A PARAMETRIC STUDY ON LATERAL LOAD RESISTANCE OF STEEL CHIMNEYS

M. Pavan Kumar
Assistant Professor of Civil Engineering, SVP Engineering College,
Visakhapatnam, Andhra Pradesh, India

P. Markandeya Raju
Professor of Civil Engineering, MVGR College of Engineering (A),
Vizianagaram, Andhra Pradesh, India

N. Victor Babu
Professor of Civil Engineering, Baba Institute of Technology and Sciences,
Visakhapatnam, Andhra Pradesh, India

K. Roopesh
Post Graduate Student of Structural Engineering,
Baba Institute of Technology and Sciences, Visakhapatnam,
Andhra Pradesh, India

ABSTRACT
This paper presents a computer aided investigation on the seismic and wind effects on chimneys of different heights in the Indian scenario. Self-supporting steel stacks (provided as chimneys) of overall height 90m and 110m subjected to wind and seismic loads are considered in this study. The chimneys are analyzed using STAAD.Pro software for seismic Zones II, III, IV and V and wind loads of basic wind speeds 39m/sec, 44m/sec, 49m/sec, and 50m/sec. Maximum shear force and bending moments developed in the steel stacks along with lateral displacements and mode shapes are determined and compared to study the structural response of steel stacks.

Keywords: Chimney, Wind Speeds, Seismic Loads, Steel, IS 800 2007, STAAD.Pro;

1. INTRODUCTION

Chimneys are very important industrial structures adopted for the emission of poisonous gases or smoke at higher altitudes. They are designed as vertical or nearly vertical structures to ensure smooth flow of gases. Industrial chimneys are commonly referred to as flue gas stacks. The height of the chimney is based on the ability required to transfer flue gases to the external environment through stack effect. Chimneys are constructed at least 5m taller than the tallest building in surrounding area of 150m radius. Different materials such as steel, concrete and bricks are used for the construction of chimneys.

Steel chimney can be designed as one of the following two types.

(a) Self-supporting steel chimneys: Lateral forces (wind or seismic forces) are transmitted to the foundation by the cantilever action of the chimney.

(b) Guyed steel chimneys: The mild steel wire ropes or guys are attached to transmit the lateral forces to ground to ensure the stability of the guyed steel chimney.

Many researchers studied the performance of chimneys under the action of lateral loads. Par Tranvik et.al. (2007) [1]studied the structural behavior of the 90 m height VEAB steel chimney in southern Sweden. The authors observed fatigue cracks before nine months of service. The authors investigated the cause of failure by regularly observing and collecting measurements of the chimney. The chimney was found to oscillate in both first and second mode of natural frequency. Raj Kumar et.al. (2011) [2]design self-supported chimneys of different heights varying from 150m to 250m in two different earthquake zones, Zone 2 and 5.Hard and soft soils were considered for study while varying wind speeds from 33m/s to 55m/s. It was concluded from the study that that stresses induced in zone 5 are almost equal to stresses induced at minimum wind speed 33m/s. Murali (2012)[3]dealt with the study of three chimneys of 55m high above ground level designed as per IS 6533 (Part 2) 1989[4]. Wind load was calculated as per IS: 875 (Part 3) 1987 [5].Three different wind speeds were considered for the design of chimneys viz., 47m/s, 50m/s and 55m/s respectively. The results indicated that the thickness of chimney remains same irrespective of the wind speed considered. Sivakonda Reddy et. al. (2013) [6]studied the effect of wind on 275m tall chimneys for I and VI wind zones of India. The results indicate that in shell completed condition, for zone I (i.e. basic wind speed 33m/s) across winds are governing and for highest wind zone of VI (i.e. basic wind speed 55m/s), along wind loads are governing. The analysis is carried out using STAAD.Proand MS EXCEL spreadsheets. AnilPradeep et.al, (2014) [7]has analyzed the 60m reinforced concrete chimney. Comparison has been made for wind and seismic analysis. Seismic analysis is done as per IS 1893(Part 4) 2005 [8] and wind analysis as per Draft Code CED38 (7892):2013. It is concluded that as zone factor increases, the magnitude of shear force and bending moment also increases. Rakshit et. al. (2015) [9]analyzed a cantilever steel chimney as per Indian standards with an objective to explain the importance of geometrical limitations in the design of cantilever steel chimney. The authors summarized the analysis and design concepts of chimneys as per Indian code provisions and incorporated them through finite element analysis. The effect of inspection manhole on the behavior of cantilever steel chimney was also studied by considering two chimney models, one with the manhole and other without manhole.Agar et. al. (2015) [10]conducted an analytical study on the performance based seismic evaluation of industrial chimneys by static and dynamic analysis. Linear static and dynamic analysis of RC and steel chimneys having height 65m were performed using SAP2000. The effect of zone on base shear, maximum lateral displacement, fundamental time period and frequency was studied by comparing the results of all the zones. Deflection at the free end of chimney is observed to be within the permissible limits of 0.003h for both the RC and steel chimney. It was concluded from this study that steel chimney is more economical in all aspects compared to RC chimney.
Saran Kumar et.al. (2015) [11] conducted an analytical study on the wind analysis and vortex shedding effect on steel chimney using computational fluid dynamics. Vortex shedding is phenomenon that occurs when air or fluid at certain velocity past a cylindrical body forms an oscillating flow that depends on the size and shape of the body. Reynolds number is used to predict fluid flow pattern. In this study, five models of chimneys with different heights and diameters at top and bottom, were designed as per IS 6533 (Part 2) 1989 [4] and wind load are calculated as per IS: 875 (Part 3) 1987 [5]. The study on the vortex shedding effect on different chimney models reveals that the wind induced vibration in the tall chimneys varies with respect to height. Chmielewski et. al. (2005) [12] studied the natural frequencies and natural modes of 250 m high multi-flue industrial RC chimney with the flexibility of soil and used finite element method for analysis. Also, experimental work to investigate the free vibration response is carried out by using two geophone sensors and experimental results are compared with analytical results. The results show that the soil flexibility under the foundation influences the natural frequency and natural time periods of vibration of the chimney by considerable margin. Yoganatham et.al. (2013) [13] opined that the analysis and design of chimneys are normally governed by wind are earthquake load. In this paper modal analysis of a RCC chimney in a cement factory is carried out using the FEM software package ANSYS. The effect of change in the dimensions of the chimney on the modal parameters such as fundamental frequency, displacement etc. are evaluated.

From the review of literature, it is observed that few studies have been conducted on the wind and seismic performance of Chimneys in the Indian scenario.

2. METHODOLOGY

2.1. General

The basic objective of this study is to investigate the seismic behavior and wind effects on chimneys in various seismic and wind zones of India. For this study, a hypothetical case of two Self-supporting steel stack chimneys of height 90m and 110m subjected to wind and seismic loads are considered as the chimney. The chimneys are considered to be of fixed base for the purpose of modeling. Methodology of the present study is discussed in the following sections.

2.2. Geometrical configuration details of steel stack

Two Self-supported steel chimney of heights 90m and 110m are designed as per Indian Standard codes IS 6533 (Part 1and 2): 1989 [14, 4] in seismic zones II, III, IV, and V for wind speeds 39m/s, 44m/s, 47m/s, and 50m/s.

The design parameters of the steel stack for 90m height are presented here.

Design Parameters considered

The top diameters of the chimneys are calculated as per IS 6533(Part 1) 1989[14]. The flare heights and the bottom diameters of the chimney are calculated as per IS 6533 (Part 2) 1989[4], Clause 7.2.3and 7.2.4. The relevant calculations are presented below.

Total height of chimney, \( h = 90 \) m

Flare height of the chimney, \( h_f = (1/3) \times 90 = 30 \) m

Top diameter of chimney, \( D = 3.5 \) m

Flare diameter of chimney, \( D_f = 1.6 \times 3.5 = 5.6 \) m

Total height of chimney, \( h = 110 \) m

Flare height of the chimney, \( h_f = (1/3) \times 110 = 40 \) m
Top diameter of chimney, \( D = 4.5 \) m  
Flare diameter of chimney, \( D_f = 1.6 \times 4.5 = 7.5 \) m  
Figures 1(a) and 1(b) show the geometry of 90m and 110m chimneys adopted for this study.

![Figure 1(a) 90 m Chimney](image1.png)  
![Figure 1(b) 110 m Chimney](image2.png)

Total 8 chimneys are considered for this study. The chimneys are lined with stainless steel whose unit weight is 78.5kN/m\(^3\). The chimney shells are categorized into 9 segments of each 10m along the height for calculation purpose.

General geometric details of the chimney are presented here.

**Height - 90m**

- Diameter of the chimney at bottom: 5.6 m  
- Diameter of the chimney at top: 3.5 m  
- Flare height: 30 m  
- Height of stack: 60 m

**Height - 110m**

- Diameter of the chimney at bottom: 7.5 m  
- Diameter of the chimney at top: 4.5 m  
- Flare height: 40 m  
- Height of stack: 70 m

**2.3. Material Properties**

The material properties of the material of the chimney are considered for all calculations as given below.

- Density of steel = 78.5kN/m\(^3\)  
- Yield stress of steel = 250kN/m\(^3\)  
- Poisson’s ratio = 0.3  
- Strain in elastic range = 0.2%  
- Modulus of Elasticity (E) of steel = 200000×10\(^6\)N/m\(^2\)
2.4. Loads acting on the steel chimney
Self-supporting steel chimneys experience various loads in both vertical and lateral displacements. Important loads that a steel chimney often experiences are wind loads, seismic loads, and temperature loads apart from self-weight, loads from the attachments, and imposed loads on service platforms.

The loads considered in this study are Self-weight of chimney, Wind loads and Seismic loads.

2.4.1. Self-weight
Self-weight of chimney is calculated as per IS 875(Part 1): 1987.

2.4.2. Wind loads
Wind effect plays an important role on chimneys as they are tall structures. For self-supported steel chimneys, wind is considered as major load.

Wind loads are designed as per IS 875(Part 3): 2015.

Design wind speed can be calculated as,

\[ V_z = V_b \times k_1 \times k_2 \times k_3 \times k_4 \]

Where,
- \( V_z \) = Design wind speed at any height \( z \) in m/s.
- \( V_b \) = Basic wind speed
- \( k_1 \) = Probability factor (Risk coefficient)
- \( k_2 \) = Terrain height and structure size factor
- \( k_3 \) = Topography factor
- \( k_4 \) = Importance factor for cyclonic region

Design wind pressure,

\[ p_z = 0.6 \times V_z^2 \]

Where,
- \( p_z \) = Design wind pressure in N/m² at height \( z \)
- \( V_z \) = Design wind velocity in m/s at height \( z \)

Wind force,

\[ P = K \times p_z \times A \]

Where,
- \( P \) = wind force in N
- \( K \) = shape factor for chimney (0.7)
- \( A \) = projected area of chimney in m²

2.4.3. Seismic loads
Seismic load is a major consideration for chimney as it is a natural load. This load is normally dynamic in nature. Seismic force is estimated as cyclic in nature for short period. For designing earthquake resistant structures, it is necessary to evaluate the structural response to ground motion and calculate respective shear force and bending moments. A structure may be considered serviceable if it is able to fulfil its operational functions for which it was designed.

Earthquake loads are designed as per the code IS 1893(Part 4): 2005.
The fundamental time period of vibration for stack-like structures is,

\[ T = C_T \sqrt{ \frac{W_t h}{E_s A g}} \]


Where,
- \( C_T \) = Coefficient depending on slenderness ratio of the structure
- \( W_t \) = Total weight of the structure including lining weight,
- \( A \) = Area of cross-section at the base of the structural shell
- \( h \) = Total height of the structure
- \( E_s \) = Modulus of elasticity of material of the structural shell
- \( g \) = Acceleration due to gravity

Horizontal seismic force

By using the fundamental time period \( T \), horizontal seismic force \( A_h \) can be obtained.

\[ A_h = \left( \frac{Z}{2} \right) \times \left( \frac{S_a}{g} \right) \times \left( \frac{I}{R} \right) \]

as per IS code 1893(Part1)2002 Clause 6.4.2.

Where,
- \( A_h \) = Horizontal seismic coefficient
- \( Z \) = Zone factor as given in IS 1893:2005 (Part 1),
- \( I \) = Importance factor as given in1893:2005 (Part 2)
- \( R \) = Response reduction factor as given in 1893:2005 (Part 4)
- \( S_a / g \) = Spectral acceleration coefficient.

**Design shear force and bending moment**

Either the simplified method or Dynamic repose spectrum modal analysis method is recommended for calculating seismic forces developed on this structure.

The shear force \( V \), and the design bending moment \( M \) shall be calculated by the following formulae.

Shear force,

\[ V = C_v \times A_h \times W_t \times D_v \]

Bending moment,

\[ M = A_h \times W_t \times h \times D \]

Where,
- \( C_v \) = Coefficient of shear force depending on slenderness ratio.
- \( A_h \) = Horizontal seismic coefficient
- \( W_t \) = Total weight of structure including lining weight
- \( h \) = Height of centre of gravity of structure above base
- \( D_v \), \( D_m \) = Distribution factors for shear and moment

**2.5. Load Combinations**

The various load combinations considered while designing the steel chimneys in STAAD.ProV8i are: as per IS 6533 (Part 2) 1989[4].

1.5× (DL+EQ(X))
1.5× (DL+EQ(-X))
1.5×(DL+EQ(Y))
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1.5× (DL+EQ(-Y))
1.5× (DL+WL(X))
1.5× (DL+WL(-X))
1.5× (DL+WL(Y))
1.5× (DL+WL(-Y))

Where,
DL = Dead load
EQ(X) = Earthquake load in horizontal direction
EQ(Y) = Earthquake load in vertical direction
WL(X) = Wind load in horizontal direction
WL(Y) = Wind load in vertical direction

2.6. Response Spectrum Method
In order to perform the seismic analysis and design of a structure to be built at a particular location, the actual time history record is required. However, it is not possible to have such records at each and every location. Further, the seismic analysis of structures cannot be carried out simply based on the peak value of the ground acceleration as the response of the structure depend upon the frequency content of ground motion and its own dynamic properties. To overcome the above difficulties, earthquake response spectrum is the most popular method in the seismic analysis of structures. There are computational advantages in using the response spectrum method of seismic analysis for prediction of displacements and member forces in structural systems. The method involves the calculation of only the maximum values of the displacements and member forces in each mode of vibration using smooth design spectra that are the average of several earthquake motions. Depending upon the type of resonance, three types of response spectra are identified namely acceleration, velocity and displacement. If the response of a single degree of freedom system to earthquake is studied in detail, the response of a system with multi degrees of freedom can found. Mass having a comparatively shorter natural period T vibrates rapidly, that of longer natural period T vibrates slowly. The method that is used for the analysis of chimneys is Response spectrum method. The nodal points that are considered while designing the chimney in STAAD. Pro are shown.

3. RESULTS AND DISCUSSION

3.1. General
For modeling, the chimney is considered fixed at the bottom and free on the top. Seismic and wind loads are applied with different combinations and all the displacements, shear force and bending moments are recorded from the post-processor of STAAD.Pro software. The behavior of a self-supporting steel chimney in terms of Nodal displacement at various heights, shear force and bending moment at each segment of a chimney is observed from the results.

3.2. Lateral Displacements
The nodal displacements due to both seismic loads and wind loads for chimneys of heights 90m and 110m have been analyzed for various earthquake zones and wind speeds and the values obtained are tabulated and plotted in the graph as shown below. All the displacement values were taken from the post-processor of STAAD.Pro software.
Figure 2 presents the comparison of lateral displacements due to Wind loads for a chimney of height 90m in 4 wind speeds. From the Figure 2, an increase in percentage of lateral displacement by 39.87, 60.50 and 72.46 for zones III, IV and V respectively when compared to zone II are observed. It is also observed that the lateral displacement at the top of steel stacks for all the seismic zones are in the permissible limit (0.004 × 90=0.36m or 360mm) as per IS 1893(Part 1)2002 Clause 7.11.1.

Figure 2 Lateral displacements due to Seismic loads for a 90 m height chimney in 4 seismic zones

Figure 3 presents the comparison of lateral displacements due to Wind loads for a chimney of height 90m in 4 wind speeds.

Figure 3 Comparison of lateral displacements due to Wind loads for a chimney of height 90m in 4 basic wind speeds.
From the Figure 3, an increase in percentage of lateral displacements by 3.14, 6.23 and 10.58 for basic wind speeds of 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to 39m/sec. It is also observed that the lateral displacement at the top of steel stacks for all the wind speeds are in the permissible limit (h/200=90/200=0.45 or 450mm) as per IS code IS 6533 (Part 2)1989 Clause 7.4.

Figure 4 presents the comparison of lateral displacements due to Seismic loads for a chimney of height 110m in 4 zones.

![Figure 4](image)

**Figure 4** Comparison of lateral displacements due to Seismic loads for a chimney of height 110m in 4 seismic zones

From the Figure 4, an increase in percentage of lateral displacements by 44.00, 58.33 and 72.64 for zones III, IV and V respectively is observed when compared to zone II. It is also observed that the lateral displacement at the top of steel stacks for all the seismic zones are in the permissible limit (0.004×110=0.99m or 440mm) as per IS code IS 1893 (Part 1)2002 clause 7.11.1.

Figure 5 presents comparison of lateral displacements due to Wind loads for a chimney of height 110m in 4 wind speeds.

![Figure 5](image)

**Figure 5** Comparison of lateral displacements due to Wind loads for a chimney of height 110m in 4 basic wind speeds.
From the Figure 5, an increase in percentage of lateral displacements by 5.84, 11.55 and 18.44 for basic wind speeds of 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to 39m/sec. It also observed that the lateral displacement at the top of steel stacks for all the wind speeds are in permissible limit (h/200=110/200=0.55 or 550mm) as per IS code IS 6533 (Part 2) 1989 clause 7.4.

Figure 6 presents the maximum lateral displacements due to Seismic loads for 90 m and 110 m height chimney in all the 4 seismic zones.

![Figure 6](image)

**Figure 6** Maximum lateral displacements due to Seismic loads for 90 m and 110 m height chimney in all the 4 seismic zones

From Figure 6, an increase in percentage of lateral displacements in chimney of 110m height by 31.46, 36.23, 27.71 and 31.91 for zones II, III, IV and V respectively is observed when compared with that of chimney of 90m height.

Figure 7 presents the comparison of maximum lateral displacements due to wind loads for a chimney of height 90 and 110m in all the 4 Seismic zones.

![Figure 7](image)

**Figure 7** Comparison of Maximum lateral displacements due to wind loads for a chimney of height 90 and 110m in all the 4 Seismic zones.
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From Figure 7, an increase in percentage of lateral displacements in chimney of 110m height by 9.93, 12.45, 15.04 and 17.86 for basic wind speeds of 39m/sec, 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to chimney of 90m height.

3.3. Shear Force and Bending Moment
The variation in shear force and bending moment in various segments of chimneys of 90m and 110m heights at different earthquake zones and wind speeds are presented in this section.

Figure 8 presents the comparison of Shear forces for 90 m height chimney in 4 seismic zones.

Figure 8 Comparison of Shear forces for a chimney of height 90m in 4 zones

From the Figure 8, an increase in percentage of shear force by 38.49, 58.99 and 72.88 for zones III, IV and V respectively is observed when compared to zone II.

Figure 9 presents the comparison of Bending moments for 90 m height chimney in 4 zones.

Figure 9 Comparison of Bending moments for a chimney of height 90m in 4 seismic zones

From the Figure 9, an increase in percentage of bending moment by 38.47, 58.99 and 72.88 for zones III, IV and V respectively is observed when compared to zone II.

Figure 10 presents the comparison of Shear forces for a chimney of height 110m in 4 seismic zones.
From Figure 10, an increase in percentage of shear force by 31.09, 34.16 and 78.10 for zones III, IV and V respectively is observed when compared to zone II.

Figure 11 presents the comparison of Bending moments for a chimney of height 110m in 4 seismic zones.

From the Figure 11, an increase in percentage of bending moment by 31.09, 34.16 and 76.44 is observed for zones III, IV and V respectively when compared to zone II.

Figure 12 presents the comparison of Maximum Shear forces for a chimney of height 90m and 110m in 4 seismic zones.
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Figure 12 Comparison of Maximum Shear forces for a chimney of height 90m and 110m in 4 seismic zones

From the Figure 12, an increase in percentage of maximum shear force for chimney of 110m height by 27.39, 18.65, 14.23, 27.71 and 41.35 for zones II, III, IV and V respectively is observed when compared to chimney of 90m height.

Figure 13 presents the comparison of Maximum Bending Moment for a chimney of height 90m and 110m in 4 seismic zones

Figure 13 Comparison of Maximum Bending Moment for a chimney of height 90m and 110m in 4 zones

From the Figure 13, an increase in percentage of maximum Bending Moment in chimney of 110m height by 41.99, 35.01, 6.86 and 53.15 for zones II, III, IV and V respectively is observed when compared to chimney of 90m height.

Figure 14 presents the comparison of Shear forces for a chimney of height 90m in 4 wind speeds.

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From the Figure 14, an increase in percentage of shear force by 22.8, 32.43 and 41.39 for basic wind speeds of 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to 39m/sec.

From the Figure 15, an increase in percentage of bending moment by 22.19, 32.43 and 41.39 for basic wind speeds of 44m/sec, 47m/sec, 50m/sec respectively is observed when compared to 39m/sec.

Figure 16 presents the comparison of Shear forces for a chimney of height 110m in 4 wind speeds.
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Figure 16 Comparison of Shear forces for a chimney of height 110m in 4 wind speeds

From the Figure 16, an increase in percentage of shear force by 22.91, 32.41 and 41.39 for basic wind speeds of 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to 39m/sec.

Figure 17 presents the comparison of Bending moments for a chimney of height 110m in 4 Wind Speeds.

Figure 17 Comparison of Bending moments for a chimney of height 110m in 4 Wind Speeds.

From the Figure 17, an increase in percentage of bending moment by 22.91, 32.39 and 41.39 for basic wind speeds of 44m/sec, 47m/sec and 50m/sec respectively is observed when compared to 39m/sec.

Figure 18 presents the comparison of Maximum Shear forces for a chimney of height 90m and 110m in 4 Wind speed.
Figure 18 Comparison of Maximum Shear forces for a chimney of height 90m and 110m in 4 Wind speed

From the Figure 18, an increase in percentage of maximum shear force in chimney of 110m height by 64.72, 64.74, 64.71, and 64.72 for basic wind speeds 39m/sec, 44m/sec, 47m/sec, and 50m/sec respectively are observed when compared to chimney of 90m height.

Figure 19 presents the comparison of Maximum Bending moments for a chimney of height 90m and 110m in 4 seismic zones.

Figure 19 Comparison of Maximum Bending moments for a chimney of height 90m and 110m in 4 seismic zones.

From the Figure 19, an increase in percentage of maximum Bending Moment in chimney of 110m height by 30.26, 71.15, 71.13 and 71.13 for basic wind speeds 39m/sec, 44m/sec, 47m/sec, and 50m/sec respectively is observed when compared to chimney of 90m height.
3.4. Response Spectrum for Frequency, Time Periods and Spectral Acceleration of 90m & 110m Height Chimney

The magnitudes of Frequency, Time periods and spectral accelerations from the response spectrum analysis (using STAAD.Pro) of chimneys of heights 90m and 110m for various Seismic zones and basic wind speeds are plotted and discussed in this section.

From the Figure 20 (a), an increase in percentage of maximum frequency in chimney of 110m height of 24.81 respectively is observed when compared to chimney of 90m height. From the Figure 20 (b), an increase in percentage of maximum Time period in chimney of 90m height of 16.35 respectively is observed when compared to chimney of 110m height. From the Figure 20 (c), maximum Spectral acceleration in chimney of 90m height is equal to that of chimney of 110m height.

4. CONCLUSIONS

From the analytical study presented in this paper, the following are some specific and general conclusions.

The maximum displacements for both the chimneys are observed for earthquake zone V. The maximum displacements for both the chimneys are found in areas with higher wind speed i.e., at 50m/s. There is more impact of wind load on the chimney when compared to seismic load. The value of shear force becomes constant after the 4th segment for both the chimneys. The value of bending moment increases with increase in height of segments from bottom to top and also with increase in seismic zones. The maximum values of shear force and bending moment shows that as the height of chimney increases the intensity of shear force and bending moment values at the bottom segment also increases at a higher rate.
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