NEW EMPIRICAL FORMULA FOR FUNDAMENTAL PERIOD OF TALL BUILDINGS IN INDIA BY AMBIENT VIBRATION TEST

by

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NEW EMPIRICAL FORMULA FOR FUNDAMENTAL PERIOD OF TALL BUILDINGS IN INDIA BY AMBIENT VIBRATION TEST

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Abstract

With the announcement of smart cities, construction of tall buildings is booming in India. There are quite a few codes for tall buildings and many of them have shortcomings in addressing the parameters for seismic design. One such parameter is the fundamental natural period of tall buildings. The expression of the fundamental period is originally developed based on Californian earthquakes and adopted by many seismic codes around the world; including current, Indian seismic code IS 1893: 2002. This paper aims to study the reliability of empirical expression of the fundamental period for tall buildings in India. For this purpose, ambient vibration tests have been carried out for 21 RC buildings, located in Mumbai and Hyderabad cities, by placing vibration sensor on topmost accessible floor. The measured periods have been compared with the code provisions. It is found in the study that as the height of the building increases, natural period is not linearly proportional to height; rather it is becoming flexible. Hence there is an urgent need for revision of the empirical expression.

Keywords: Fundamental Period; Tall Building; Ambient Vibration; Earthquake Resistant Design.

1. Introduction

Urbanization is rapidly increasing in every city in India. Huge infrastructure developmental plans have been laid by government and private organizations. Large advertising boards of tall buildings (up to 30 or 40 floors) already started attracting people to invest in these infrastructure plans. However, from the point of view of seismic hazard prevailing in the country, "Will these buildings survive during future earthquakes?" is a question to be answered before proceeding for construction.

In last 2.5 decades, 7 moderate earthquakes have been witnessed: Bihar-Nepal border (M6.4) in 1988, Uttarkashi (M6.6) in 1991, Killari (M6.3) in 1993, Jabalpur (M6.0) in 1997, Chamoli (M6.8) in 1999, Bhuj (M6.9) in 2001, A&N Islands (M9.3) in 2004, Muzzafarabad (M7.2) in 2005, Sikkim (M6.8) in 2011 and more recently Twin Earthquakes in the neighborhood Nepal. These earthquakes have clearly exposed the lack of understanding of seismic hazard of the country. Sometimes, even when the hazard is understood, the lack of knowledge is exposed on earthquake resistant design and construction practice of reinforced concrete structures. The professionals involved in building construction should be more concerned with the safety of building infrastructure during future earthquake events.

There are several earthquake safety issues involved in planning, designing and constructing tall buildings. Some issues related to seismic behavior are still not resolved even in developed countries, like USA and Japan. The situation in India is that there are few codes which specify guidelines for earthquake resistant design of structures. However, the guidelines given in this code are useful for regular and relatively small, low-rise buildings. When it comes to tall buildings, every structure is special, several parameter needed to be considered. One such parameter is fundamental natural period, '*T*'.

In case of seismic design of building the fundamental natural period helps in finding out the base shear to be resisted by the structure and mode shape gives the distribution of base shear at every storey. For equivalent static method [1], which is very common philosophy in many seismic codes around the world, the fundamental period will decide the spectral acceleration coefficient (Fig. 1) and there by the seismic demand i.e., base shear to be resisted by the structure. Over estimation of the time period values from computer based analysis gives the lower value of design base shear which is not true in reality. The value arrived by such analysis is not reliable because of non-availability of accurate modeling of unreinforced masonry (URM) infill walls in a software package. Substantial skill is required to overcome modeling challenges such as material property, boundary conditions, stiffness contribution of nonstructural elements etc.

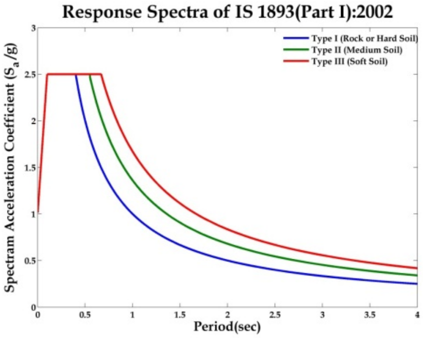

Fig.1– Design Acceleration Spectrum

At initial stage in design of building, when the exact size of the structural members is unknown, the fundamental time period can be calculated by the empirical expression suggested by the seismic code of a country. Traditionally this empirical period formulae are derived from the measured period of buildings which were shaken strongly but not deformed into the inelastic range. Such a data is most useful but slow to accumulate as it involves installation of permanent accelerometer and earthquake causing strong shaking of such buildings is infrequent in nature [2]. In the absence of such data one can go for a period measured by ambient vibration technique.

There is no explicit formula defined in IS 1893:2002 for RC SW structural system hence such type of building comes in 'other' category and code recommend the use of empirical expression of RC MRF building with infill wall, $T=0.09H/(D)^{0.5}$. Current approximate formulae present in the IS 1893:2002 are adopted from an earlier version of US codes which are based on the measured period of US buildings, shaken in the elastic range, during Californian earthquakes (Fig. 2). Ambient vibration tests conducted by Arlekar & Murty [3] on 19 RC MRF buildings with brick masonry infill walls in Kanpur, indicated that the Indian codal expression for fundamental natural periods are inadequate for Indian buildings. Hence there is a need to check the applicability of the existing formulae and if necessary a new formula should be tailored for Indian buildings.

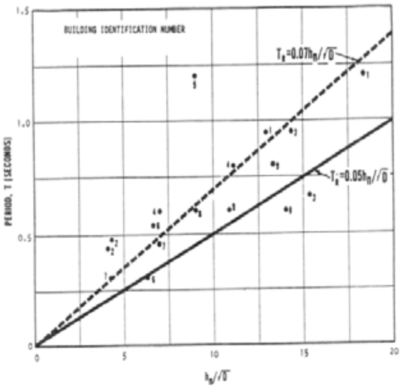

Fig.2–Observations on RC frame buildings during San Fernando Earthquake (From FEMA 369, 2001)

This paper shows the results of ambient vibration tests on 21 high-rise reinforced buildings whose measured period are compared with Indian codal provision. New empirical formulae, of natural period T, are proposed based on Height and lateral resisting system for the RC highrise buildings. At the end, lateral load demand of the highrise buildings with new proposal and current empirical expression are compared.

2. Period of vibration of reinforced concrete buildings

Generally the fundamental period of RC buildings are correlated with number of storey, height of the building, width of the building along the direction of shaking and the wall area present at ground storey. There is no explicit formula defined in IS 1893:2002 for RC SW structural system hence such type of building comes in 'other' category and code recommend the use of Eq. (1).

$$T = \frac{0.09\,H}{\sqrt{D}} \tag{1}$$

Where '*H*' is the he Height of building, m. This excludes the basement storeys, where basement walls are connected with the ground floor deck or fitted between the building columns. But it includes the basement storeys, when they are not so connected. And '*D*' is the base dimension of the building at the plinth level, in m, along the considered direction of the lateral force.

In ATC3-06 [4] in Eq. (1), $H/\sqrt{d}$ was multiplied by 0.05 as shown inFig. 2, when '*H*' and '*D*' are in feet. As discussed by Pinho and Crowley [5] this formula comes from the equation of the frequency of vibration of a cantilever (considering shear deformation only), with the thickness of the wall considered to be more or less constant and thus only the width/length of the building is an input parameter, as presented in Eq. (2).

$$T = 4\sqrt{\frac{m}{\kappa G}}\frac{H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{A}} = \frac{\alpha H}{\sqrt{D t_w}} = \frac{\alpha_1 H}{\sqrt{D}} \tag{2}$$

Where 'm' is the mass per unit length, 'G' is the shear modulus, 'κ' is the shape factor to account for non-uniform distribution of shear stresses, 'D' is the length of the cantilever, 't_w' is the thickness. Some codes use this formula specifically for buildings with both frames and shear walls, some use the equation for reinforced concrete MRF with masonry infill panels, but many specify it for use with any building except moment resisting space frames. There are many countries which adopted such formula, including, but not limited to, are ATC3-06:1978 [4], IS 1893-1984 [6], KBC 1988 [7], NBCC 1995 [8].

Proposed draft [9] of Indian seismic code have added one new expression for buildings with concrete or masonry shear walls. The approximate fundamental period permitted to be evaluated by the Eq. (3).

$$T = \frac{0.075}{\sqrt{A_W}} h^{0.75} \tag{3}$$

Where 'A_W' is the total effective area of the walls in the first storey of the building, in 'm^2', and can be calculated by Eq. (4).

$$A_w = \sum \left[A_{wi} \left(0.2 + \left(\frac{L_{wi}}{h} \right)^2 \right) \right]; \qquad L_{wi}/h \leq 0.9 \tag{4}$$

Where 'A_{wi}' is the effective cross sectional area of the wall 'i' in the first storey of the building, in 'm^2'. 'L_{wi}' is the length of the shear wall 'i' in the first storey in the considered direction of the lateral forces, in metre and 'h' is the height of building in metre. The ratio of 'L_{wi}/h' is restricted to 0.9 because for squat type of building in which length or breadth of building is large compared to its height lead to larger value of A_w.

In 1998, Goel and Chopra started working to improve the empirical formulas to estimate the fundamental vibration period of concrete SW buildings. They discussed how there is little correlation between the $H/\sqrt{D}$ of Eq. (1) and the period of vibration. This could be because the shear walls do not extend for the whole dimension D of the building, but for just a small proportion. Whereas eq. (3) was found to be more correlated to the period as it was including explicitly the dimensions of the walls, but this also found too conservative. The proposed formula was developed based on the fundamental period of a cantilever, considering flexure and shear deformations.

Chun et. al. [10] realized that Korean apartment buildings consist of walls and flat slabs without columns and beams hence dynamic characteristics of such buildings would defer from the US buildings, having beams and columns, from which fundamental periods were derived and adopted in Korean Building Code [7]. Moreover such buildings are having characteristics like slender, lightweight and having shear-wall dominant system. Ambient vibration studies were conducted on fifty apartment buildings (78 data points), of 10 to 25 stories, between the period of March, 1996 to April 1997. The average normalized power spectrums (ANSP) were generated to identify the natural frequencies of buildings. The Korean seismic code formula (Eq. (1)), for shear wall buildings, found to be giving much shorter values for longitudinal direction and longer for transverse direction for most buildings which were completely different as compare to measured data.

The construction scenario has changed in the last 15 years. The average height of buildings in Indian cities has risen. There are so many skyscrapers started coming in the Indian metro cities. Hence there is an urgent need to check the applicability of the existing formula.

3. Period of vibration of reinforced concrete buildings

3.1 Ambient Vibration Test

Ambient vibration tests can capture the linear behaviour of the structure. Hence in the absence period data measured during actual earthquake events one can go for a period measured by ambient vibration technique. This is true because the energy required to deform the structure in the fundamental mode of vibration is the least. The contribution of the fundamental mode is usually dominant in the ambient vibration response of the structure. Thus, the approach of deriving dynamic characteristics of a structure by ambient vibration measurement is considered adequate only for ascertaining the properties associated with the fundamental mode of vibration. The source of ambient vibration can be wind, sea waves, vehicles, machinery and human produced excitation. And the source of ambient vibration will vary based on the structure e.g., ambient noise because of wind will be predominant in tall buildings compare to that in the short buildings.

Trifunac[11] stated that though forced and ambient vibration testing is based on small levels of excitation, compared to strong earthquake ground motions, but still it offers a sound basis for rational improvements in the vibration theory. In 1997, 19 reinforced concrete (RC) moment resisting frame (MRF) buildings, with unreinforced masonry (URM) infill walls, were surveyed by ambient vibration survey in order to develop the empirical expression for the fundamental period of Indian buildings [12].

Canadian researchers had taken a research project which involves the development of a period database for multistory buildings in Montreal, Canada, using ambient vibrations. This database will not only be helpful for evaluating the fundamental period formulae, given in the National Building Code of Canada 2005, but also serves the objective of developing an improved equations for the low-amplitude fundamental periods of buildings in Montreal which in turn provides the conservative estimate for design purpose. Study proves that such an approach has the potential of improving the prediction of the fundamental period provided that new proposal should be based on sufficient number of buildings data set [13]. In the same year one more study carried out with an objective of evaluation of fundamental vibration periods of Turkish RC buildings having a frame-type structural system, and consider the effect of infill walls. The study proposed the formula for the estimation of the elastic vibration period of mid-rise RC frame-type buildings in Turkey [14].

3.2 Investigated Buildings

Twenty one numbers of RC buildings having more than sixty meter height (i.e., greater than twenty floors) are surveyed between April to December 2014 which are located in Hyderabad and Mumbai cities. The variation in number of floors is from seventeen to forty-two and majority of them are either residential with couple of building used for commercial purpose. The average floor-to-floor height of residential building was ranging between 2.9 to 3.4m with only exception of MUM07 building having 3.60m as floor to floor height. Whereas for commercial buildings they are around 3.75 to 3.90m. The variation in height at ground storey or basement was a common feature. The building features discussed above are summarized in. Typical RC high-rise buildings surveyed in this study are shown in Fig. 3.

(a) (b) (c)

Fig.3–Examples of typical high-rise buildings (a) MUM03 (b) MUM07 and (c) MUM08

Table 1 –Fundamental Period of RC SW buildings measured using ambient vibration test

S. No.	Building ID	Number of Storey	Height (m)	Typical F.F. Height (m)	Type	Dimensions (m)		Time period (sec)	
						Longer (L)	Shorter (D)	Longer (T_L)	Shorter (T_D)
1	MUM05	20	58.60	2.90	Residential	30.74	19.91	0.987	0.811
2	MUM02	21	63.00	3.00	Residential	49.07	24.80	1.137	1.154
3	MUM14	22	66.00	3.00	Residential	26.40	23.30	1.365	1.204
4	HYB18	22	66.00	3.00	Residential	81.08	25.45	1.078	1.154
5	MUM01	23	69.00	3.00	Residential	49.07	24.80	1.122	1.388
6	MUM15	25	71.86	3.00	Residential	24.67	13.63	1.107	1.545
7	MUM03	25	75.00	3.00	Residential	48.19	40.62	1.412	1.365
8	MUM16	26	77.86	3.00	Residential	37.60	16.80	1.222	1.545
9	HYB20	27	81.00	3.00	Residential	73.43	20.58	1.170	1.280
10	HYB32	26	83.60	3.26	Residential	50.46	42.31	1.138	1.122
11	MUM08	31	90.95	2.90	Residential	52.54	35.18	1.517	1.638
12	MUM06	37	119.60	3.20	Residential	46.39	29.72	1.780	2.340
13	MUM07	37	137.70	3.60	Residential	51.54	37.85	2.340	2.642
14	HYB31	42	146.75	3.40	Residential	33.34	29.50	3.033	3.033

MUM=Mumbai; HYB=Hyderabad

Table 2 - Fundamental Period of RC buildings above 20 storey (>60m) measured using ambient vibration test

S. No.	Building ID	Number of Storey	Height (m)	Typical F.F. Height (m)	Type	Dimensions (m)		Time period (sec)	
						Longer (L)	Shorter (D)	Longer (TL)	Shorter (TD)
1	MUM02	21	63.00	3.00	Residential	49.07	24.80	1.137	1.154
2	HYB12	22	65.60	3.00	Residential	28.94	26.56	0.920	0.963
3	HYB13	22	65.60	3.00	Residential	44.55	28.97	0.952	0.910
4	HYB53	22	66.00	2.95	Residential	27.00	27.00	1.050	1.050
5	MUM14	22	66.00	3.00	Residential	26.40	23.30	1.365	1.204
6	HYB18	22	66.00	3.00	Residential	81.08	25.45	1.078	1.154
7	HYB23	17	66.23	3.90	Commercial	67.64	24.45	0.871	1.154
8	MUM01	23	69.00	3.00	Residential	49.07	24.80	1.122	1.388
9	MUM15	25	71.86	3.00	Residential	24.67	13.63	1.107	1.545
10	MUM03	25	75.00	3.00	Residential	48.19	40.62	1.412	1.365
11	MUM16	26	77.86	3.00	Residential	37.60	16.80	1.222	1.545
12	HYB20	27	81.00	3.00	Residential	73.43	20.58	1.170	1.280
13	HYB32	26	83.60	3.26	Residential	50.46	42.31	1.138	1.122
14	HYB42	28	86.37	3.00	Residential	43.11	40.38	1.388	1.154
15	HYB19	24	87.14	3.75	Commercial	80.26	46.03	1.241	1.204

16	MUM08	31	90.95	2.90	Residential	52.54	35.18	1.517	1.638
17	MUM06	37	119.60	3.20	Residential	46.39	29.72	1.780	2.340
18	MUM07	37	137.70	3.60	Residential	51.54	37.85	2.340	2.642
19	HYB31	42	146.75	3.40	Residential	33.34	29.50	3.033	3.033
20	MUM09*	35	110.80	3.20	Hotel+Office	65.84	34.92	3.723	2.925
21	MUM10*	37	115.40	3.20	Proposed Office	48.60	37.50	3.561	2.482

**Outlier; MUM=Mumbai; HYB=Hyderabad*

3.3 Testing Equipment and Procedure

For this study relatively low price and high performance micro-tremor portable 'IT Kyoshin' Vibration sensor was used which was developed as a part of Indo-Japan collaborative research project (DISANET) sponsored by JST and JICA. These force balance acceleration sensors can measure recording of range +0.25g to -0.25g in resolving power 5310^{-3} cm/sec^{2}. The resolving power of the AD converter are 24 bits. However, effective resolving power is 18bit equivalency. This vibration sensor was connected with Ethernet cable to the mac book, to store the vibration data. A single point observation at the roof top or maximum accessible floor level was recorded for 15-45 minutes. Whenever possible the sensor was kept very near to the center of the building and readings are taken at the rate of 100 data points per second. Sensor are aligned and leveled (Fig. 4), in such a way that two horizontal axes of the sensor become parallel to the longitudinal and transverse direction of the building.

Fig.4–Leveling and Aligning of sensor on roof top

3.4 Result of Experimental Analysis

Table 1 and Table 2 shows the fundamental period values of buildings along longer and shorter direction which are identified based on the Fourier spectrum analysis. MATLAB code has been written to do analysis of the recorded data. Typical procedure consists of reading a 15-30 min raw data, stored in mac book, and doing a baseline correction. Butterworth band pass filter was designed for removal of noise and unwanted frequencies. Based on user input lower and higher cutoff frequencies, the filter is capable of filtering the frequency of order four. Now this baseline and filtered time history are divided in to one minute window and fifteen numbers of undisturbed windows are selected for further analysis. The Fourier spectrum of this fifteen number of one minute window is computed (Fig. 5) and finally average spectrum of this fifteen minute data is plotted to identify the fundamental natural frequency of the structure (Fig. 6), along the direction under consideration. Inverse of frequency will give us the desire fundamental natural period of the building in seconds.

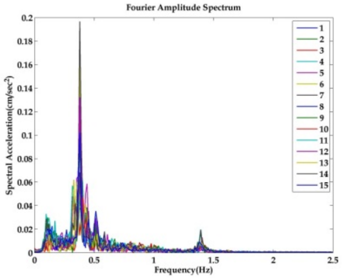

Fig. 5–Example of Fourier Amplitude Spectrums of fifteen one minute window of building (MUM07) along shorter (NS) direction

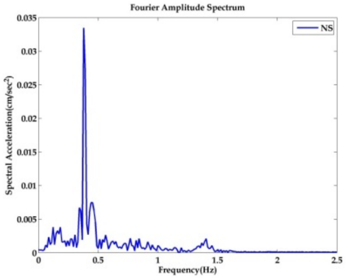

Fig. 6– Example of Fourier Amplitude Spectrums of fifteen one minute window of building (MUM07) along shorter (NS) direction

4. Regression Analysis of Measured Period

Regression analysis is carried out in two parts, in first set fourteen number of high-rise buildings are considered whose lateral load resisting system consist of RC SW and in second set regression analysis is carried out for all nineteen buildings having height more than 60m irrespective of their lateral load resisting system. The power law and linear regression analysis is adopted to establish the relation between the period and the various building parameters such as height (‘*H*’), width (‘*D*’) and product of lateral dimension (‘*A*’) of the buildings. In such analysis, both variables are often transformed by means of a logarithm. The resulting data is plotted on a “log-log” scale, where a linear model is then fit by Eq. (5).

$$y = a_1 + a\,x \tag{5}$$

Where $y = log\ (T)$ and $x = log\ (H/D^{0.5})$ or $log\ (H/D)$ or $log\ (H/A^{0.5})$ or $log\ (H)$. The parameter ‘a_1’ and ‘a’ are determined by minimizing the squared error between the measured period and computed periods, and then ‘C_t’ was back calculated from the relationship $a_1 = log\ (C_t)$.

The evaluation of the regression analysis is done with the help of standard error of estimate S_e (Eq. (6)) and the coefficient of determination R^2 (Eq. (7)). The expression with the coefficient of determination close to 1.0 represents a good fit. The upper and lower bound were also calculated by adding or subtracting S_e from the C_t value (Eq. (8) and (9)). Lowering the ‘C_t’ is done because ‘S_e’ approaches the standard deviation for large number of samples and we will get ‘$C_{t_{low}}$’ which will ensure that 15.9% of the measured periods would fall below the curve corresponding to it. If desired, one can also go for ‘$C_{t_{low}}$’ corresponding to some other non exceedance probabilities.

$$S_e = \sqrt{\frac{\sum(\log T_i - \log \bar{T}_i)^2}{n-2}} \tag{6}$$

$$R^2 = 1 - \frac{n\sum(\log T_i - \log \bar{T}_i)^2}{(n\sum \log {T_i}^2) - (\log T_i)^2} \tag{7}$$

$$\log C_{t_{low}} = \log C_t - S_e \tag{8}$$

$$\log C_{t_{upper}} = \log C_t + S_e \tag{9}$$

Where ‘T_i’ and ‘$\bar{T}_i$’ are the ‘i^{th}’ data and regression estimate values of natural periods, respectively. And ‘n’ is the total number of data points.

4.1 Regression Analysis based on Lateral Resisting System

This type of buildings is not common throughout India but they are gaining popularity in metropolitan cities. More and more number of such buildings are started coming in cites to meet the demand of residential and commercial space. We have fourteen number of such buildings under this category out of which four are from Hyderabad and rest ten are from Mumbai (Table 1).

There is no explicit formula defined in IS 1893:2002 for RC SW structural system hence such type of building comes in 'other' category and code recommend the use of same empirical expression, $T = 0.09H/\sqrt{D}$. The plot of comparison between the measured period and codal provision is shown in Fig. 7. On first look codal provision looks okay as it underestimate the natural period for most of the building under study. But it has S_e =0.238 and R^2=0.527 indicates the poor fit. Hence there is a need to derive an explicit empirical expression which represents a natural period of such type of buildings.

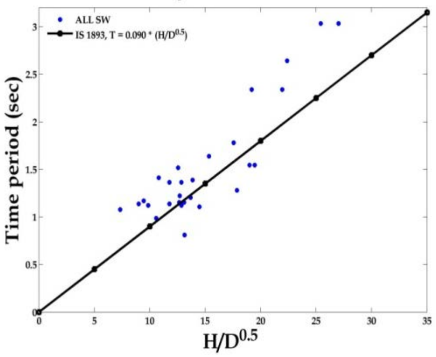

Fig. 7–Comparison of measured period of RC SW buildings with IS 1893:2002

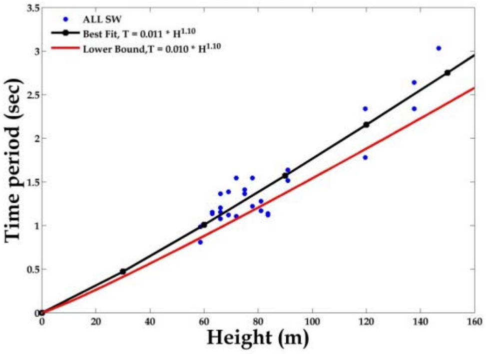

Fig. 8–Plot of experimental data and proposal expression for natural period of RC SW buildings

Regression analysis carried out for H, $H/D^{0.5}$ and $H/A^{0.5}$ and results are tabulated in Table 3. Among various relationships, relationship between 'T' and 'H' found to be optimum. Unconstrained regression analysis between 'T' and 'H' gave expression $T=0.011\ H^{1.1}$ with S_e = 0.135 and R^2= 0.846. It is desirable that the expression for natural period be easy to remember hence constrained model with power = 1 was computed but it leads to change in S_e and causing reduction in R^2. So for RC SW buildings new expression was established as Eq. (10), where H is height of the building in metre and T in seconds. The plot of this expression with the measured period is shown in Fig. 8.

$$T = 0.01\ H^{1.1} \tag{10}$$

Table 3 – Result of Regression Analysis of all RC SW Buildings

Model	C_t	A	S_e	R^2	C_{low}	C_{upper}
$T = C_t H^a$	0.011	1.10	0.135	0.846	0.010	0.013
$T = C_t H^a$	0.017	1.00	0.138	0.840	0.015	0.020
$T = C_t H^a$	0.146	0.86	0.200	0.665	0.119	0.178
$T = C_t \left(\frac{H}{\sqrt{D}}\right)^a$	0.150	0.850	0.200	0.665	0.123	0.184
$T = C_t \left(\frac{H}{\sqrt{D}}\right)^a$	0.101	1.00	0.205	0.648	0.082	0.124

$T = C_t \left(\frac{H}{\sqrt{D}} \right)^a$	0.090	1.00	0.238	0.527	-	-
IS 1893:2002	0.802	0.652	0.264	0.417	0.616	1.045
$\mathrm{T} = \mathrm{C_t} \left(\frac{\mathrm{H}}{\sqrt{\mathrm{A}}} \right)^{\mathrm{a}}$	0.011	1.10	0.135	0.846	0.010	0.013

4.2 Regression Analysis based on Height

This dataset comprises of twenty one buildings from Hyderabad and Mumbai city, out of which two buildings being outlier. The fundamental period and building parameters of these building are tabulated in Table 2. It consists of buildings from 17-42 storeys with a height variation of 63-146m. The fundamental period variation was found to be 0.871 to 3.033 sec.

The most relevant expression of such buildings in IS 1893:2002 is, $T = 0.09H/\sqrt{D}$. The plot of comparison between the measured period and codal provision is shown in Fig. 9. Though this underestimates the period of most of the buildings but have very poor R^2 = 0.568 with S_e= 0.213.

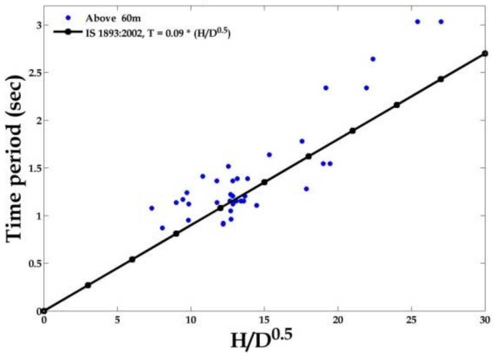

Fig. 9–Comparison of measured period of RC buildings above 20 floors with IS 1893:2002

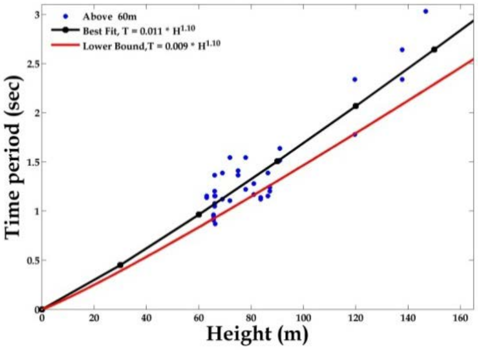

Fig. 10–Plot of experimental data and proposal expression for natural period of RC buildings above 20 floors with infill wall panel

Regression analysis carried out for H, $H/D^{0.5}$, H/D and $H/A^{0.5}$ and results are tabulated in Table 4. Among various relationships once again relationship between T and H found to be optimum. Unconstrained regression analysis between T and H gave expression $T=0.009\ H^{1.14}$ with S_e = 0.142 and R^2= 0.806. It is desirable that the expression for natural period be easy to remember hence constrained model with power = 1.1 was computed which gave S_e=0.143 and R^2= 0.805. Due to very small change in S_e and R^2value lead to adoption of this proposal. A lower bound expression for RC buildings above 20 floors with infill wall panels can be used as Eq. (11). Where 'H' is height of the building in metre and 'T' in seconds. The plot of this expression with the measured period is shown in Fig. 10.

$$T = 0.009\ H^{1.1} \tag{11}$$

Table 4 –Regression models result for Building above 20 storey (>60m)

Model	$\boldsymbol{C_t}$	***a***	$\boldsymbol{S_e}$	$\boldsymbol{R^2}$	$\boldsymbol{C_{low}}$	$\boldsymbol{C_{upper}}$
$T = C_t H^a$	0.009	1.14	0.142	0.806	0.008	0.010
$\boldsymbol{T = C_t H^a}$	**0.011**	**1.10**	**0.143**	**0.805**	**0.009**	**0.012**

$T = C_t H^a$	0.017	1.00	0.147	0.794	0.014	0.019
$T = C_t\left(\frac{H}{\sqrt{D}}\right)^a$	0.137	0.88	0.186	0.671	0.114	0.165
$T = C_t\left(\frac{H}{\sqrt{D}}\right)^a$	0.15	0.85	0.19	0.67	0.12	0.18
$T = C_t\left(\frac{H}{\sqrt{D}}\right)^a$	0.099	1.00	0.190	0.657	0.082	0.120
IS 1893:2002	0.090	1.00	0.213	0.568	0.073	0.111
$T = C_t\left(\frac{H}{D}\right)^a$	0.950	0.42	0.262	0.343	0.731	1.235
$T = C_t\left(\frac{H}{\sqrt{A}}\right)^a$	0.791	0.64	0.244	0.430	0.620	1.010

4. Discussion and Conclusions

It was recognized that there is a need for defining explicit formula for RC SW building as current provision is found to be conservative for such buildings. There are no expressions for natural period classification based on height of the building. Proposed empirical equations are found to be more or less same with different S_e values since the majority of buildings above 20 floors, in our database, are of RC SW type buildings. Hence they were similar with different S_e values. It was also recognized that there is a need for defining explicit formula based on height for buildings whose lateral resisting system are not know initially.

The following salient conclusions are drawn from the present study:

a) With advancement of science and technology numbers of tall buildings have been increased in India. A new formula for tall buildings should be introduced explicitly.

b) Current empirical expression found to be over-conservative for RC SW buildings. Empirical expression of RC SW wall should be stated separately and should not be included in ‘other’ category.

c) The empirical expression for estimating the fundamental natural periods for RC SW buildings with infill panels can be taken as Eq. (12). Where, H is height of building from the base (in m)

$$T = 0.01\, H^{1.1} \tag{12}$$

d) For RC buildings above 20 floors (>60m) fundamental natural period can be found out from Eq. (13). Where, H is height of building from the base (in m)

$$T = 0.009\, H^{1.1} \tag{13}$$

In future, such expression should be revised periodically by expanding database of building natural periods. Since our surveyed buildings were consisting of good number of SW type structural system the proposed equation of fundamental natural period for building heights may not be valid for all RC buildings. Involvement of government agencies would help in getting the true representative samples of buildings from different seismic zones. Both the formulae proposed are based on the ambient vibration study only, the database of measured period of buildings which were shaken strongly but not deformed into the inelastic range should be collected and a new expression should be proposed.

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