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I.S. code provisions for seismic design of tall chimneys

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Synopsis

The provisions of IS : 1893-1984 for earthquake analysis and design of tall chimneys have been reviewed. It is seen that the design seismic force specified by the Indian code is very much on the lower side. Ten chimneys with height ranging from 107.5 m to 336.2 m have been analysed by the finite element method and the results compared with those from expressions recommended in the code. It is seen that for the given design spectrum the code overestimates base shear by 45 - 70%, and therefore the corresponding expression in the code needs to be revised.

Key words

Chimney; Concrete; Earthquake; Finite element.

Introduction

Seismic design forces in India are governed by the Indian Standard Criteria for Earthquake Resistant Design of Structures IS : 1893-1984 [3]. This code lays down the seismic design force requirements for

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various structures including stacklike structures, that is chimneys and other structures in which mass and stiffness is more or less uniformly distributed along the height. The code was first published in 1962 and has since been revised four times (1966, 1970, 1975 and 1986) in view of continuously accumulated knowledge and experience on earthquake resistant design. Chimneys form an important component of major industries and power plants. While damage to chimneys in an earthquake may not directly lead to loss of life, it may cause shut down of power plants and important industries. In this paper, the seismic design requirements in the code for tall chimneys have been reviewed. It is shown that the seismic design forces are rather low and need to be revised upwards by incorporating suitable value of importance factor (I) and performance factor (K) for such structures. Also the expression for base shear needs to be revised.

I.S. code provisions

The provisions of IS : 1893-1984 [3] concerning chimneys are described here. The fundamental period of vibration is to be calculated by

$$T = C_T \sqrt{\frac{W_t h'}{E_s A g}} \tag{1}$$

where

C_T = a coefficient depending upon slenderness ratio = 1.8 k for tall chimneys with $k \geqslant 50$

W_t = total weight of the structure

h' = height of chimney

E_s = modulus of elasticity of material of the structural shell

A = area of cross-section at the base of the shell

g = acceleration due to gravity

$k = h'/r_e$

and r_e = radius of gyration of the structural shell at the base section.

Using this time period, horizontal seismic coefficient (α_h) is to be obtained from

$$\alpha_h = \beta \, I \, F_o \frac{S_a}{g} \tag{2}$$

where

β = a coefficient that depends on the soil-foundation system and is 1.0 for raft foundation

I = importance factor

F_o = seismic zone factor

S_a/g = average acceleration coefficient. It may be noted that the code does not give a specific value of damping to be used in obtaining S_a/g. However, Appendix F of the code recommends damping as 2 to 5% for steel structures and 5 to 10% for concrete structures.

The shear force and bending moment at a section above the base are given by

$$V = C_v \alpha_h W_t \left[\frac{5}{3} \frac{x'}{h'} - \frac{2}{3} \left(\frac{x'}{h'} \right)^2 \right] \tag{3}$$

$$M = \alpha_h W_t \bar{h} \left[0.6 \left(\frac{x'}{h'} \right)^{0.5} + 0.4 \left(\frac{x'}{h'} \right)^4 \right] \tag{4}$$

where

C_v = coefficient depending on slenderness ratio of chimneys

x' = distance from top of chimney

and $\bar{h}$ = height of center of gravity of the structure above its base.

ACI code provisions

The ACI 307-79 [1] specifies the design seismic base shear or total lateral force as

$$V = ZUCW \qquad \text{or} \qquad V = ZUCW_1 \tag{5}$$

where

U = use factor that varies from 1.3 to 2.0

V = total shear at the base

W = total weight of chimney without lining

W_1 = total weight of chimney including corbel supported lining

and Z = zone coefficient (= 0.3, 0,5 and 1.0 for zones 1, 2, and 3, respectively).

$$C = 0.1/\sqrt[3]{T} \tag{6}$$

The value of the fundamental period of vibration of unlined chimneys may be approximated by

$$T = \frac{1.8\ H^2}{(3\ D_1 - D)\ \sqrt{E}} \tag{7}$$

where

H = height of chimney in ft

D_1 = outside diameter of chimney at base in ft

and D = outside diameter of chimney at top in ft.

If the chimney has a lining supported by the shell, but not structurally an integral part thereof, T shall be multiplied by the factor $\sqrt{W_1/W}$.

Design seismic force level

The Indian code provisions are incomplete or ambiguous in many ways. For instance an explicit specification of damping for the structure is lacking. This leaves the design engineer with a discretion to use damping value, leading to varying level of earthquake protection to the same chimney if designed by different engineers. A good design specification must specify damping to be used with the given design spectrum. For instance, according to Housner and Jenning [2], there are four major factors which combine to determine the capacity of structures to resist earthquakes : the level of the design spectra, the designated spectral damping, the permissible stresses and strains, and the method of determining the natural periods of vibration of the structures. Design criteria can be incomplete unless all four of the factors involved are specified.

It is thus suggested that the next revision of IS : 1893 should have specific mention of damping to be used not just for chimneys but for all structures. For instance the code already makes a specific suggestion on the damping to be used for design of overhead water tanks.

The code suggests the value of I as 1.5 for important service and community structures. Thus, an average industrial chimney will not come under this category and will be designed for I as 1.0. However, the code includes "important power houses" among those structures which will be designed for I = 1.5. This may be extrapolated to mean that the chimneys of such important power houses may also be designed for I = 1.5. The issue of importance factor has been well debated by the ACI committee (ACI terms this as use factor, U) and it recommends this to range from 1.3 to 2.0. The explaination given by the ACI is :

"Chimneys do not, as a rule, represent as great a hazard to life and limb as do buildings with human occupancy. On the other hand, damage to chimneys may result in shutdown of the plants or industries which are important to the recovery of large population centres from the effects of severe earthquakes. For example, the desirability of continuity in the function of utilities after an earthquake is self-evident. However, there are instances of other industrial installations where damage may be tolerated or where the projected life of the chimney is short. For these reasons, a use factor (U factor) ranging from 1.3 to 2.0 was introduced in the specification. It was believed that chimneys designed for U = 2.0 would be relatively damage free and serviceable after a strong shock. The lower limit of U = 1.3 was intended to produce safe chimneys although their serviceability may be impaired

Thus, there seems to be a need for an explicit specification of the importance factor for chimneys in the I.S. code and this value may range from 1.5 to 2.0.

In codes of most of the seismically active countries the seismic coefficient used for structures such as chimneys and water tanks is much higher than that for the buildings. Even though ACI 307-79 does so by providing a higher value of C, this is usually done by specifying a much higher value of K (performance factor) for other structures. For instance American codes specify $K = 2.0$ for structures other than buildings as compared to $K = 0.67$ for buildings with ductile frame, i.e., three times that for the ductile frames. This may be explained as : "Because self-supported stacks have limited redundancy with only a single load path to ground it is not practical to design for ductile behaviour. They should be required to respond elastically to the maximum design earthquake" [4]. On the other hand in the Indian code with the absence of K for other structures (e.g., water tanks, chimneys, bridges etc.), it amounts to taking $K = 1.0$ for such structures which is the same as for a building with ductile frames. This leads to much lower level of design earthquake forces for such structures in the Indian code.

As an example, consider a tall concrete chimney on a raft foundation ($\beta = 1.0$) with natural period $T = 2.4$ sec located in zone V in India. Taking I as 1.0, F_o for zone V as 0.4, and S_a/g for 5% damping and 2.4 sec period as 0.05, this amounts to $\alpha_h = 0.02$ and thus the design base shear, $C_v \alpha_h W_t$, is equal to $0.03 W_t$. Thus, the design base shear is only 3% of weight of the chimney. On the other hand, as per ACI the same chimney, if located in zone 3 ($Z = 1.0$) of US seismic map, will be designed for the base shear ranging from 9.7% to 14.9% of its weight depending on the value of U taken. It may be noted that the design force as per Indian code will be further reduced if one were to take damping in concrete as 10% instead of 5% which the code seems to allow in its present form. This large difference in the design seismic force in the two countries is not due to any significant difference in the perceived seismic hazard between zone 3 of USA and zone V of India. This becomes obvious when one compares the design seismic force for buildings in the two countries in these same zones (Fig. 1). It therefore becomes obvious that there is a need to upgrade the design seismic force level in IS : 1893 by specifying appropriate values of damping, importance factor (I) and performance factor (K).

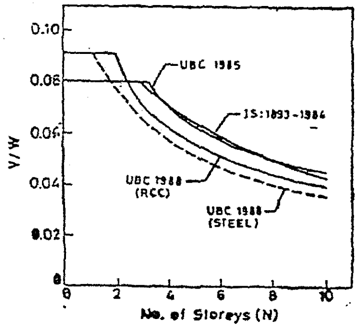

Fig. 1 Base shear coefficient for ductile buildings (Zone V of India, Zone 3 of U.S.A.)

Parametric study

Ten tall chimneys were adapted from Rumman [5, 6] for a parametric study (Table 1). Dynamic analysis of these chimneys was carried out by finite element method to study the implications of I.S. Code provisions for a fixed seismic design spectrum. Response in the first six modes was combined by the square root of sum of squares. The design spectrum was taken same as in IS : 1893-1984 [3]. Table 2 compares the results. The time period estimate by I.S. code is quite reasonable with the maximum difference being only 13%. On the other hand the code over estimates base shear by 45% to 71%. This difference is due to the presence of factor C_v, which is 1.5 for tall chimneys, in base shear expression of the code.

One of the basic difference between dynamics of multistorey buildings and tall chimneys is worth mentioning at this stage. In multistorey buildings first mode contributes maximum towards base shear and higher modes always contribute much smaller percentage of base shear. On the other hand fundamental period of tall chimneys may be around 2.0 to 5.0 seconds for which the value of α_h for first mode becomes quite small as compared to that in second or third mode. Thus the second and third modes also contribute significantly to the base shear in the case of tall chimneys. It appears that IS : 1893-1984 incorporates C_v greater than one in base shear calculation in order to incorporate the higher mode contributions. However, from the results reported in Table 2 it is clear that this value of C_v is very much on the higher side and needs revision.

On the other hand, the I.S. code formula estimates base moment quite accurately with the maximum difference being only 13%. This rather accurate estimation is because the coefficient C_v is not included

Table 1 Main dimensions of chimneys

Sl. No.	Height (m)	(L/R) base	Outer dia (m)		Shell thickness (m)		Total Wt (N)	Grade of Conc.
			Top	Bottom	Top	Bottom		
1	215.5	29.8	6.10	21.10	0.200	0.610	1.16×10^8	M30
2	110.0	32.8	7.00	10.00	0.500	0.500	3.39×10^7	M20
3	107.5	33.4	7.19	9.40	0.200	0.300	2.26×10^7	M30
4	215.0	34.5	9.60	18.21	0.250	0.600	9.88×10^7	M20
5	243.8	35.8	11.10	19.80	0.230	0.540	1.13×10^8	M30
6	274.3	35.6	10.40	21.90	0.225	0.640	1.52×10^8	M30
7	137.2	36.8	5.00	10.90	0.200	0.350	3.01×10^7	M30
8	335.0	36.8	14.70	26.70	0.250	0.950	3.28×10^8	M20
9	336.2	38.2	12.90	25.60	0.230	0.680	2.33×10^8	M30
10	162.8	45.4	5.70	10.70	0.200	0.560	3.89×10^7	M30

Table 2 Comparison of results

Sl. No.	Period (Sec)		Base shear ($\times 10^7$ N)		Base moment ($\times 10^8$ N/m)	
	FEM 1 mode	IS code	FEM (6 modes)	IS code	FEM (6 modes)	IS code
1	2.421	2.540	0.289	0.442	2.34	2.39
2	1.937	1.927	0.104	0.170	0.483	0.639
3	1.860	1.891	0.071	0.115	0.373	0.399
4	3.045	3.247	0.231	0.329	1.85	1.96
5	3.273	3.485	0.260	0.379	2.41	2.58
6	3.523	3.813	0.335	0.511	3.39	3.68
7	2.350	2.330	0.080	0.132	0.468	0.510
8	4.559	5.156	0.650	1.110	8.45	9.59
9	4.500	4.894	0.470	0.793	6.17	6.97
10	2.641	2.844	0.097	0.141	0.569	0.586

in the moment expression. In the first instance, it appears unusual that the height of C.G. of the chimney has been taken as a lever arm to be multiplied to "shear" (base shear divided by C_v) for calculation of base moment. This apparent "discrepancy" is because for a rigid structure, base moment is equal to base shear times height of C.G. of the structure while for the fundamental mode of a flexible structure such a lever arm is much more than the height of C.G. of the chimney. However, a close look at base shear and base moment indicates that for slender chimneys, it is not unreasonable. In the second and higher modes, shear contribution is relatively much more significant than the moment contribution and this lowers the lever arm.

The parametric study was also carried out to evaluate the shear and moment distribution expressions with height. It was seen that the shear distribution expression of the code is quite satisfactory while the expression for moment distribution is somewhat inaccurate near the top of the chimney where it is too conservative. Also it was seen that the higher mode contribution to shear is very much significant while to moment higher modes do not contribute as significantly. In general, a minimum of three modes must be considered for shear calculation. Also, three modes appear to be adequate for most practical purposes as the difference between six mode and three mode response is in the range of 0.8% to 6%. For moment calculation, even one mode gives fairly reasonable values although for moments near the base consideration of at least two modes is desirable.

Summary and conclusions

The I.S. code provisions for seismic design of tall chimneys have been reviewed. It is seen that the I.S. code specifies very low design seismic force. This is mainly due to the absence of appropriate provision of importance factor (I) and performance factor (K) for chimneys. Moreover, a specific value of damping to be used with the design spectrum is missing giving rise to possible variation in the level of earthquake protection to chimneys designed by different engineers.

I.S. code expression for time period is found to be quite accurate and gives a value which is a little on the higher side (upto 13 percent). The code tends to over estimate the base shear to the extent of 45 to 70%. This is due to an unusually large factor, C_v, included in the base shear expression which needs to be revised. Base moment by I.S. code is 2 to 13% more than the actual base moment which is quite satisfactory. This is so because factor, C_v, has not been included in the base moment expression. The method of shear distribution with height given in the code is quite accurate. For distribution of moment I.S. code tends to be somewhat conservative near the top of chimney. It would be best if instead of the given expressions for design shear and moment a dynamic analysis procedure similar to that of uniform bending beam is recommended in the code. Such a method can be tailored to allow "hand calculations" in design offices.

References

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Books review

Design of Steel Structures

P. DAYARATNAM
A.H. Wheeler & Co., Allahabad
p. 832, 1990.

This book based on IS : 800-1984 provides a wide spectrum of design of steel structures. There are 17 chapters. The first five chapters deal with the design of connections, tension, compression and bending members. The next three chapters deal with plate girders, gantry girders and beam-column joints. The next few chapters deal with loads on industrial buildings based on the IS : 875-1987, and design of various types of industrial buildings including towers and water tanks. There is a chapter on the theory of plastic design. The design of steel bridges is discussed in detail. The text book provides detailed illustrations and diagrams, solutions using computer aided analysis design and this book should be very useful to the undergraduate students and consulting engineers.

Vibrations, Dynamics and Structural Systems

M. MUKHOPADHYAY
Oxford & IBH Publishing Co., New Delhi
Soft Bound, p. 400, 1989 Price Rs. 96

This book presents a comprehensive treatment of vibration analysis of structures. Starting from the analysis of single degree of freedom systems, the subject is developed into more advanced topics. There are sixteen chapters. The first four chapters deal with the free and forced vibrations of single degree of freedom systems. The analysis of multidegree of freedom systems is discussed in chapters five to seven. The next two chapters are devoted to continuous systems. The finite element and finite difference methods for vibration analysis of beams and plates are discussed in chapters 12 and 13. The author has briefly introduced non-linear analysis and random vibrations. An outline of computer programs is also included. The book lays emphasis on the application of vibration analysis through examples and exercises. It should prove useful to graduate students.