# Chapter 2. Estimation of Wind Load Effects

Wind forms the predominant source of loads, in tall freestanding structures – like chimneys. The effect of wind on these tall structures can be divided into two components, known respectively as

- along-wind effect
- across-wind effect

Along-wind loads are caused by the 'drag' component of the wind force on the chimney, whereas the across-wind loads are caused by the corresponding 'lift' component. The former is accompanied by 'gust buffetting' causing a dynamic response in the direction of the mean flow, whereas the latter is associated with the phenomenon of 'vortex shedding' which causes the chimney to oscillate in a direction perpendicular to the direction of wind flow. Estimation of wind effects therefore involves the estimation of these two types of loads.

## 2.1 Along Wind Effects

Along-wind effect is due to the direct buffeting action, when the wind acts on the face of a structure. For the purpose of estimation of these loads the chimney is modeled as a cantilever, fixed to the ground. The wind is then modeled to act on the exposed face of the chimney causing predominant moments in the chimney. Additional complications arise from the fact that the wind does not generally blow at a fixed rate. Wind generally blows as gusts. This requires that the corresponding loads, and hence the response be taken as dynamic. True evaluation of the along-wind loads involves modeling the concerned chimney as a bluff body having incident turbulent wind flow. However, the mathematical rigor involved in such an analysis is not acceptable to practicing engineers. Hence most codes use an 'equivalent static' procedure known as the gust factor method. This method is immensely popular and is currently specified in a number of building codes including the IS (IS:4998) code. This process broadly involves the determining of the wind pressure that acts on the chimney due to the bearing on the face of the chimney, a static wind load. This is then amplified using the ‘gust factor’ to take care of the dynamic effects.

This study involves the evaluation of the along-wind loads by using the methods specified in a number of codes like

- CICIND (Model Code for Concrete Chimneys, 1998)
- ACI 307-95
- IS 4998 (Part 1) : 1992

### 2.1.1 Basic Design Wind speed

One of the primary steps to finding the along-wind loads is to get the basic design wind speed. The determination of the effective wind pressure is based on the basic wind speed. The basic wind speed ($V_b$) is defined (by the CICIND code) as the mean hourly wind speed at 10m above the ground level in open flat country without having any obstructions. This means that the wind speed is measured at a height of 10m above the ground at the location of the chimney and is averaged over an hour. The ACI code suggests a wind speed averaged over a period of the order of 20min to 1hr. The IS code however uses the basic wind speed based on peak gust velocity averaged over a short time interval of about three seconds. The value of the basic wind speed must be established by meteorological measurement. Normally though it is not necessary to actually do the measurement for a particular region. The values as suggested from published Wind Maps specified by the codes may be used. Basic wind speeds generally have been worked out for a return period of 50 yrs.

It may me noted that the ACI follows the FPS system and therefore in the following discussion the formulae by the code appear different from the SI system of the other two codes.

### 2.1.2 Wind Profile

Wind flow is retarded by frictional contact with the earth’s surface. The effect of this retardation is diffused by turbulence in wind flow across a region known as the ‘atmospheric boundary layer’. The thickness of this boundary layer depends on the wind speed, terrain roughness and angle of latitude. The rougher the terrain, the more effective the retardation to the mean flow, and hence, greater is the gradient height. The effect of this gradient is the wind flow now assumes a profile that varies with height from 0 at the surface to the maximum at the end of the ‘atmospheric boundary layer’.

The variation of mean wind speed with height Vz is generally described by the power law.

$$V_z = V_b\,(Z / Z_o)^{\alpha} \qquad \textbf{(2.1)}$$

Where $V_z$ is the profile with respect to height. $V_b$ is the basic wind speed, Z is the height above ground level, $Z_o$) is a height of the boundary layer and α is the terrain factor. The values of the various factors are specified by the respective codes.

The CICIND code suggests the following code for the purpose of evaluation of the wind speed profile.

$$V(z) = V_b\,k(z)\,k_t\,k_i \qquad \textbf{(2.2)}$$

Where:

V(z) is the hourly mean wind speed at level z

z is the height above ground level

$V_b$ is the basic wind speed specified

k(z) is given by the equation

$$k(z) = k_s\,(z / 10)^{\alpha} \qquad \textbf{(2.3)}$$

$k_s$ scale factor, equal to 1.0 in open flat country

α is the terrain factor

$k_t$ topographical factor

$k_i$ interference factor

The ACI code gives the following formula for obtaining the Wind profiles

$$V(z) = (1.47)0.78(80/V_R)^{0.09}\,V_R(z/33)^{0.14} \qquad \textbf{(2.4)}$$

Where $V_R$ is the basic wind speed. The equation also converts from the basic wind speed in mph to ft/s as required for the calculations.

The IS:875 however does not give a wind profile but gives a wind velocity at any height $V_z$.

$$V_z = V_b\,k_1\,k_2\,k_3 \qquad \textbf{(2.5)}$$

Where $V_z$ is the required wind speed, $V_b$ is the basic wind speed. $k_1$ is a probability factor (risk), $k_2$ is the terrain, height and structure size factor,$k_3$ is a topography factor. The values of these factors can be gauged from the Tables given in the IS code.

### 2.1.3 Design Wind Pressure

The obtained wind velocities are assumed to act on the face of the chimney. The corresponding pressure on the surface has to be evaluated next. This is done with the help of the drag coefficient. This coefficient is defined in a number of ways in all the codes. The main concept however is that the square of the velocity acting at any point is to be multiplied by this coefficient to get the pressure acting at that point. The coefficient takes into account factors like – slenderness of the column, ribbed quality of the surface, the effect of having a curved surface etc.

The wind pressure then is multiplied with the density of air and the exposed area to get the actual static loads acting on the chimney.

The CICIND code calculates the loads with the following formula

$$w_m(z) = 0.5\, \rho_a\, v(z)^2\, C_D\, d(z) \qquad \textbf{(2.6)}$$

Which is more than just the pressure calculation. However the term $C_D$ refers to the coefficient that depends on the slenderness of the column. The value of this coefficient depends on the h/d ratio and can be obtained from the code. It varies between 0.6 and 0.7 for change in the h/d ratio from 5 to 25. The term $w_m(z)$ is basically the ‘weight’ acting on the cantilever for which it has to be designed.

The Indian code converts the velocity profile into its corresponding pressure profile with the help of the following formula

$$p_z = 0.6\, V_z^2 \qquad \textbf{(2.7)}$$

The value of 0.6 is the drag coefficient specified.

The ACI code suggests a very similar function, however specifying the coefficient to be 0.0013 as opposed to 0.6, mainly to keep it consisting with the FPS system used by the code.

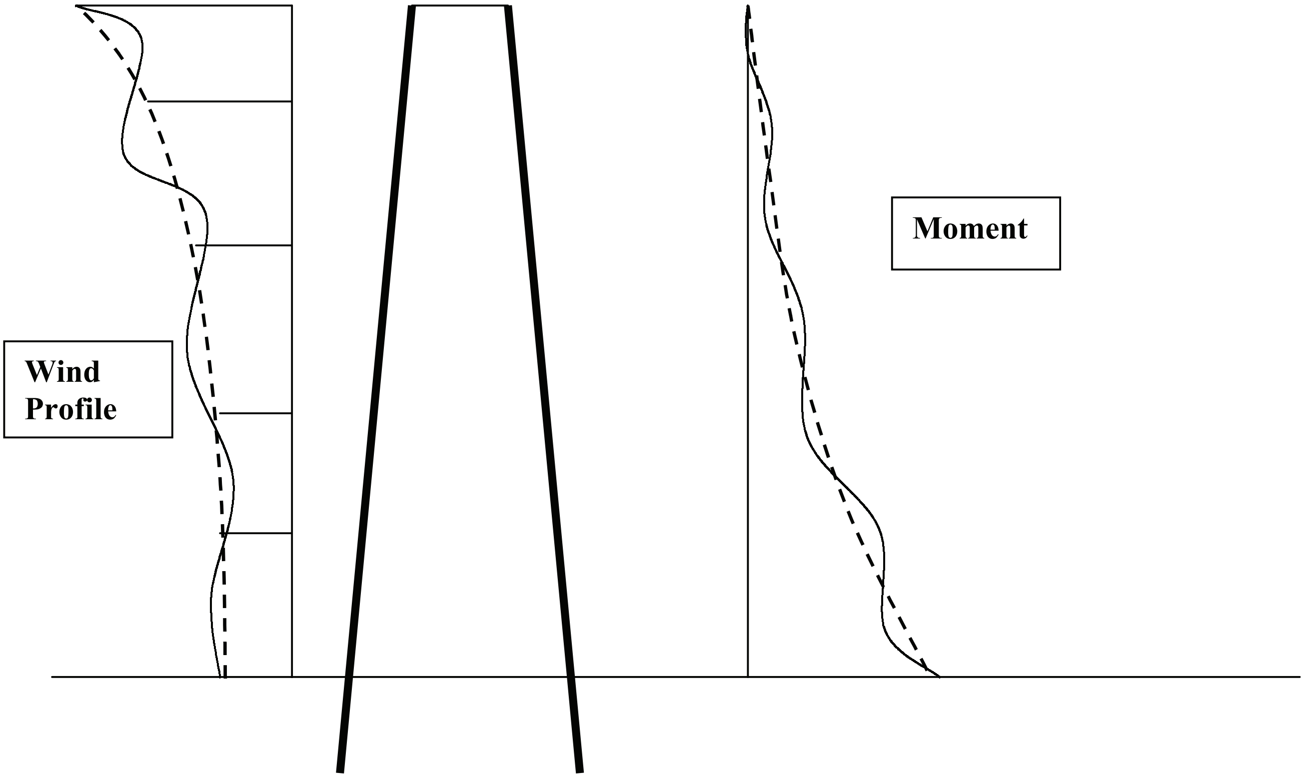


**Figure 2.1 – Wind profile and Response**

### 2.1.4 Force resultants

The pressure values obtained in the earlier case are then converted into the corresponding force values. The chimney is idealized to be a vertical cantilever, fixed to the ground. The load that acts can be takes as a continuous load acting on this cantilever. The calculation of the force resultants of shear and moment are trivial.

In reality the base of the chimney is broad. Hence the shear resisting capacity of the chimney is high. In fact shear also may manifest itself as moment due to the deep beam effect. Hence the more important resultant to calculate here is the moment as compared to either the shear or the axial force.

The moment at any point on the cantilever can be calculated by integrating the moment from the end to that point. Hence the functions given to calculate the moment too are integrals.

The CICIND code gives the following main formula for the purpose of calculation of the gust factor moments in chimneys

$$w_g(z) = \frac{3(G-1)z}{h^2} \int_0^h w_m(z) z dz \qquad \textbf{(2.8)}$$

where

G is the gust factor (will be looked into later)

h is the height of the top of the shell above the ground level

z is the height above the ground level

$w_m(z)$ is the mean hourly wind load per unit height at height z

The IS code gives two methods for the evaluation of along-wind loads on chimneys, both of which are discussed below.

The IS simplified method

This method, as the name suggests, is a simple procedure to come up with the load values for a given configuration. The formula suggested for this method is

$$F_Z = p_Z.C_D.d_Z \qquad \textbf{(2.9)}$$

Where the factor CD is to be taken as 0.8. This is actually a vast simplification of the procedure outlined in the IS:875 which specifies the distribution of the value of the drag coefficient around the periphery of the cylindrical shell. This method however does not take into account the effect of the dynamic quality of the incident wind on the chimney.

The second method given by the code is the random response method. The equations for the same are given below and terms explained. The need and use of the Gust factor however is discussed later.

$$F_{zf} = \frac{3(g-1)}{H^2} \frac{z}{H} \int_0^H F_{zm} z dz \qquad \textbf{(2.10)}$$

Where $F_{zf}$ is the wind load in N/m height due to the fluctuating component of the wind at height z. The whole load is given by

$$F_z = F_{zm} + F_{zf} \tag{2.11}$$

The wind load due to the hourly mean wind component is given by

$$F_{zm} = \overline{p_z} C_D d_z \tag{2.12}$$

where pz gives the design pressure at hourly mean wind component and is pbtained by the equation

$$\overline{p_z} = 0.6\overline{V}^2 z \tag{2.13}$$

In the equation for the fluctuating component of the wind load the gust factor G is used. The equations and the concept involved are discussed later.

The ACI code gives the following code for the purpose of calculation of the along-wind load. This code too divides the load due to the wind into two parts – the mean load and the fluctuating component. The mean load is calculated by the formula

$$\overline{w}(z) = C_{dr}(z) d(z) \overline{p}(z) \tag{2.14}$$

Where the value

$C_{dr}$ = 0.65 for z < h-1.5d(h)

$C_{dr}$ = 1 for z > h-1.5d(h)

And the value of the mean pressure has been given.

The fluctuating load component has been taken equal to

$$w'(z) = \frac{3.0 z G_{w'} M_w(b)}{h^3} \tag{2.15}$$

Where M is the base bending moment due to the constant load acting on the chimney. It is basically an integral of the weight acting on the chimney multiplied with the distance from the base. The Gust factor G is calculated by

$$Gw' = 0.30 + \frac{11.0\left[T_1 \overline{V}(33)\right]^{0.47}}{(h+16)^{0.86}} \tag{2.16}$$

For a preliminary design the Time period of oscillation can be calculated with the help of an equation suggested by the code. However the code requires the time period to be calculated with the help of dynamic analysis for the final design. Analysis here was done by modeling the chimney using a program STRAP.

### 2.1.5 Dynamic Effects and the Gust Factor

All along-wind loads that act on the chimney are not due to the static wing bearing on the surface of the chimney alone. There is a significant change in the applied load due to the inherent fluctuations in the strength of wind that acts on the chimney. It is not possible of feasible to take the maximum load that can ever occur due to wind loads and design the chimney for the same. At the same time it is very difficult to quantify the dynamic effect of the load that is incident on the chimney. Such a process would be very tedious and time consuming. So most of the codes make use of the gust factor to account for this dynamic loading. To simplify the incident load due to the mean wind is calculated and the result is amplified by means of a gust factor to take care of the dynamic nature of the loading.

The gust factor is defined as the ratio of the expected maximum moment $M_0$ to the mean moment $M_{m0}$ at the base of the chimney. It is accordingly denoted as G0 and is referred to as the base gust factor.

The CICIND code gives the following formula for the calculation of the Gust factor.

$$G = 1 + 2gi\sqrt{B + \frac{ES}{\zeta}} \qquad \textbf{(2.17)}$$

Where g is peak factor with

$$g = \sqrt{2\log_e vT} + \frac{0.577}{\sqrt{2\log_e vT}} \qquad \textbf{(2.18)}$$

the turbulence intensity

$$i = 0.311 - 0.089\log_{10} h \qquad \textbf{(2.19)}$$

background turbulence $$B = \left[1 + \left(\frac{h}{265}\right)^{0.63}\right]^{-0.88} \qquad \textbf{(2.20)}$$

energy density spectrum $$E = \frac{123\left(\frac{f_1}{V_b}\right)h^{0.21}}{\left[1+\left(\frac{330f_1}{V_b}\right)^2 h^{0.42}\right]^{0.83}} \qquad \textbf{(2.21)}$$

size reduction factor $$S = \left(1+5.78\left(\frac{f_1}{V_b}\right)^{1.14} h^{0.98}\right)^{-0.88} \qquad \textbf{(2.22)}$$

damping $\zeta$ is a fraction of the critical damping and is taken as 0.016. $f_1$ is the natural frequency in the first mode of vibration.

h is the height of the shell above the ground in m and $V_b$ is the basic wind speed. T is the sample period and v is effective cycling rate.

The equation for the Gust factor used by the ACI code is given earlier.

The IS code probably borrowed its gust factor equation from the CICIND code as both the equations are remarkably similar. Only the names given to some of the factors are different. The factors and the equations themselves are the same

A typical chimney of 250m was chosen to calculate the along-wind loads. The dynamic analysis was done using a structural analysis program called STRAP.

### 2.1.6 Analysis using STRAP

For the purpose of analysis the chimney was modeled in STRAP. The chimney was idealized into 32 components outside the ground and one component inside the ground (to take care of fixity and the effect of the foundation), a total of 33 components. The various components were taken to be cylindrical objects. Hence the chimney was idealized as 33 hollow cylinders stacked upon each other.

The thickness of the components of the chimney were varied according the thickness of the actual chimney at the middle of each section. A fixed joint was assumed after 32 nodes.

For the purpose of dynamic analysis the weight data was calculated by the program itself. This however was strictly not correct because there would be the additional weight of the lining inside the chimney. Hence a lining of a layer of bricks was assumed and the weight calculated by the program was corrected with a factor to account for the weight of the lining. The calculation of the factors was done with the help of a small program that actually calculated the volume ratios for the purpose.

The chimney itself was assumed to be of a standard dimensions and ratios as given below.

| **Attribute** | **Value** |
|---|---|
| Height | 250m |
| Height to Base Diameter | 7 |
| Top Diameter to Base Diameter | 0.6 |
| Base Diameter to base thickness | 35 |
| Top thickness to base thickness | 0.4675 |

**Table 2.1 – Chimney Attributes**

The results of dynamic analysis of the modeled chimney are given below

| Mode | Time Period |
|---|---|
| 1 | 0.2345 |
| 2 | 1.0266 |
| 3 | 2.4826 |
| 4 | 3.6286 |
| 5 | 4.4460 |

**Table 2.2 – Results of dynamic analysis**

These values of time periods of oscillations and the corresponding frequencies (1/Time Period) were used for the calculations of the Gust factor.

### 2.1.7 Expected maximum moments

The moments were calculated for the model chimney assumed earlier and the results are shown in the graph below

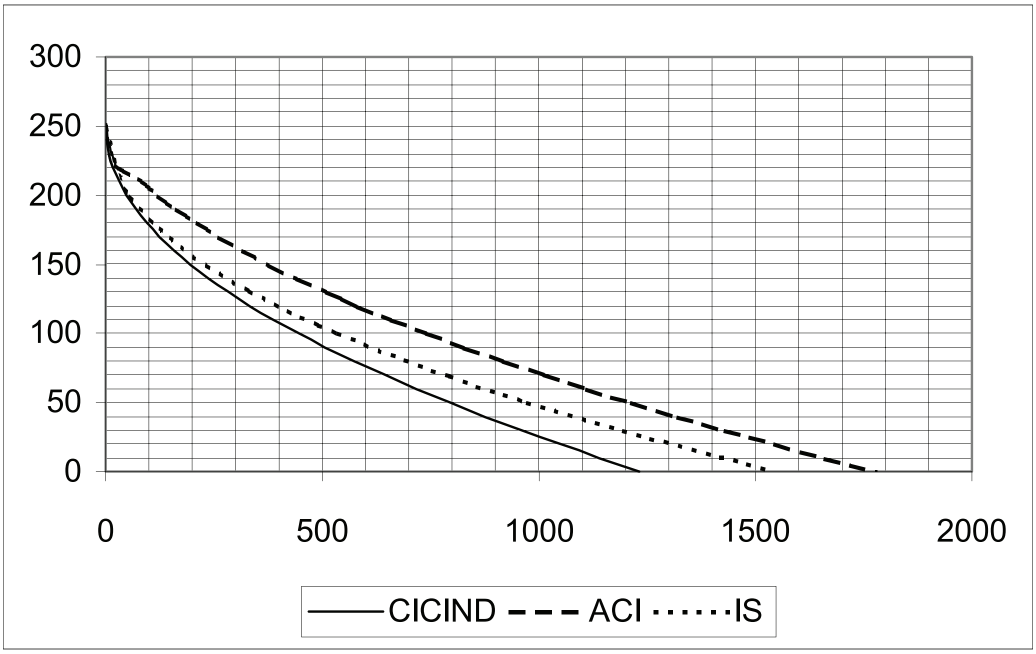


**Figure 2.2 – Moment profiles (comparative)**

As is visible, there is considerable difference in the expected maximum base moments of the chimney using the three codal methods.

Additionally the base gust factors for the three methods are given below

| Code | Base Gust factor |
|---|---|
| IS | 1.85 |
| CICIND | 1.85 |
| ACI | 1.993 |

**Table 2.3 – Base Gust factors (comparative)**

## 2.2 Across Wind Effects

Recommendations for considering the across-wind loads have been included into the codes only recently. In spite of considerable research the problem of accurately predicting the across-wind response has to be fully resolved. Hence the CICIND code does not take into account across-winds. For this study the codes used therefore were the IS 4998(Part 1): 1992 and the ACI 307-95.

A tall body like the chimney is essentially a bluff body as opposed to a streamlines one. The streamlined body causes the oncoming wind flow to go smoothly past it and hence is not exposed to any extra forces. On the other hand the bluff body causes the wind to 'separate' from the body. This separated flow causes high negative regions in the wake region behind the chimney. The wake region is a highly turbulent region that give rise to high speed eddies called vortices. These discrete vortices are shed alternately giving rise to 'lift forces' that act in a direction perpendicular to the incident wind direction.

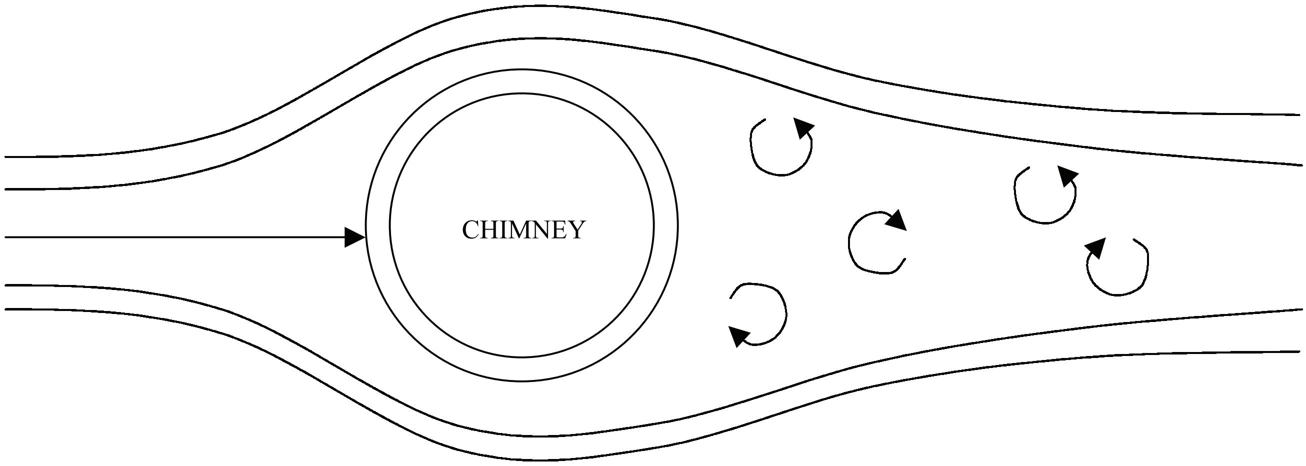


**Figure 2.3 – Across wind effect**

These lift forces cause the chimney to oscillate in a direction perpendicular to the wind flow.

### 2.2.1 Vortex Shedding

The phenomena of alternately shedding the vortices formed in the wake region is called vortex shedding. This is the phenomena that gives rise to the across-wind forces.

This phenomena was reported by Strouhal, who showed that shedding from a circular cylinder in a laminar flow is describable in terms a non-dimensional number $S_n$ called the Strouhal number.

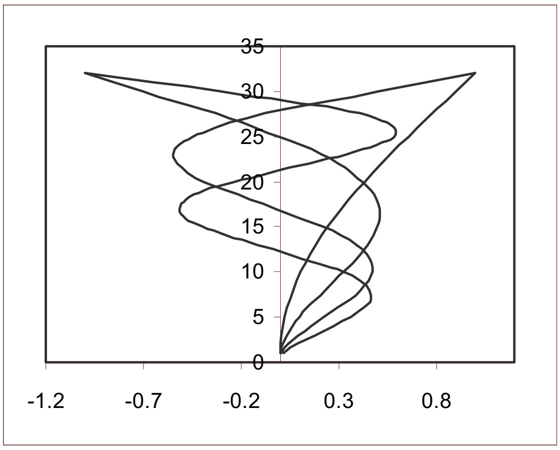
$$S_n = \frac{shedding\_frequency \times diameter\_of\_cylinder}{mean\_flow\_velocity} \quad \textbf{(2.23)}$$

The phenomena of vortex shedding and hence the across-wind loads depends on a number of factors including wind velocity, taper factors etc., that are specified by the codes. Codal estimation of the across-wind loads also involves the estimation of the mode-shape of the chimney in various modes of vibration. This is obtained as follows.

### 2.2.2 Chimney Modeling and estimation of shape factor and time period

As discussed earlier dynamic analysis of the chimney was done using the structural analysis program STRAP. A model chimney with the parameters shown earlier was modeled and dynamic analysis performed on it. The required mode shapes were obtained from the program itself.

The results from the analysis are given below with the normalized mode shapes on the left and the corresponding frequencies of vibration on the right. It may be noted that although four mode shapes have been assumed for the purpose of analysis, in reality only the first two modes are actually active. This is because the wind velocity required to make the chimney vibrate in higher mode shapes is very high.



Mode shapes 1 to 4

Frequencies:

Mode 1: 0.2345 hz

Mode 2: 1.0266 hz

Mode 3: 2.4826 hz

Mode 4: 3.6286 hz

**Figure 2.4 – Mode shapes**

### 2.2.3 Estimation of Moments

The various codal methods for the purpose of estimation of along-wind loads are as follows.

The IS code, gives two methods for the estimation of across-wind loads. These are called respectively the simplified method and the random response method. The amplitude of the vortex excited oscillation is to be calculated by the equation.

$$\eta_{oi} = \left\{ \frac{\int_0^H d_z \phi_{zi} dz}{\int_0^H \phi^2{}_{zi} dz} \right\} \times \frac{C_L}{4\pi S_{2n} K_{si}} \tag{2.24}$$

Where $\eta_{oi}$ is the peak tip deflection due to vortex shedding in the $i_{th}$ mode of vibration in m, $C_L = 0.16$, H is the height in meters, $K_{si}$ is the damping parameter for the $i^{th}$ more of vibration, $S_n$ strouhal number = 0.2 and $\Phi_{zi}$ is the normalized mode shape.

Calculations of oscillation calculated using this formula are acceptable till 4 percent of the effective diameter. For values more that this the resultant is amplified using a given formula.

Once this value is obtained the sectional shear force $F_{zoi}$ and Bending moment $M_{zoi}$ at any height zo for the $i_{th}$ mode of vibration, as obtained as follows.

$$F_{zoi} = 4\pi^2 f_1^2 \eta_{oi} \int_{zo}^{H} m_z \phi_{zi} dz \tag{2.25}$$

$$F_{zoi} = 4\pi^2 f_1^2 \eta_{oi} \int_{zo}^{H} m_z \phi_{zi} dz \tag{2.26}$$

Where $f_i$ is the natural frequency in the $i_{th}$ mode of vibration and $m_z$ is the mass per unit length of the chimney at section z in kg/m.

The mass damping factor Ksi required for the earlier equation is calculated using the formula

$$K_{si} = \frac{2 m_{ei} \delta_s}{\sigma d^2} \tag{2.27}$$

$m_{ei}$ is the equivalent mass per unit length in kg/m in the $i^{th}$ mode of vibration, $\delta_s = 2\pi\beta$, and $\beta = 0.016$ (structural damping factor), $\sigma$ is the mass density of air taken as 1.2 kg/m$^3$ and d is the effective diameter taken as average diameter over the top 1/3 height of the chimney in m.

The equivalent mass per unit length in the i$^{th}$ mode of vibration can be calculated using the formula given below. It is basically dependant on the amount of mass that is available given the mode shape.

$$m_{ei} = \frac{\int_0^H m_z \phi^2{}_{zi} dz}{\int_0^H \phi^2{}_{zi} dz} \qquad \textbf{(2.28)}$$

The oscillation is caused by the wind. The mode in which the chimney vibrates is decided by the wind speed. Higher modes need a higher wind speed for excitation. Hence it is possible to know the wind velocities that causes shedding in the i$^{th}$ mode. It is done with the help of the following equation.

$$V_{cri} = \frac{f_1 d}{S_n} \qquad \textbf{(2.29)}$$

Since higher wind speeds are required to excite higher modes of vibration, it is not necessary to consider all the modes of vibration for the purpose of design. All modes which can be excited up to wind speeds of 10 percent above the maximum expected at the height of the effective diameter shall be considered for subsequent analysis. If the critical winds for any mode of vibration, exceeds the limits specified earlier, the code allows the assumption that the problem of vortex excited resonance will not be a design criteria for that and higher modes. In these cases across-wind analysis may not be required.

The across-wind analysis using the random response method is also specified by the code. The relevant expressions are given for chimneys of two types – those with little or no taper and those with significant taper. Taper is defined as

$$taper = \frac{2(d_{av} - d_{top})}{H} \qquad \textbf{(2.30)}$$

When the value of the taper is less than 1 in 50 (or 2 percent) the chimney is said to have little taper.

For chimneys with little or no taper, the expression to calculate the modal response at critical wind speed as given in equation 2.24 earlier

$$\eta_{oi}=\frac{\dfrac{1.25C_L d\phi H_1}{\pi^2 S^2{}_n}\times\dfrac{\sigma d^2\sqrt{\left\{\dfrac{\sqrt{\pi L}}{2(\cap+2)}\right\}}}{m_{ei}}}{\sqrt{\dfrac{1}{H}\int\phi^2{}_{zi}dz}\sqrt{\beta-\dfrac{k_a\sigma d^2}{m_{ei}}}} \qquad \textbf{(2.31)}$$

Where the RMS lift coefficient is taken as 0.12, correlation length in diameters is taken as 1.0 and the aerodynamic damping coefficient is taken as 0.5.

Chimneys that are significantly tapered have the following equation

$$\eta_{oi}=\frac{\sigma\overline{C_L}d^4{}_{ze}\phi_{zei}\phi H_1\sqrt{\dfrac{\pi L}{2t}}}{2\pi^2 S^2 m_{ei}\int_0^H\phi^2{}_{zi}d_{zi}\sqrt{\dfrac{\beta-k_a\sigma d^2}{m_{ei}}}} \qquad \textbf{(2.32)}$$

Where $z_{ei}$ is the height in m at which a given expression is maximum in the $i^{th}$ mode of vibration. The term $\alpha$ in the expression is the power law exponent which was discussed earlier with respect to the wind profiles. The value of this depends on the Terrain Category and varies from 0.10 to 0.34.

The critical wind speed for exciting the mode of vibration is determined by the equation.

$$V_{cri}=\frac{f_1 d_{ze\,i}}{S_n} \qquad \textbf{(2.33)}$$

Calculations begin by first taking $z_{ei}$ =H and progressively decreasing till a maximum in $\eta_{oi}$ is observed. Also if the required velocity for excitation in any mode is greater than the maximum velocity, the chimney will not be assumed to experience much across-wind loads in that and higher modes. If this applies to the first mode of vibration itself then the chimney has negligible across-wind loads.

The ACI code considers the across-wind loads due to vortex shedding for in the design of chimneys when the critical velocity is between 0.5 and 1.3 $V_{zcr}$. Across-wind loads are not considered outside this range.

Te critical velocity is calculated using the function.

$$V_{cr}=\frac{fd(u)}{S_t} \qquad \textbf{(2.34)}$$

Where the $S_t$ is the Strouhal number and is calculated using

$$S_t = 0.25\left(0.333 + 0.206\log_e \frac{h}{d(u)}\right) \tag{2.35}$$

d(u) is the mean outside diameter of the upper 1/3 of the chimney in feet, and h is the height above the ground level.

The peak base moment at the critical velocity if determined by the equation.

$$M_a = \frac{G}{g} S_S C_L \frac{\rho a}{2} V^2{}_{cr} d(u) h^2 \bullet \sqrt{\frac{\pi}{4(\beta_s + \beta_a)}} \bullet S_p \sqrt{\frac{2L}{\left[\frac{h}{d(u)} + C_E\right]}} \tag{2.36}$$

$M_a$ is evaluated over a range of wind speeds in the specified range of 0.5 to 1.3 $V_{cr}$ to determine the maximum response. For values of velocity greater than $V_{cr}$ the value of $M_a$ is multiplied with

$$\left\{1.4 - \frac{4}{3}\left[\frac{\overline{V} - \overline{V}(z_{cr})}{\overline{V}(z_{cr})}\right]\right\}\frac{1}{1.4} \tag{2.37}$$

The values of the various terms are given in the code including the peak factor, mode shape factor and specific gravity of air.

The code also gives a formula for the calculation of the time period in the second mode of vibration, although the final design needs a dynamic analysis. The values obtained from the STRAP program were used in this calculations.

The results of the analysis are given below

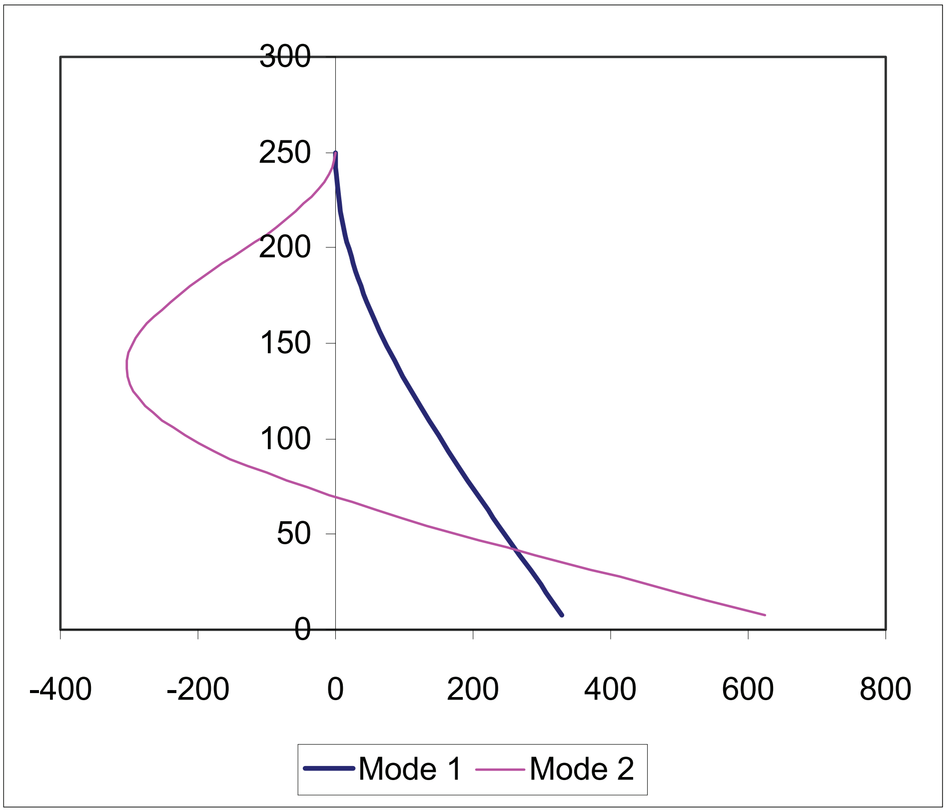
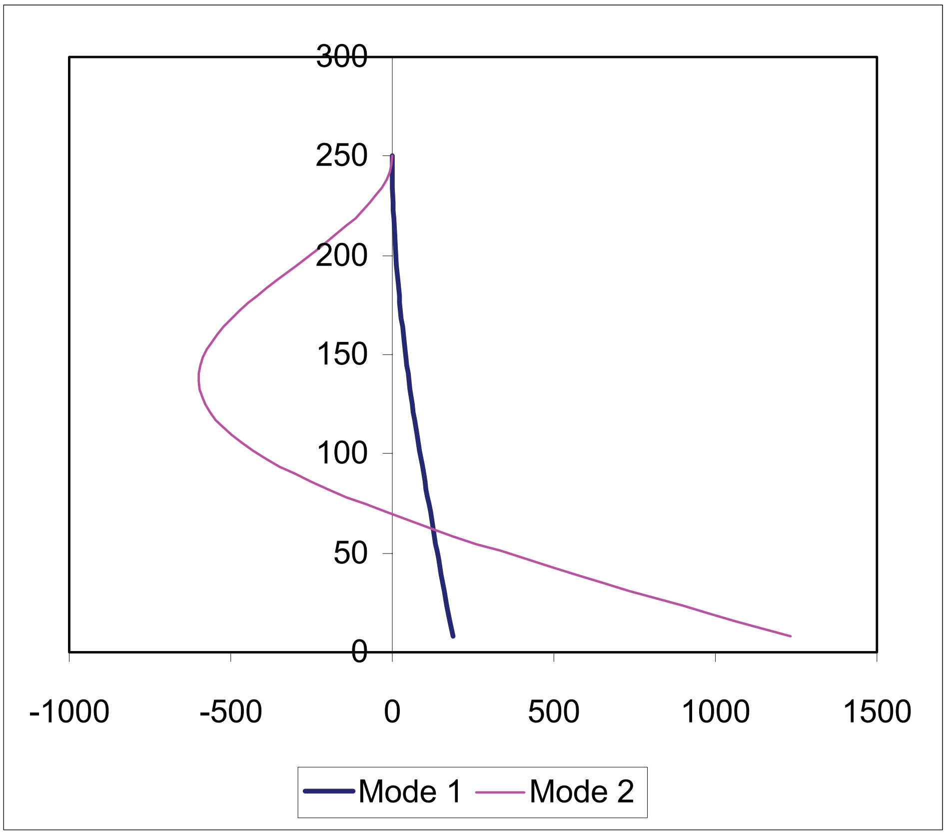


**Figure 2.5 – IS Simplified method & Figure 2.6 – IS Random Response Method**



The first graph refers to the result of the IS simplified method, whereas the second graph refers to the IS Random response method.

As can be seen from the graph the moments in the first mode of vibration are very similar for both the methods of calculation, whereas the moments for the second mode of vibration vary a lot. The moments obtained from the Random response method are almost double that obtained using the simplified method. In fact the Random response method given higher moments for the second mode of vibration and lower moments for the first mode of vibration, as compared to the simplified method.

The base moments as calculated using the ACI method are given below

| *(All values MNm)* | **Across-wind** | **Along-wind** | **Gust Factor** | **Max Moment** |
|---|---|---|---|---|
| **Mode 1** | 125.46 | 432.98 | 1.8854 | 825.922 |
| **Mode 2** | 98.86 | 432.98 | 1.592 | 696.56 |

**Table 2.4 – Base Moments (ACI)**

It is seen that the values obtained using the ACI method are very small as compared to the IS method. This is especially true of the across-wind loads.

## 2.2. Variation of moments with change in H by D ratio

An analysis was done to find the change in across-wind loads with change in **Height** to **Base diameter** ratio.

For the purpose of the Analysis, Chimneys with the following parameters were used

Height : 250 m
Height to Base diameter Ratio : 7, 9, 11, 12, 13, 15, 17
Top diameter to Base diameter Ratio : 0.6
Base diameter to Base thickness Ratio : 35
Top thickness to Base thickness Ratio : 0.4675

The following methods were employed for the same

1. IS Approximate Method
2. IS Random Response Method
3. ACI – 95 Method (Also CICIND approved)

Estimation of Free Vibration parameters like the **mode-shapes** the free **frequency** and the **Weight data** for the calculations were calculated by modeling the chimney in STRAP. The modeling was done with the chimney broken down into 32 elements. Vibration Analysis was done for modes 1 to 5 but only the first two were required for the purpose of Moment calculations.

### 2.2.5 Conclusions from the variational analysis

- The Across-Wind Moments were inversely proportional to the H by D Ratio. The Moments consistently increased with fall in the H/D Ratio for all methods of estimation.
- The Approximate method of the IS code gave consistently **higher** moments as compared to the Random Response Method for vibrations in the **first** mode.
- The Approximate method of the IS code gave consistently **lower** moments as compared to the Random Response Method for vibrations in the **second** mode.
- The IS method gave higher moments in the second mode of vibration as compared to the first mode in both its methods.
- The ACI method gave very small values as compared to the IS methods for the base moment in all cases
- Anomalously the moments in the second mode were lower in the ACI method as compared to those in the first mode.

All relevant Data can be found in the subsequent pages. It may be noted that the higher moment curves correspond to lower H/D ratio.

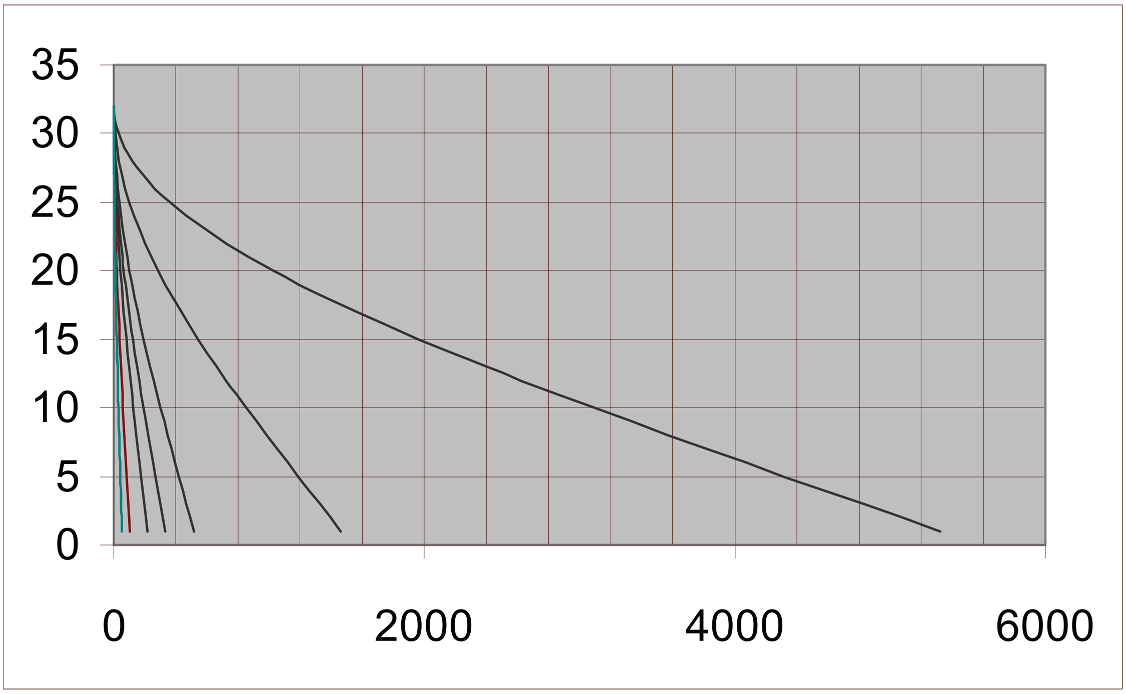


Figure 2.7 – IS Approximate Method – Mode 1

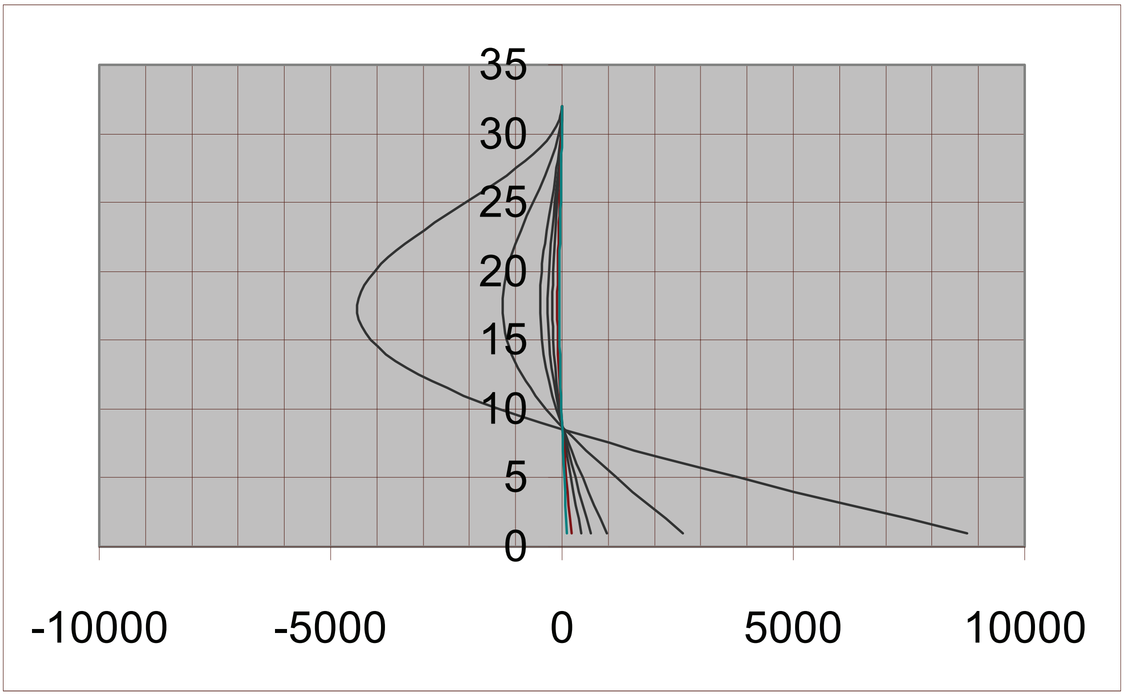


Figure 2.8 IS Approximate Method – Mode 2

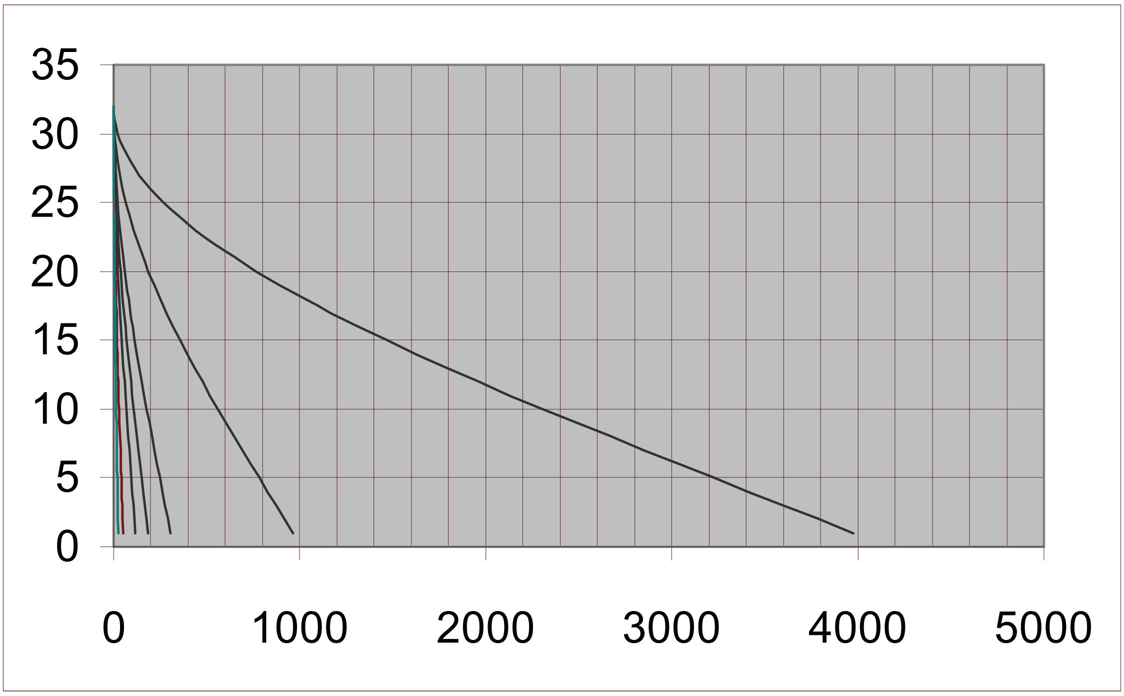


Figure 2.9 IS Random Response Method – Mode 1

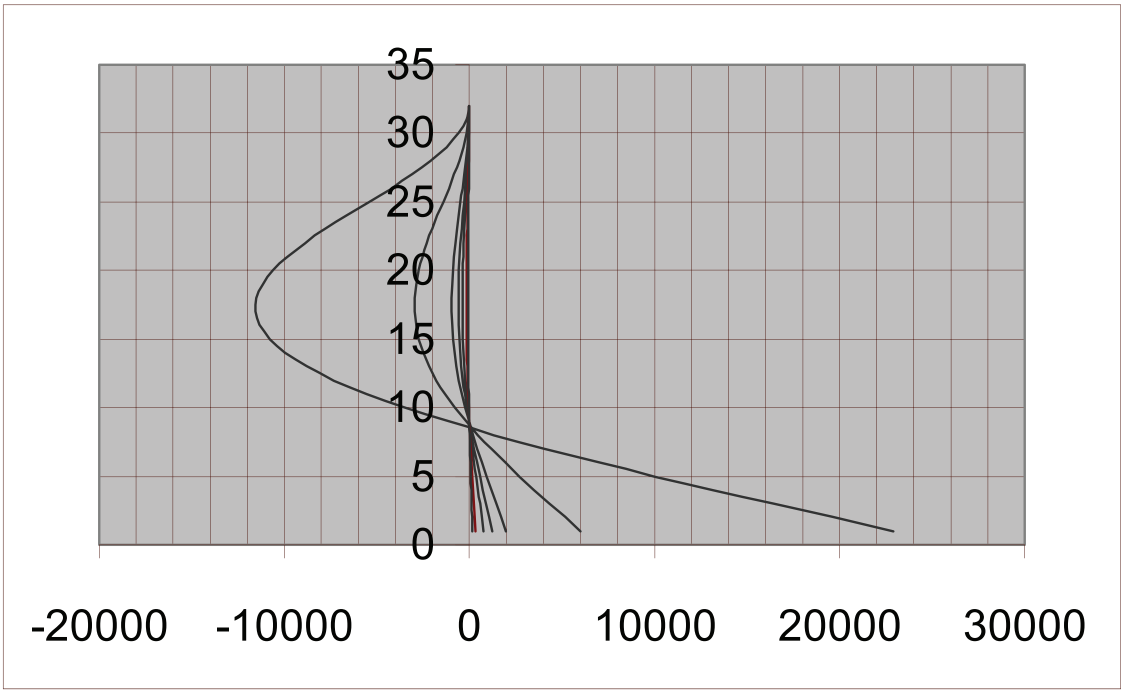


Figure 2.10 IS Random Response Method – Mode 2

| H/d | 7 | 9 | 11 | 12 | 13 | 15 | 17 |
|---|---|---|---|---|---|---|---|
| **Mode 1** | 641.15 | 340.566 | 204.425 | 144.783 | 114.783 | 77.271 | 55.244 |
| **Mode 2** | 411.482 | 225.483 | 142.764 | 107.867 | 87.404 | 59.786 | 42.523 |

**Table 2.5 ACI Method (all modes)**

Conclusion

The wind loads form the major sources for moments on Tall free standing structures like chimneys. We have looked at the two kinds on wind-loads that act on chimneys and also have presented the calculations for a standard chimney.