G+2	10.8	0.5	0.6	1.0
11	G+1	7.2	0.3	0.4	0.7
12	GF	3.6	0.2	0.3	0.4

Table 8 Values of Time Period (sec) 7 Bays

S. No.	Number of storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	2.2	2.7	4.1
2	G+10	39.6	2.0	2.5	3.8
3	G+9	36	1.8	2.3	3.4
4	G+8	32.4	1.6	2.0	3.0
5	G+7	28.8	1.4	1.8	2.7
6	G+6	25.2	1.3	1.6	2.4
7	G+5	21.6	1.1	1.4	2.1
8	G+4	18	0.9	1.1	1.7
9	G+3	14.4	0.7	0.9	1.4
10	G+2	10.8	0.6	0.7	1.1
11	G+1	7.2	0.4	0.5	0.8
12	GF	3.6	0.2	0.3	0.4

Table 9 Values of Time Period (sec) 6 Bays

S. No.	Number of storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	2.5	3.1	4.6
2	G+10	39.6	2.3	2.8	4.2
3	G+9	36	2.1	2.6	3.9
4	G+8	32.4	1.9	2.3	3.5
5	G+7	28.8	1.7	2.1	3.1
6	G+6	25.2	1.5	1.8	2.7
7	G+5	21.6	1.3	1.6	2.3
8	G+4	18	1.1	1.3	2.0
9	G+3	14.4	0.8	1.1	1.6
10	G+2	10.8	0.6	0.8	1.2
11	G+1	7.2	0.5	0.6	1.0
12	GF	3.6	0.3	0.3	0.5

Table 10 Values of Time Period (sec) 5 Bays

S. No.	Number of storey	Height (m)	Column Size (mm)		
			500×500	400×400	300×300
1	G+11	43.2	3.0	3.6	5.3
2	G+10	39.6	2.7	3.3	4.9
3	G+9	36	2.5	3.0	4.4
4	G+8	32.4	2.2	2.7	4.0
5	G+7	28.8	2.0	2.4	3.6
6	G+6	25.2	1.7	2.1	3.1
7	G+5	21.6	1.5	1.8	2.7
8	G+4	18	1.3	1.6	2.3
9	G+3	14.4	1.0	1.3	1.9
10	G+2	10.8	0.8	1.0	1.4
11	G+1	7.2	0.5	0.7	1.0
12	GF	3.6	0.3	0.4	0.6

Table 11 Fundamental Period of Vibration (sec) for Grid Length 5 m

Base Width 30.0×30.0 m					
Number of Storeys	Height (m)	Column Size (mm)			
		1000×1000	750×750	600×600	500×500
G+20	77.6	3.8	3.9	4.2	4.7
G+16	63.2	3.0	3.1	3.4	3.8
G+12	48.8	2.2	2.4	2.6	2.9
G+8	34.4	1.5	1.6	1.8	2.0
G+4	20	0.8	0.9	1.0	1.2
GF	5.6	0.2	0.3	0.3	0.4

Table 12 Fundamental Period of Vibration (sec) for Grid Length 6 m

Base Width 36.0×36.0 m					
Number of Storeys	Height (m)	Column Size (mm)			
		1000×1000	750×750	600×600	500×500
G+20	77.6	4.6	4.7	5.1	5.6
G+16	63.2	3.6	3.8	4.1	4.5
G+12	48.8	2.7	2.9	3.1	3.5
G+8	34.4	1.8	2.0	2.2	2.4
G+4	20	0.9	1.1	1.2	1.4
GF	5.6	0.2	0.2	0.3	0.4

Table 13 Fundamental Period of Vibration (sec) for Grid Length 7 m

Base Width 42.0×42.0m					
Number of Storeys	Height (m)	Column Size (mm)			
		1000×1000	750×750	600×600	500×500
G+20	77.6	5.4	5.7	6.0	6.6
G+16	63.2	7.3	4.6	4.9	5.4
G+12	48.8	3.2	3.5	3.7	4.1
G+8	34.4	2.2	2.4	2.6	2.9
G+4	20	1.1	1.3	1.5	1.6
GF	5.6	0.2	0.3	0.4	0.4

Table 14 Fundamental Period of Vibration (sec) for Grid length 8 m

Base Width 48.0×48.0 m					
Number of Storeys	Height (m)	Column Size (mm)			
		1000×1000	750×750	600×600	500×500
G+20	77.6	6.3	6.6	7.1	7.7
G+16	63.2	5.0	5.3	5.7	6.2
G+12	48.8	3.8	4.1	4.4	4.8
G+8	34.4	2.5	2.8	3.0	3.3
G+4	20	1.6	1.5	1.7	1.9
GF	5.6	0.2	0.3	0.4	0.5

Proposed equations will give more accurate period values than the current code equations. The proposed equation is developed by multiple nonlinear regression analysis. The program SPSS v16 is used to perform the regression analysis. Several equation forms (Eqs. (15)-(18)) were investigated, including power models of varying form, quadratic models, polynomial models, and linear models. The equations were modified including structural parameters in varying ways, such as height, the ratio of the total cross-sectional area of columns to total plan area of the building, number of bays in longitudinal direction and number of bays in the transverse direction.

$$T = C_1 (N_b . N_l)^{C_2} . H^{C_3} \tag{15}$$

$$T = C_1 . \left(\frac{N_b}{N_l} \right)^{C_2} . H^{C_3} \tag{16}$$

$$T = C_1 (A)^{C_2} . H^{C_3} \tag{17}$$

$$T = C_1 . (N_b . N_l)^{C_2} . \left(\frac{A_c}{A_b} \right)^{C_3} H^{C_4} \tag{18}$$

This equation form will be referred to as a 3-variable power model. The four regression parameters are obtained by minimizing the sum of the squares of the distances between the actual data points and the regression curve. For each regression, the standard deviation of the residuals (σ) and r-squared (R^2) values are found. These values indicate how well the regression equation fits the sample Rayleigh data.

Consequently, Eq. (18) with parameters C_1=0.005, C_2=-0.061, C_3=-0.55, and C_4=1.049 is proposed as the best-fit equation for determining the approximate fundamental period of moment resisting frames, for which regression results are given in Table 15.

The value of R^2 is always between 0 and 1, with higher values indicating that the regression model fits the data better. A value of R^2=1.0 means that the curve passes through every data point, whereas R^2=0 means that the regression model does not describe the data any better than a horizontal line passing through the average of the data points. In this study, a value of R^2=0.945 indicates that 94.5% of the variation in the dependent variable is explained by the regression model.

Table 15 Results of Regression Analysis for Eq. (18)

ANOVA		
Source	Sum of Squares	d_f
Regression	19522.44701	4
Residual	452.2884999	616
Uncorrected Total	19974.73551	620
Corrected Total	8282.463489	619
Dependent variable: T		
a. *R* squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .945		

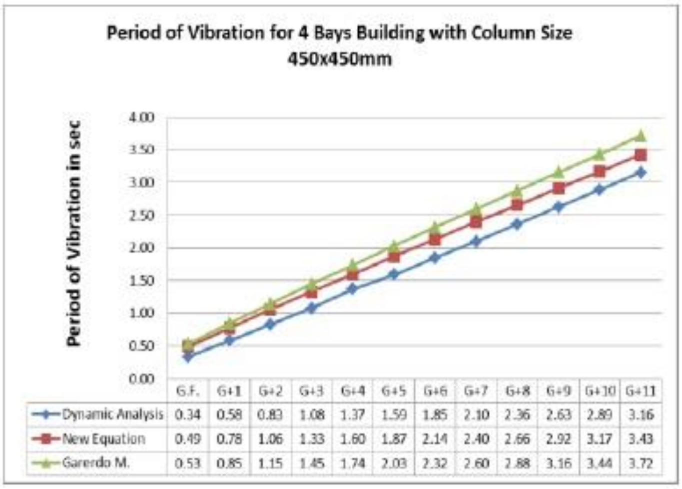

Fig. 2 Period in sec for 4 bays

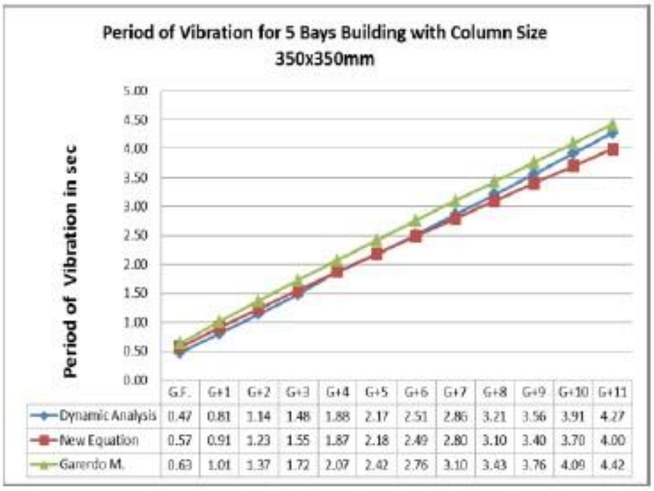

Fig. 3 Period in sec for 5 bays

5. Conclusions

Regression analysis was performed on total 318 results obtained from the dynamic analysis and Eqs. (15)-(18) were derived. For validation of the new equations, another 72 building configurations were considered and calculated the value of time period using Eq. (17), values so derived were compared by performing dynamic analysis and also the value of time period derived by using equation proposed by Garerdo *et al.* (2009). It is observed from the Figs. 2 and 3 that the values of time periods from the new equations are almost matching with the values proposed by

Garerdo *et al*. (2009) and the variation observed to be in between 5% to 10% while comparing the values of dynamic analysis and the new equation, the variation comes out to be ± 30%. Therefore, height alone seems inadequate to evaluate period of vibration and the results of this study suggest that plan area of the building, a number of bays in either direction and stiffness of the structure should also be added in simplified relationships for evaluation of the time period of vibration in seismic analysis.

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