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# Wind effects on water towers-influence of various dynamic parameters

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## Abstract

Wind flows relative to the surface of ground and produces loads on the structures standing on the ground. The effect of the wind on the structures is of prime importance. Most of the designers consider the static effect of wind on the structure. But for tall structures the wind interacts with the structure dynamically. The Indian standard code IS 875 (Part-3) 1987 deals with the wind effects on the structures. Water towers are critical structures from the point of the wind effect. Towers of height 16 m, 20 m, 24 m and 28 m are considered in the present analysis. Fundamental frequency is computed by the method given in Indian standard IS 1893-1984. In the computation of fundamental frequency two conditions a) Tank empty and b) Tank full with water are considered. It is found from the study that static pressures are less compared to those given by the gust effectiveness factor method (GEFM). Dynamic interaction between the fluctuating wind component and the structure are considered in GEFM and equivalent static wind pressures are evolved. GEFM is more rational and realistic and recommended for wind load design of water towers.

**Keywords**: Gust pressure, fundamental frequency, static pressure, background factor, resonance.

## Introduction

In structural design, predicting the wind response of structures has become important due to the sensitivity of certain types of structures to the wind loads. Wind tunnel tests are used for predicting the response but reliable data from full scale measurements are scarce. From the design point of view the tanks may be classified as per their shape. Rectangular tanks, circular tanks, intze type tanks, conical bottom tanks and suspended bottom tanks are some of the types. A water tank supported on staging of given height is treated as a point like structure. For lateral load analysis, the whole structure is treated as a cantilever with a point load acting at the free end. The point load consists of the weight of the tank and water.

Peter Irwin (2008) discussed the role of wind as a friend or foe. As a governing load in the design of tall buildings the wind is a foe. By placing the wind turbine on top of tall building to harvest the wind, the role of wind is that of a friend. The statistical theory for the wind loading of structures was given by Davenport (1961). Scruton (1963 & 1966) discussed the wind effects on tall stacks, towers, masts, tall buildings, cooling towers and suspension bridges. Studies were conducted on the vibrations of an actual house and a steel tower. The vibrational behaviour is related to the turbulence in the wind. Vickery (1970) pointed out that more attention should be paid to damping in controlling the flow induced vibrations of structures.

*Static wind pressures on water towers:*

Water towers are generally considered as rigid structures and hence static wind pressures are computed as per the Indian standard code. In computing the wind pressure variation along the height, exposed areas of the columns and braces are considered. The wind force resulting from the wind pressures acting at the center of the tank in the lateral direction is predominant.

*Gust pressures on water towers:*

Water tanks supported on staging are treated as point like structures. As the height of the staging is increased the tower becomes slender. The fundamental frequency of this point like structure mainly depends on the mass concentrated at the top. The value of the frequency gets reduced with the increase in the height of the tower.

Wind Pressures as per IS 875-(Part 3)-1987

Wind pressures acting at any height on a structure are computed by the methods recommended by the IS code (IS 875-(Part 3)-1987). The code has recommended two methods for computing the wind pressures based on the requirement.

*Static method:*

Design +wind speed ($V_z$) at any height can be calculated as follows:

$V_z=V_bK_1K_2K_3$ [4]

Where $V_z$ = Design wind speed at any height z in m/sec,
$V_b$=Basic wind speed for any site
$K_1$ = probability factor (risk coefficient)
$K_2$ = Terrain, height and structure size factor and
$K_3$ = Topography factor
$K_1$ ,$K_2$ and $K_3$ are given by means of tables in the code [4].

The design wind pressure at any height above mean ground level shall be obtained by the following relationship between wind pressure and wind velocity.

$P_Z=0.6V_Z^2$ , Where $P_z$ = Design wind pressure in $N/m^2$ at height z,

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$V_z$ = Design wind velocity in m/s height z.

**Gust effectiveness factor method**

*Hourly mean wind:*

The variation of hourly mean wind speed with height shall be calculated as follows.

$\overline{V_z} = V_b * K_1 * \overline{K_2} * K_3$.

Where $\overline{V_z}$ = hourly mean wind speed in m/s at height z.

$V_b$ = regional basic wind speed in m/s;

$K_1$ = probability factor.

$\overline{K_2}$ = terrain and height factor.

$K_3$ = topography factor.

These factors are given in the code [4].

*Along wind load:*

Along wind load on structure on strip area ($A_e$) at any height (Z) is given by: $F_z = C_f * A_e * \overline{p_z} * G$

Where, $F_z$ = along wind load on the structure at any height z corresponding to strip area $A_e$.

$C_f$ = force coefficient for the building,

$A_e$ = effective frontal area considered for the structure at height z,

$\overline{p_z}$ = design pressure at height z due to hourly mean wind obtained as $0.6 * v_z^2$ (N/m$^2$),

G= gust factor (peak load /mean load) and is given by:

$G = 1 + g_f r * \text{sqrt}(B (1 + (\Phi))^2 + SE/\beta)$

$g_f r$ = peak factor defined as the ratio of the expected peak value to the root mean value of a fluctuating load, and r= roughness factor which is dependent on the size of the structure in relation to the ground roughness.

The value of '$g_f r$' is obtained from (Fig. 8 of the code)[4].

B = background factor indicating a measure of slowly varying component of fluctuating wind load and is obtained from Fig. 9 of the code [4].

S= size reduction factor is obtained from Fig.10 of the code [4].

E = measure of available energy in the wind stream at the natural frequency of the structure is obtained from Fig.11 of the code [4].

β= Damping coefficient (as fraction of critical damping) of the structure (Table 34 of the code) [4].

$\Phi = g_f r * \text{sqrt}((B)/4)$ and is to be accounted only for buildings less than 75 m height in terrain category 4 and for buildings less than 25 m high in terrain category 3, and is to be taken as zero in all other cases.

$\lambda = C_y b / C_z h$ and $F_o = C_z f_o h / V_h$

Where $C_y$ = lateral correlation constant which may be taken as 10 in the absence of more precise load data,

$C_z$ = longitudinal correlation constant which may be taken as 12 in the absence of more precise load data,

B = breadth of a structure normal to the wind stream,

H = height of a structure,

$V_h = V_z$ = hourly mean wind speed at height z,

$f_o$ - natural frequency of the structure, and

L (h) = a measure of turbulence length scale.

**Details of the present study:**

The present study deals with the computation of wind pressures on water towers of various heights. The wind pressures are computed by using both the methods as already described. Water towers with heights varying from 16 m to 28 m are considered for wind pressure analysis to highlight the criticality by the gust loads. The details are as follows:

*Example on computation of wind pressures in the case of a typical water tower of height 16 m.*

*Tank details:* Capacity of water tank = 50,000 Lit.; Dimensions of the tank = 4 m x 4m (Square); Height of the staging = 16 m; Thickness of side walls, bottom slab and roof slab = 150 mm; Dimensions of the ring beam and staging beams (Braces) = 200 mm x 300 mm; Grade of concrete= M 20; Grade of steel= Fe 415; Total weight of the tank = 339.15 KN say 340 KN; Total weight of staging portion = 240 KN; Weight of water when the tank is full = 500 KN

*Fundamental frequency:* The fundamental frequency of the water towers is calculated approximately by following the procedure as given in IS 1893-1975 (Sections 5.2.7.2 & 5.2.7.3 of SP-22-1982). The design shall be worked out both when the tank is full and when empty. When empty, the weight "w" used in the design shall consist of the dead load of the tank and one third the weight of staging. When full, the weight of water is to be added to the weight under empty condition.

Hence, weight of staging to be considered = 240/3 = 80 Kg.

a) Weight considered when the tank is empty = 340+80=420 KN
b) Weight considered when the tank is full = 340+80+500=920 KN

Following the codal procedure, the tank frequencies are calculated as W = 4.19 $H_Z$ and 2.80 $H_Z$ for empty and full conditions. The values of frequencies computed in the similar manner for various heights are plotted in Fig.1.

*Calculation of wind pressure by static method:*

a) As per IS: 875 (Part-3)-1987, the basic wind speed ($V_b$) at 10m height of Hyderabad city is 44m/sec (Table 2.1 of the code) [4].

As per clause 5.3 of code, the design wind speed is given by $V_z = V_b * K_1 * K_2 * K_3$.

Where, Risk coefficient ($K_1$) = 1.0 (Table 2.2 of the code) [4].

Topography factor ($K_3$) =1.0 (as per clause 5.3.3of the code) [4].

Terrain factor ($K_2$) = 0.978 (at 16m high water tower, as per Table 2.3 of the code) [4].

Design Wind Speed $V_z$ = 44* 1.0* 0.978*1.0 = 43.3 m/sec.

Design Wind Pressure at 16m high water tower = $P_z$ = $0.6 * V_z^2 = 0.6 * (43.03)^2$ = 1110.95 N/Sq.m.

*Wind pressures by gust effectiveness factor method:*

a) 16m high water tower (empty)

As per the code [4], the basic wind speed ($V_b$ ) at 10m height of Hyderabad city is 44 m/sec. (from the code) [4].
Risk coefficient ($K_1$) = 1.0 (Table 2.2 of the code) [4].
Topography factor ($K_3$) = 1.0 (as per clause 5.3.3 of the code) [4].
Terrain factor ($\overline{K_2}$) = 0.558 (for category 3 at 16 m high water tower, as per the code) [4]
and as per clause 8.2.1 of the code [4].
Hourly Mean Wind Speed in m/sec at height 'z' is $\overline{V_z} = V_b * K_1 * \overline{K_2} * K_3$.
= 44* 1.0* 0.558* 1.0 = 24.55 m/sec.
Mean wind pressure at 16m height = $P_z = 0.6 * V_z^2 = 0.6 * (24.55)^2$ = 351.62 N/Sq.m.
As per clause 8.3 of the code [4],
Along wind load on a structure on a strip area ($A_e$) at any height (z) is given by:

$F_z = C_f * A_e * \overline{p_z} * G$

Where

$F_z$ = along wind load on the structure at any height z corresponding to strip area $A_e$

$C_f$ = force coefficient for the building = 1.0

$A_e$ = effective frontal area considered for the structure at height z = 1.0 (unity),

$P_z$ = design pressure at height z due to hourly mean wind = 361.62 N/Sq.m .

G = gust factor $\left(\frac{Peakload}{Meanload}\right)$, and is given by:

$G = 1+ g_f r \text{ Sqrt } (B (1+ø)^2 + SE/β)$

From Fig. 5 of the code [4] Peak and roughness factor $g_f r$ = 2.1 at 16 m height.
From Fig. 5 of the code [4] Turbulence length scale L ($_h$) = 800 at 16 m height.
$\lambda = C_y b / C_z h$ Where,
$C_Y$ = lateral correlation constant = 10
$C_z$ = longitudinal correlation constant = 12
b = breadth of a structure normal to the wind stream = 4 m.
h = height of a structure = 16 m,

λ = (10*4)/(12*16) = 0.208

And $C_z$ h/L($_h$) = (12*16)/800 = 0.24
From fig. 6 of the code, background factor 'B' = 0.82 at 16 m height.
Reduced frequency $F_o = C_z\ f_o\ h/V_h$
Where, natural frequency of 16 m high water tower = $f_o$ = 4.19 cycles/sec
$V_z$ = Hourly mean wind speed at 16 m height = 24.55 m/sec.
$F_o$ = (12*4.19*16)/24.55 = 32.77
From fig.7 of the code, size reduction factor 'S' = 0.035, at 16 m height.
fo L($_h$)/$V_h$ = (4.19*800)/24.55 = 136.54
ø = $g_f$ r. B/4 = 2.1. 0.82/4 = 0.48
From fig. 8 of the code, the gust energy factor 'E' = 0.020
Damping coefficient of the structure = β = 0.016 (for R.C. structures)
As per code, gust factor G=1+ $g_f$ r Sqrt (B (1+ ø)² + SE/β)
= 1+2.1 Sqrt (0.82 (1+0.48) ² + (0.035*0.020)/0.016) = 3.859
Gust pressure $F_z$ = 1.0*1.0*3.859*361.62 = 1395 N/Sq. m
Similarly gust pressures for tank full conditions is worked out as 1398 N/Sq. m.

*Presentation of results:*

Proceeding in the similar manner, the gust pressures are computed for various heights of the tank. Both tanks empty condition and full condition are considered. The results are given in Table 1 and plotted in Fig. 4. The resonant component (SE/β) for different heights is plotted in Fig. 2. The gust factor 'G' is plotted for different heights in Fig. 3.

*Table 1. Comparison of static & gust pressures of water towers*

| Tower height from base (m) | Static pressure N/m² | | Gust pressure N/m² | |
|---|---|---|---|---|
| | Tank empty | Tank full | Tank empty | Tank full |
| 16 | 1110 | 1110 | 1395 | 1398 |
| 20 | 1185 | 1185 | 1513 | 1540 |
| 24 | 1232 | 1232 | 1590 | 1640 |
| 28 | 1280 | 1280 | 1653 | 1707 |

## Results and discussion

The results of the wind load analysis of water towers are discussed herein.

*Variation of fundamental frequency for different water towers:*

The fundamental frequency is computed for different heights of water towers. The fundamental frequency for a 16 m high water tower is 4.19 cycles/sec and this decreases to 1.61 cycles/sec in the case of tank empty condition. For the tank full condition the fundamental frequency for 28 m height tower is 1.61 cycles/sec and this reduces to 1.12 cycles/sec. As the height of the tower is increased it becomes more flexible which is reflected by the reduction in the frequency values. When the frequency of the structure is lower because of the flexibility, there is a possibility of the structure interacting with the wind dynamically.

*Influence of hourly mean wind speeds on gust pressures:*

To compute the along wind pressures, hourly mean wind pressures are multiplied by the gust factor. Hourly mean wind pressure increases rapidly with height. It is seen that the mean wind pressure increased from 290.40 N/m$^2$ at 4 m height to 484.62 N/m$^2$ at height of 32 m showing an increase of nearly 67%. Because of this increase in the values of mean wind pressures with height, the overall gust pressures increase with the height of tower.

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*Background effect on gust pressures:*

The gust effectiveness factor, which considers the along wind load, considers the effect of background and resonance in the fluctuating wind. The background factor depends on the height of the tower and turbulence length scale "$L_{(h)}$" value. With increase in tower height the "$L_{(h)}$" value also increases for given terrain category. But for increased value of "$L_{(h)}$" the background factor decreases. It can be seen that the value of background factor is 0.82 for a 16 m height water tower and it is 0.90 for a 28 m high water tower. The difference is small. Hence, it is clear that the change in the background contribution in the wind component is negligible with the increased height of the water towers.

*Effect of resonance component on gust effectiveness factor:*

The resonance component is given by "SE/β". As the damping coefficient 'β' is constant (0.016), the resonance mainly depends on the size reduction factor 'S' and available energy at the fundamental frequency. By taking into account the size reduction factor and gust energy factor, the resonance component "SE/β" is computed. It can be seen that the resonant component increases with height of the water tower. In the case of 16 m high water tower it is 0.044 and in the case of 28 m high water tower it is 0.231, when the tank is empty. In the case of 16 m high water tower it is 0.081 and in the case of 28 m high water tower it is 0.422, when the tank is full. Hence, it can be seen that in general "SE/β" increases with height of the tower. This is because of change in the values of the fundamental frequency.

*Effect of size reduction factor:*

In working out resonant component, the damping coefficient 'β' is a constant. The size reduction factor 'S' depends on the reduced frequency for a given 'λ' value, for a given tower. The reduced frequency decreases with the height of the tower and as a result the size reduction factor gets increased with the height of the water tower.

***Fig. 1. Variation of fundamental frequency for water towers of different height***

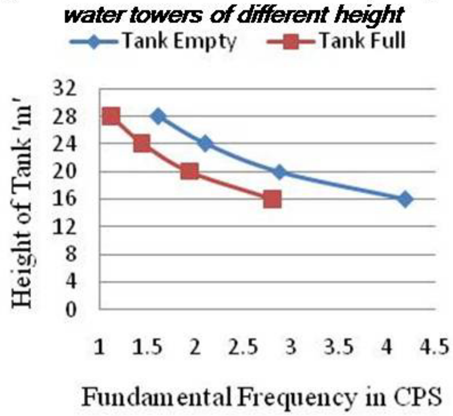



***Fig. 2. Resonant component(SE/β) For water towers of different heights***

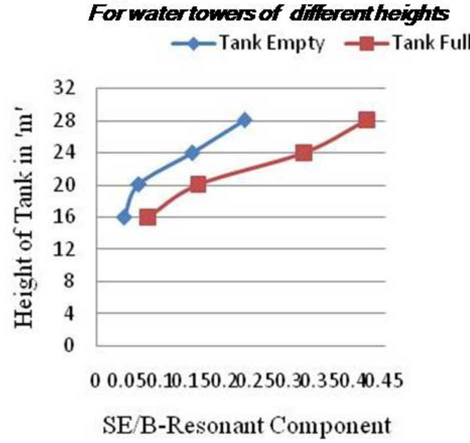
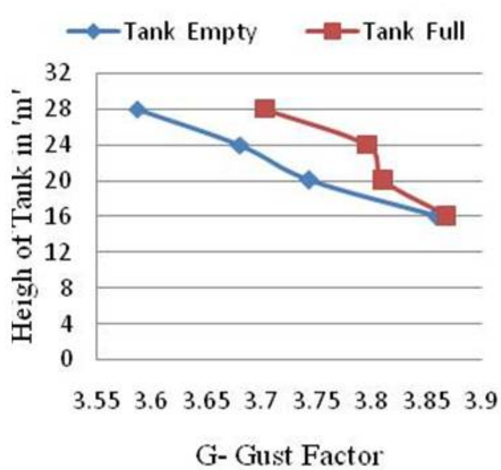



***Fig. 3. Variation of gust factor for water towers of different heights***




*Influence of spectral energy:*

The gust effectiveness factor mainly takes into account the interaction of the wind with the structure. The atmospheric wind is fluctuating and its nature is described by a mean spectrum. The code [5] has adopted the wind spectrum for the country. The mean spectrum gives the energy content with respect to fundamental frequency. It can be seen that as the height water tower increases the energy content also increases in the range 0.020 for 16 m height water tower to 0.037 for 28 m height water tower.

*Influence of peak and roughness factor on gust factor:*

The gust effectiveness factor is computed as equal to the mean value plus the effect of overall fluctuation. The fluctuation part is computed by combining the background and resonance effect with "$g_f r$". The "$g_f$" is termed as peak factor defined as the ratio of the expected peak value to a root mean square value of the fluctuating pressure. 'r' takes into account ground roughness and the size of the structure. The values of "$g_f r$" are given in the IS code. It is clear that as the height of the water tower increases, the value of "$g_f r$" decreases. It can be seen that this is due to the decrease in wind turbulence as the height increases, as the influence of ground roughness becomes insignificant.

*Variation of gust factor for different heights:*

The value of gust factor decreases with height of water tower. In the case of 16 m high water tower it is 3.859 and in the case of 28 m high water tower it is 3.586, when the tank is empty. In the case of 16 m high water it is 3.868 and in the case of 28 m high water tower it is 3.703, when the tank is full. The variation of gust factor is represented in Fig. 3. It is observed from the figure, that the gust factor varies uniformly from

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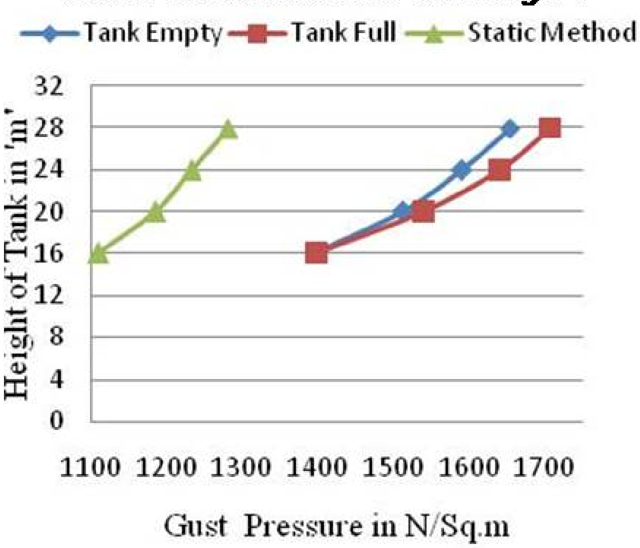
top. This clearly indicates that as the height of water tower increases its flexibility also increases. The fundamental frequency decreases and overall gust factor decreases.

*Variation of gust pressures with height of tower:*

In the case of water towers the gust pressures are computed considering the tank empty and full conditions. In the case of empty the gust pressure increases from 1395 N/m² for 16 m high water tower to 1653 N/m² for 28 m high water tower. Similarly, in the case of tank full condition the gust pressure increases from 1398 N/m² for 16 m high water tower to 1707 N/m² for 28 m high water tower. On the basis of the above discussion, it is clear that the gust pressure increases by about 18% in case of tank empty and 22% in case of tank full over the initial height.

**Fig. 4. Variation of gust pressures For water towers of different heights**




*Comparison of static pressure and gust pressure:*

From Table 1 it is clear that the static wind pressures are increasing from 1110 N/m² for 16 m high water tower to 1280 N/m² for 28 m high water tower. The increase is also seen in the case of gust effectiveness factor method. Even though, the gust factor decreases with the increase in height of water tower, the gust pressures increase with height of the water tower. The same is also valid for multistoried tall frames [(2)].

In this case the variation of static and gust pressures are increasing uniformly with the increase in the height of water tower. Gust pressures are more in magnitude compared to static pressures. Out of the two methods available for the wind load analysis, the static method does not take into consideration the dynamic nature of the structure and the possible interaction with the fluctuating wind. The gust effectiveness factor method takes into account the dynamic interaction between the wind and the structure and as such is more rational and reliable compared to the static method.

## Conclusion

The following are the conclusions drawn from the present study:

- For normal heights of water towers they can be classified as rigid even though the fundamental frequency gets reduced with the height.
- The background factor almost remains same for normal heights of water tower; its Influence on gust pressures for different heights almost remains same.
- The resonance component which depends on size reduction factor and spectral energy increases with height of the water tower.
- The values of the gust factor decreases with height of the water towers. However, the overall gust pressure increases with height because the increase in mean pressure is predominant.
- Static pressures are same irrespective of whether the tank is full or empty. Gust effectiveness factor method takes into account both tank empty and full conditions. It is more realistic.
- Wind pressures computed by the gust effectiveness factor are more realistic and safer for design compared to the static pressures.

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