Effect of Fundamental Period on Seismic Design of Reinforced Concrete Structures

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Abstract

Seismic design of reinforced concrete structures is becoming more important in high seismic areas of developing courtiers, because of increased seismic activity. There are number of well defined design codes like Uniform Building Code (UBC) 1997, Federal Emergency Management Agency (FEMA), Washington, 1997, and International Business Code (IBC) 2000, etc. which are used in developed countries for seismic design. Seismic design depends on the base shear (V) of the building which acts on the building when any seismic activity happens. UBC 1997 gives empirical equations for calculation of 'V'. The coefficients involve in calculation of (V) depend upon the construction practices and design technique prevailing in the developed countries. Similarly this code gives two methods for the calculation of fundamental period 'T' of the building. This paper describes the influence of structure's fundamental period on the seismic design characteristics. Two different methods define by UBC 1997 have been used in the paper to estimate the fundamental period of the structure. Based on the analytical findings, the research concludes the ineffectiveness of method B for structures with large fundamental period in high seismic zones. T_A and T_B are discussed in detail along with the factors on which T_A & T_B depend. Graphs between base shear coefficient (Vc) and period (T) are developed and discussed for all seismic zones. Moreover, a regular high rise reinforced concrete building is analyzed, designed and compared for both fundamental periods. Comparison shows an ample variation in the forces, design and civil cost of same building for the two cases.

Keywords: Uniform building code, seismic design, fundamental period, building height, reinforced concrete structures

1.0 INTRODUCTION

The frequency of occurrence of earthquake is increasing day by day. The buildings designed according to prevailing codes are also damaged by these off & on jolts. Many lacunae in construction as well as design have come to light while analyzing the failures due to earthquake. In order to design a structure to withstand an earthquake, the forces on the structure must be specified. The exact forces that will occur during the life of the structure cannot be known. When any earthquake hits the structure, seismic forces arise from the vibration of the mass of the structure. The frequency of these vibrations and corresponding period play an important role in response of the structure. The period can be determined from the equations defined in specified building codes. It is therefore important that careful consideration should be given to the fundamental period of a building in its planning and design stage.

According to UBC-1997, the world is divided into different seismic zones with respect to the intensity of seismic hazards. For a particular zone when a maximum intensity of earthquake jolts any building, the code gives formulae to estimate maximum limit of base shear. Base shear generates seismic forces which will act on a building. Base shear is the only factor which makes the seismic design of the structure different from its gravity design. Base shear is the combination of base shear coefficient (will be termed as Vc) and building dead weight. Vc is multiplied by building's dead weight to find out the magnitude of Base Shear. The coefficient of Base Shear is dependent upon i) seismic zone coefficient Z, ii) soil profile coefficient Ca & Cv, iii) Building response coefficient Rwx & Rwz, iv) building importance factor I, v) fundamental period T. All of above mentioned parameters excluding fundamental period are constant, for any Intermediate Moment Resisting Frame (IMRF) or Special Moment Resisting Frame (SMRF), in a particular zone & soil profile except fundamental period. Code defines two methods for determination of period either T_A or T_B, and variation among both periods may be up to 30 % for zoned 4 and 40% for rest of the zones. This variation generates a marginal difference in design forces which are addressed in this study.

In this regards B N Pandya (4) has published a paper presenting a study carried out to compare the fundamental natural period (FNP) obtained by free vibration analysis of reinforced concrete buildings considering various configuration irregularities with the values of FNP obtained from empirical formulae given by Indian Standard Code IS 1893 (Part 1): 2002, International Building Code IBC 2000 and Federal Emergency Management Agency FEMA 368. It was found that structural configuration irregularities tend to increase the FNP and that the IS 1893 (Part 1): 2002 empirical formula gives FNP which is almost half the computed values. The IBC 2000 and FEMA 368 empirical formula gives FNP, which varies marginally from the computed values.

2.0 PERIOD AND STATIC LATERAL FORCE PROCEDURE

The period 'T' of the structures is defined as "elastic fundamental period of vibration, in seconds, of the structure in the direction under consideration"
UBC-1997 presents a stepwise procedure for determination of lateral forces.
The flow diagram to represent the calculation procedure for different seismic parameters is shown here.

CALCULATION FLOW

I → R → Zone Z →Soil Profile Type → Cv → T → W → V → Ca → V(max) → V(min) → Ft → Fx → Vx → Mx → Drift → Reliability

The following equations represent the relationship of base shear with period.

$V = C_v I\, W/RT$ eq. (1) $V_{max} = 2.5 C_a W/R$ eq. (2) $V_{min} = .11 C_a W$ eq. (3)

Where: V = Base shear, W = Total dead load, R = Response modification factor, T = Time period. C_a = Acceleration based ground response coefficient, C_v = Velocity based ground response coefficient, I = Importance factor,

In this paper combination of C_v, I, R & T is considered as base shear coefficient (V_c).

2.1 GOVERNING PARAMETERS OF PERIOD BY METHOD 'A'

In UBC 1997 following formula is used for the calculation of Fundamental period (T) for all the buildings from Method 'A'.

$$T = C_t (H_n)^{3/4} \qquad \text{eq. (4)}$$

C_t = .035 (.0853) for steel moment resisting frames.
C_t = .030 (.0731) for reinforced concrete moment resisting frames.
C_t = .02 (.0488) for all other buildings.
H_n = Height in feet (meters)

The value of Ct for structures with concrete or masonry shear walls may be taken as $.1/\sqrt{Ac}$ (For SI: $.0743/\sqrt{Ac}$ for A_c in m^2).

The value of A_c shall be determined from the following formula

$$A_c = \sum A_e [0.2 + (D_e/H_n)^2] \qquad \text{eq. (5)}$$

The value of D_e/h_n use in formula shall not exceed 0.9.

Fundamental period calculated form Method 'A' is termed as T_A depends upon height, so it remains constant for a particular building. C_t is dependent upon type of building, type of material and also upon construction methodology.

2.2 GOVERNING PARAMETERS OF PERIOD BY METHOD 'B'

In UBC 1997 the calculation of Fundamental period from Method 'B' is termed as T_B calculated following the structural properties and deformational characteristics of the resisting elements in a properly substantiated analysis. The value T_B shall not exceed 30 percent greater than the value of T_A obtained from Method A in Seismic Zone 4 and 40 percent in Seismic Zone 1, 2 and 3. The fundamental time period may be T_B computed by using the following formula.

$$T = 2\pi \sqrt{(\Sigma w i \delta i^2 \div g\, \Sigma f_i \delta_i)} \qquad \text{eq. (6)}$$

The value of f_i represents any lateral force distributed. The elastic deflection δ_i shall be calculated using the applied lateral forces, f_i.

As T_B is dependent upon weight & deflection of the structure, so it is highly variable. Deflection can be reduced by increasing stiffness of the structure and weight is also variable due to architectural considerations or any other building's usage requirement.

Base shear calculated from T_A is normally more than that calculated from T_B. Apparently, T_B seems to be more realistic than T_A as it considers many factors as shown in its equation. But codes give freedom to use any one method, so importance of its use is of much interest. Selection of T (either by method A, or by method B makes a marginal change in design) is made in this research.

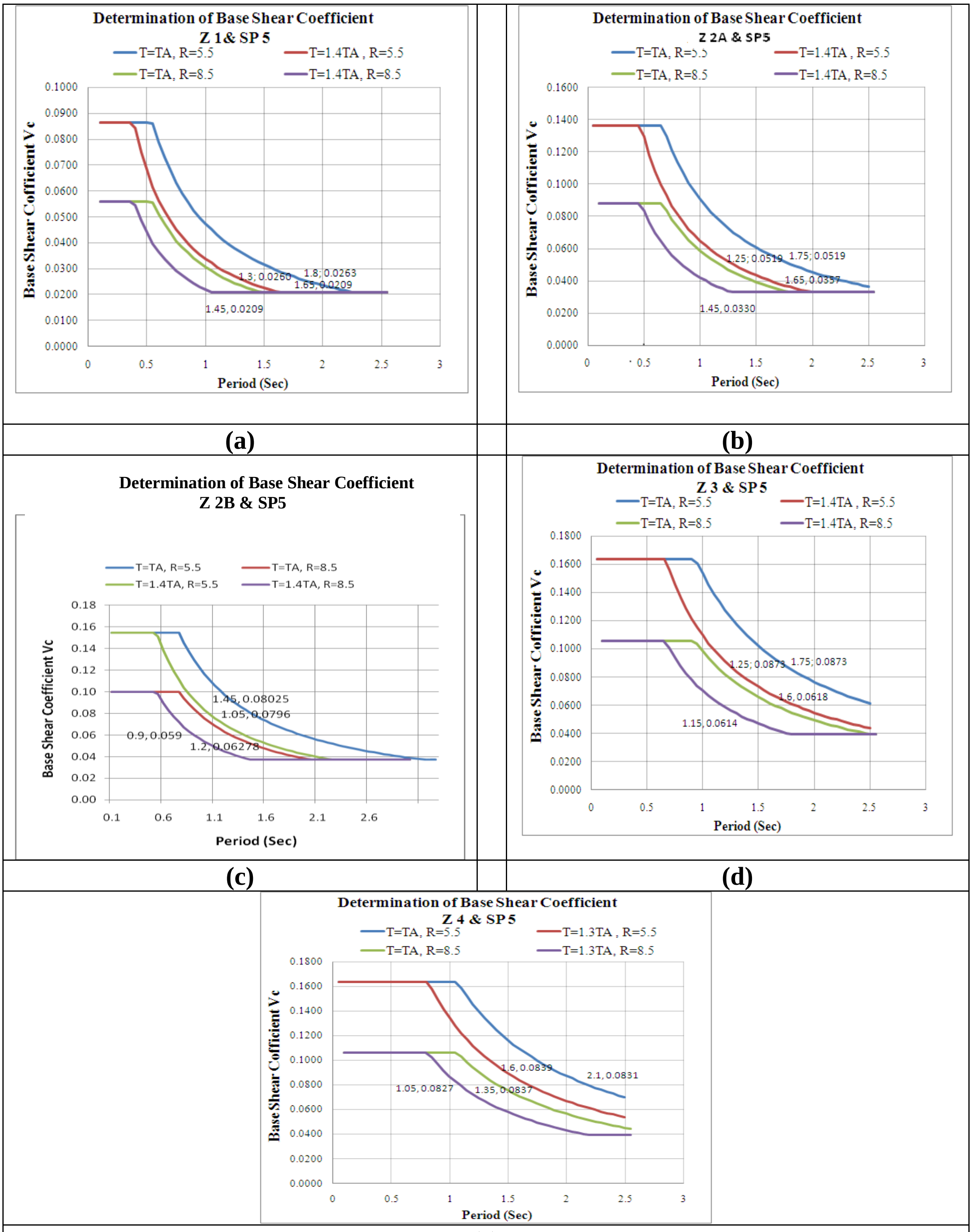
The coefficients C_t, R and I depends on the construction methodologies and construction techniques. The construction techniques in developed countries are very well defined and followed. In developing countries these design codes are applied in design but importance is not given to construction techniques, which make the design vulnerable and doesn't give the same level of safety against earthquakes. Therefore it is vital requirements to either strictly follow the same level of construction methodologies or revise those coefficients against prevailing construction practices in developing countries.

2.3 RELATIONSHIP BETWEEN BASE SHEAR COEFFICIENT AND PERIOD

The relationship between base shear coefficient & period is shown in eq. (1) to eq. (3). In these equations all the parameters are fixed for a particular zone and soil profile except period will depend upon the structure. Thus graph can be plotted for determination of base shear coefficient against different values of period. Graphs are plotted against different values of period.

These graphs show the range of period for any building vary from T_A to $T_B \leq 1.4T_A$ in Zone 1, 2A, 2B & 3, for zone 4 period ranges is T_A to $T_B \leq 1.3T_A$. These graphs are developed for all zones and soil profiles but only graphs for soil profile E in all zones are presented here due to insufficiency of space available for this paper. If the building need to design against T_A

Another interesting thing presenting in these graphs is same base shear coefficient against two different periods. As in zone 3 V_C is .00618 against period 1.6 if T_B is considered and 1.15 if T_A is considered. This shows that 201ft high RC frame building will have same V_C with T_B, as it is for 129ft high building with $T_{A.}$



(a) **(b)**

(c) **(d)**

(e)

Figure 01: Graphs Between Base Shear Coefficient and Period for Soil Profile 'E' Shown as SP5 and Seismic Zones Zone 3 and & Zone 4

3.0 CASE STUDY

Regular Structure selected for this research is (3B +G+ 16) 20 storey office building to see the effect of fundamental period on the structural design. Different structural elements of the building have following properties.

i) All basement beams are 12”x27”, ii) All peripheral floor beams are 13½”x36”, iii) All internal floor beams are 12”x36”, iv) Columns from lower basement to 2nd floor are 48”x48”, v) Columns from 3rd floor to 6th floor are 42”x42”, vi) Columns from 7th floor to 10th floor are 36”x36”, vii) Columns form 11th floor to 14th floor are 30”x30”viii) Columns from 15th floor to 20th floor are 24”x24”, ix) Thickness of Pile Cap/ Raft is 66”, x) Thickness of Basement Wall is 12”.ix) Building is 243ft high. Penthouse height is 18.5ft.

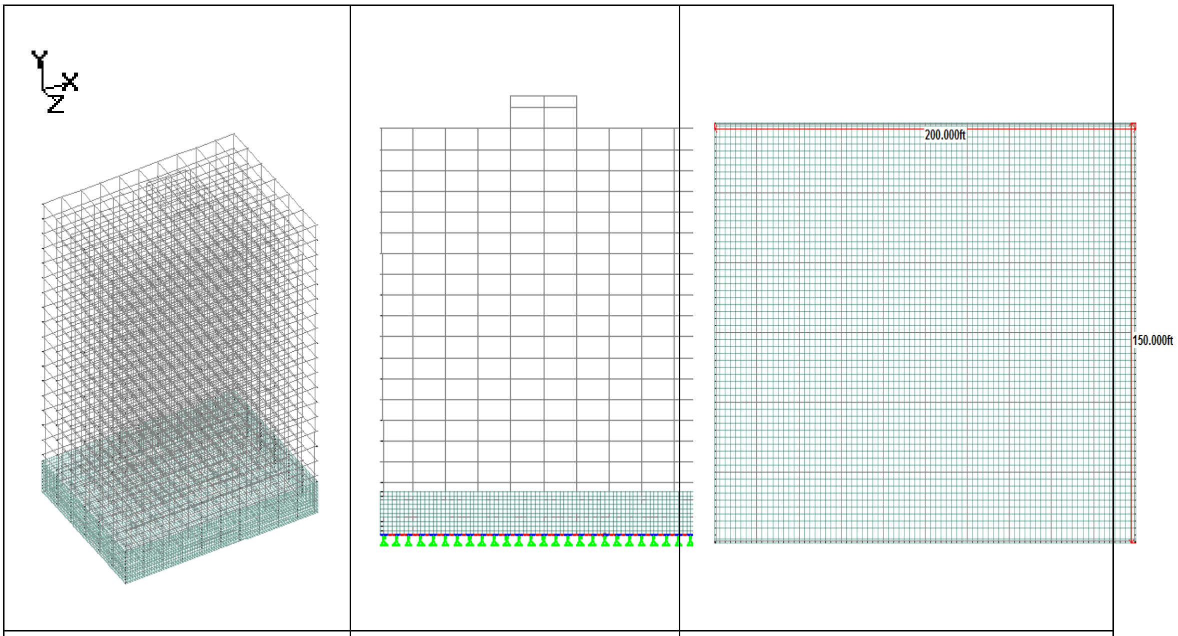
3.1 GENERAL PARAMETERS

Building is designed for basic five loads i) Seismic Load in X-dir, ii) Seismic Load in z-dir, iii) Dead Load, iv) Live Load, v) Roof Live Load. Seismic and factored Load combinations are determined from basic load combination 1612.2.1 of UBC-1997. Seismic parameters considered are i) R_{WX} & R_{WZ}= 8.5, ii) I=1, iii) N_A & N_V= 1, iv) S=5, v) Z=.3 & .4. The schematic views of the building are shown in Fig-02.

Pile foundation is provided as recommended by Geo-Tech investigation report. Fig 02 (b) shows the spring which are designed against piles stiffness calculated with following formula using values given in report.

K (FY) = Pile Capacity/Settlement.

In material properties all main reinforcing steel is deformed bars with 60 ksi yield strength, where as for secondary steel is mild with 40 ksi yield strength, fc' compressive strength of concrete for columns is 4 ksi & 3 ksi for other structural members.



(a) 3D View (b) Front View (c) Top View

Figure 02: StaadPro Model of Structure

3.2 STRUCTURAL ANALYSIS

In structural analysis following parameters are determined, which are used in calculation of design forces for all structural elements.

3.2.1 FUNDAMENTAL PERIOD

Time period provided for structural design is calculated against total height of building excluding penthouse, shown as follows

- T_A 1.795 in X & Z DIR. for Zone 3 & 4 (considering building height only)
- T_B 2.34 (1.3 T_A) in X-DIR & Z-DIR for Zone 4,
- T_B 2.34 (1.3 T_A) in X-DIR 2.513 (1.4T_A) in Z-DIR. For Zone 3

Comparison of both designs with time period T_A and T_B is shown in terms of percentage reduction in forces.

3.2.2 BASE SHEAR & DEFLECTION

Base shear determined in both directions is tabulated in Table (01). For a particular building displacement of nodes make a considerable variation in design forces due to PΔ effect. Therefore values of maximum displacement are also noted for each model. Displacements are only noted against factored loads with seismic force combination to make a comparison.

Table (01)

	BASE SHEAR (KIPS)				**DEFLECTION (INCHES)**			
SOIL PROFILE ‘E’	T_A		T_B		T_A		T_B	
	X DIR	**Z DIR**	**X DIR**	**Z DIR**	**X DIR**	**Z DIR**	**X DIR**	**Z DIR**
Zone 3	10248.44	10248.44	7861.51	7371.52	10.978	14.32	9.178	11.607
Zone 4	11712.5	11712.5	9003.83	9003.83	12.545	16.365	10.503	13.78

3.3 STRUCTURAL DESIGN

3.3.1 PILES / PILE CAP-RAFT

Piles design is not in the scope of this project, only forces acting on piles are shown. In building in Zone 3 & 4, almost 70% piles have governing forces against gravity loads so design remains same either T_A or TB is used. For 30% piles governing forces are against seismic load combinations. Thus when pile designed with T_A is compared with T_B the reduction in axial forces is 6% and in plane forces are also reduced up to 25%.Piles with 30” diameter and 76 ft length is assumed to be sufficient for both designs.

Pile cap/raft with 66” thickness is provided. The reduction in design of raft for a building in Zone 3 with T_B is 8% & 16% for top moment in longitudinal & transverse direction, where as bottom moment is reduced 13.5% & 58.7% for exterior & inner column strip in longitudinal. For transverse direction it is 21% & 27% respectively. Area of steel is reduced in only on those locations where flexural moment governs and reduction is almost in same percentage as moment reduced. The reduction in design of raft for a building in Zone 4 with T_B is 9% for top moment in longitudinal & transverse direction, where as bottom moment is reduced 20% for exterior column strip in longitudinal & transverse direction. Area of steel is reduced in only on those locations where flexural moment governs and reduction is almost in same percentage as moment reduced.

12” thick retaining wall is provided all around the basement. For design of retaining wall moment does not govern and only minimum reinforcement against temperature and shrinkage is provided. Results for columns and beams are tabulated below.

3.3.2 COLUMNS

Table (02)

Typical Column Represents	Percentage reduction with TB in Z=3				Percentage reduction with TB in Z=4			
	P	MX	MY	As	P	MX	MY	As
Exterior Column	-1%	-	-3%	-3%	-1%		-3%	-3%
Inner Column	-1%	-	-2%	-3%	-1%		-2%	-3%

Design of 20 storey columns is divided into 5 parts. Each 4 storey have same X-section and almost they have similar results, so same design is used for 4 storey column. In general almost all columns up to 16 storeys have minimum 1% area of steel. So there is no comparison. Whereas last four storey column are designed against governing forces and area of steels varies marginally. Some results are presented in Table (02) shown above.

3.3.3 BEAMS

Beams results also tabulated to represent the comparison given in Table (03). Where (M_{+ive}) & (M_{-ive}) represents bottom and top moments of beams. (T) represents torsion and (V) represents shear in beams.

Table (03)

Average Beam Results with Storey Level	Percentage reduction with T_B in Z=3						Percentage reduction with T_B in Z=4					
	M_{+ive}	M_{-ive}	T	V	Bottom Steel req.	Top Steel req.	M_{+ive}	M_{-ive}	T	V	Bottom Steel req.	T S r
1ST TO 5TH	19%	25%	20%	12%	17%	26%	18%	24%	19%	12 %	19%	2
5TH TO 10TH	21%	28%	13%	17%	20%	29%	19%	25%	12%	16 %	20%	2
11 TH TO 15TH	18%	27%	3%	14%	18%	29%	17%	24%	3%	13 %	18%	2
16TH TO 20TH	5%	5%	2%	3%	4%	5%	5%	5%	2%	3%	7%	8

4.0 COST ANALYSIS

In both cases concrete outline of all structural members is kept same. Therefore comparison is only possible among area of steel ratio of all structural elements of the structure. The accumulative concrete quantity for both cases is 423,000 CFT. Whereas G-60 steel required for case study in Zone 3 is 5435 tons with T_A and 16% reduction is found for T_B. Similarly for case study in Zone 4, G-60 steel required is 5877 ton for T_A with 12% reduction for T_B. Total civil cost for both cases is 926million PKR with T_A & 846.8 million PKR with T_B for case study in Zone 3 and for case study in Zone 4 total civil cost is 968 million PKR with T_A and 904.5 million PKR with T_B. Thus 8.6% cost is reduced if building is designed with T_B as compare to T_A in zone 3 & soil profile E, where as 6.6% cost is reduced for same building in zone 4 & soil profile E. Cost is only reduced due to steel, if concrete outline does not kept same there will be further reduction in cost. This cost analysis was done in 2009 and schedule of rates prevailing at that time in Pakistan were used.

5.0 CONCLUSIONS & RECOMMENDATIONS

The following conclusions have been made from this study.

1. The base shear coefficient V_C of the building with Intermediate moment resisting frame (IMRF) designed with T_A is 54.5% more than Special Moment Resisting Frame (SMRF) system. Similarly if same building is designed with T_B ($1.4T_A$) than V_C will be 40% reduced, giving the design near to SMRF design without any SMRF detailing.
2. The graphs in Fig (01) depicts that building with Time period 0.5 sec. to 2 sec. which corresponds to 5 to 20 storey height buildings, there is marginal increase in base shear if T_A is used as compared to T_B.
3. Reinforced concrete building with height 60 ft or less has T_A & T_B equal to 0.6 sec, as shown in Fig 01, (d & e). So the building V_C will remain same for zone 3 & 4 in soil profile 'E'. Thus five storey height building will have same design either in zone 3 or 4. For the two most critical zones in loose soil profile, our design will not change. This needs reconsideration of factors for calculation of V_C.
4. The present study shows that if building is designed with larger period T_B the result shows less deflection see Table 1, and also more economical design as compared to design of same building with higher deflection and lower period T_A. The other formula for calculation of time period T_B as shown in eq. (6) depends on displacement. So when the lateral displacements will be increased then Time period will also be increased. This contradicts to each other.
5. The height of the building used in Method 'A' for time period is also contradictory. Design code says if penthouse area is less than 10% of the total area of the building than penthouse height should not included in total height of building for calculation of time period with Method A. The height of the building plays important role in calculation of base shear so the percentage of penthouse are in relation to total area of building should be reconsidered to make the design more economical.
6. Similarly if the building have a basement without seismic/expansion joints, we must consider that height in total height of the building.
7. The variable involves in a calculation of base share with eq. (1) to eq. (3) are C_a & C_v should also be reconsidered especially for zone 3 & 4 in soil profile 'E' to make the design different in these zones.
8. Construction material and techniques are different for all over the world. Therefore value of C_T may not be constant for all regions. It should be estimated for a particular area according to prevailing practices.

9. For any value of period corresponding height of the building can be determined using following Eq. $H = ^{4/3}(T/Ct)$ eq.(7)
   Where H is in feet and T is in seconds. Thus for assisting quick design graph between V_C & H can also be developed and can be presented in further studies.

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