APPLICATION OF PSEUDO-STATIC METHOD TO DETERMINE WIND LOADING ON HIGH-RISE BUILDING IN VIETNAM

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Abstract

The paper presents method to determine wind load on a high-rise building by direct dynamic method (according to current Vietnam standard TCVN 2737:1995). At the same time, based on the design procedures of C. Dyrbye and S.O. Hansen, the authors proposed the formula to determine the gust factor for high-rise buildings with wind parameters according to TCVN 2737:1995 (wind profile, length scale, turbulence intensity, spectral density, power-spectral density function). Numerical example according to proposed formula to determine the gust factor and wind load.

Keywords: *Wind load; high-rise building; pseudo-static method; gust factor.*

1. Introduction

Currently, the calculation of wind load on buildings and structures in general, domestic engineers use the Vietnam standard TCVN 2737:1995 (and TCXDVN 229:1999) [1, 2], which are based on SNiP of old Soviet Union standard 2.01.07-85* [3] with direct dynamic calculation method for wind load. Contrary to the direct dynamic calculation method, the pseudo-static method is used as the basis for many national standards, including ISO 4354:2009 (International Standard), ASCE 7-16 (American standard), EN 1991-1-4:2004 (Eurocode), AIJ RLB 2004 (Japanese standard), AS/NZS 1170.2:2002 (Australian and New Zealand standards), CSA S37-2001 (R2006) (Canadian standard), NBCI:2005 (Indian standard) etc. [4].

Seeing that, the calculation of wind load on structures in general, tall buildings in particular according to the design standards will be different, the difference shown through wind parameters (wind profile) or wind turbulence (turbulence intensity, length scale, power-spectral density function), as well as aerodynamic coefficient (force factor). For the Vietnam standard TCVN 2737:1995, calculated by the direct dynamic method, using the value of wind pressure corresponding to the wind speed at 10 m height, a 20 years return period and a 3 seconds averaging time. Specifically, in TCVN

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2737:1995 the total wind pressure W is determined as the sum of average (static) W_t and pulse (dynamic) W_p components:

$$W = W_t + W_p \tag{1}$$

Next, the paper present the dynamic response of the structure under wind load, calculation of wind load according to Vietnam standard (TCVN 2737:1995) and proposal formula for calculating the gust factor with wind parameters according to TCVN 2737:1995, numerical example to clarify the studies.

The goal of this study is to present a pseudo-static method to calculate the gust factor for high-rise buildings in Vietnam, based on the design procedures of the C. Dyrbye and S.O. Hansen [5]. However, due to the limitation of the article length, this article will only examine the behavior of tall buildings in the direction of along wind, while the problems of across wind and torsion will be presented in the next articles.

2. Dynamic response of the structure under wind load

The high-rise building with height H and width D shown in Figure 1 is considered, assumming that the structures has a multi-degree of freedom. The coordinate system is defined: x-axis is along wind, z-axis is a coordinate to height of the structure.

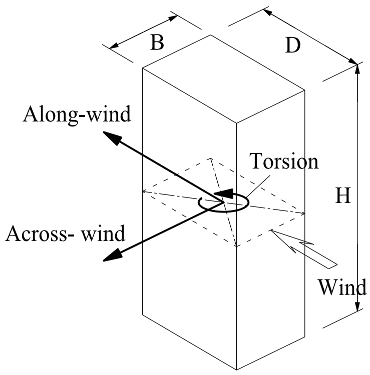

Figure 1. Definition of load and wind direction

2.1. Determine the wind load according to TCVN 2737:1995

a) Static component

Characteristic value of static components of wind load W_t at height z compared to the reference height is determined by the formula:

$$W_t = W_0 \times k(z) \times c \tag{2}$$

where W_0 is a value of normative wind pressure, taken from the wind region; $k(z)$ is the topographic factor (the roughness coefficient) $k(z) = 1.844(z/z_g)^{2m_t}$; c is the aerodynamic coefficient (for high-rise buildings c = 0.8 + 0.6 = 1.4); m_t, z_g are terrain exposure constants taken from Table 1.

Table 1. Terrain exposure constants

Exposure	m_t	$z_g\,(m)$	k_{10}
A	0.07	250	1.18
B	0.09	300	1.00
C	0.14	400	0.66

b) Dynamic component

According to Vietnam standards [1, 2], building structures with symmetrical plan have basic natural frequency f_1 smaller than the limit value of natural frequency f_L, dynamic component of wind load is determined by the formula:

$$W_{p(k)} = m_k \times \xi \times \Psi \times y_k \tag{3}$$

where m_k is the mass of the building part, at the height of z_k; ξ is dynamic coefficient; y_k is horizontal displacement of the building part at height z_k corresponding to the first vibration form; Ψ is the coefficient, determined by the formula:

$$\Psi = \frac{\sum_{k=1}^{n}\left(y_k \times W_{pk}\right)}{\sum_{k=1}^{n}\left(y_k^2 \times m_k\right)} \tag{4}$$

W_{pk} is dynamic component evenly distributed of wind load in the k^{th} part of the building, $W_{pk} = W_k \times \zeta_k \times \upsilon$; υ is spatial correlation factor of dynamic pressure of wind load corresponding to the first form of vibration; ζ_k is coefficient of dynamic pressure of wind load at height z_k, depending on terrain exposure: $\zeta_A = 0.303\left(z/10\right)^{-0.07}$; $\zeta_B = 0.486\left(z/10\right)^{-0.09}$; $\zeta_C = 0.684\left(z/10\right)^{-0.14}$; W_k is static component, normative value of wind load at height $W_k = W_t \times B_k \times h_k$ with B_k, h_k is width and height of reference surface size corresponding to k^{th} part.

In summary, the total wind load on the k^{th} storey is:

$$W_k^{tot} = \gamma_w\left(W_k + W_{p(k)}\right) = \gamma_w W_k\left(1 + \frac{W_{p(k)}}{W_k}\right) = \gamma_w W_k G_k \tag{5}$$

in which $\gamma_w = 1.2$ is the coefficient transferred from wind period 20 to 50 years; $G_k = 1 + W_{p(k)}/W_k$ is the gust (dynamic) factor at the k storey. Here, the authors propose an approximate formula to calculate the gust factor with wind parameters according to TCVN 2737:1995.

2.2. Gust factor for multi-storey buildings according to C. Dyrbye and S. O. Hansen [5]

The gust factor G, defined as the ratio between a static wind load which gives the maximum response of the structure during a reference time interval, taken as T = 3 seconds, and the mean wind load which give the mean response of the structure. The gust factor is calculated as shown below:

$$G_{ref} = 1 + 2k_p I_{u,ref}\sqrt{\theta_b^2 k_b + \theta_r^2 k_r} \tag{6}$$

where $I_{u,ref}$ is turbulence intensity at the reference point with a height z_{ref} above terrain, for multi-storey buildings taken at the top of roof $z_{ref} = h$. The turbulence intensity is determined by formula [2] $I_u(z) = \gamma_t^*(z) = 2.45(r_t)^{0.5}(z/10)^{-m_t}$. According to Vietnam standard TCVN 2737:1995, r_A = 0.002, r_B = 0.005, r_C = 0.01, from there:

$$I_{u,A} = 0.110(z/10)^{-0.07}; I_{u,B} = 0.173(z/10)^{-0.09}; I_{u,C} = 0.245(z/10)^{-0.14}$$

θ_b and θ_r are factors incorporate the effects of different influence function for the mean and fluctuating response, respectively. In the design process often taken $\theta_b = \theta_r = 1.0$, those are the values that are suitable for most common structures.

k_p is the peak factor, defined as the ratio between the peak and standard deviation of fluctuating load within reference time interval T = 3 seconds. The peak factor is calculated as:

$$k_p = \sqrt{2\left|\ln(\nu T)\right|} + \frac{0.5772}{\sqrt{2\left|\ln(\nu T)\right|}} \tag{7}$$

where ν is the zero-upcrossing frequency. The zero-upcrossing frequency ν is calculated from background and resonant contribution as:

$$\nu = \sqrt{\frac{n_0^2 k_b + n_e^2 k_r}{k_b + k_r}} \tag{8}$$

n_e is the natural frequency (Hz) of the along-wind vibrations of the structure; n_0 is the representative frequency (Hz) of the gust loading on rigid structures. Frequency n_0 is approximated by:

$$n_0 = 0.3\frac{U(z_{ref})}{\sqrt[4]{hb}\sqrt{L_u}}; n_0 \le n_e \tag{9}$$

$L_u = L(z_{ref})$ is integral length scale at reference height z_{ref}, L_u = 1200 m. If the equation (9) gives $n_0 > n_e$ then $n_0 = n_e$; h, b are reference dimensions of the structure (height and width of high-rise buildings).

Background response factor k_b

$$k_b = \frac{1}{1+\frac{3}{2}\sqrt{\left(\frac{b}{L_u}\right)^2+\left(\frac{h}{L_u}\right)^2+\left(\frac{3}{\pi}\frac{b}{L_u}\frac{h}{L_u}\right)^2}} \tag{10}$$

Resonant response factor k_r

$$k_r = \frac{\pi^2}{2\delta} R_N\left(z_{ref}, n_e\right) K_s\left(n_e\right) \tag{11}$$

where δ is the logarithmic damping decrement of the along-wind vibration equal to $\delta = 0.30$ for building.

The non-dimentional spectral density $R_N\left(z_{ref}, n_e\right)$ defined as (from Davenport (1967)):

$$R_N\left(z, n\right) = \frac{2}{3}\frac{f_L^2}{\left(1+f_L^2\right)^{4/3}} \tag{12}$$

with non-dimentional frequency $f_L = nL/U(z)$, where $L \approx 1200$ m. Average wind speed at height z, $U(z)$ depends on height: $U\left(z\right) = U_{10,t}\left(z/10\right)^{m_t} = V_0\beta_u\left(z/10\right)^{m_t}$, in which $V_0 = \sqrt{\frac{W_0}{0.0613}}$; $\beta_u = \sqrt{k_{10}}$ coefficient, taking into account the change in wind speed; k_{10}, m_t are terrain exposure constants, determined according to Table 1.

The size reduction function $K_s(n_e)$ is given in the expression:

$$K_s\left(n_e\right) = \frac{1}{1+\sqrt{\left(G_y\phi_y\right)^2+\left(G_z\phi_z\right)^2+\left(\frac{2}{\pi}G_y\phi_y G_z\phi_z\right)^2}} \tag{13}$$

$$\phi_y = \frac{10bn_e}{U_{ref}};\ \phi_z = \frac{10hn_e}{U_{ref}} \tag{14}$$

The constants G_y, G_z are taken from Table 6.1 of the document [5], depending on the load variation function g_y, g_z defined in the y, z directions. For high-rise buildings $g_y = 1$, $g_z = z/h$, $G_y = 0.5$, $G_z = 0.375$ (Table 6.1 of document [5]).

The gust factor for the k^{th} storey of high-rise buildings with the stiffness and the weight are constant with height can be calculated by the formula:

$$G_k = 1+\left(G_{ref}-1\right)\times\left(z_k / z_{ref}\right)^{1.5} \tag{15}$$

where z_k is the height of the k^{th} floor.

3. Numerical example

Determining the wind load action on frame structure from 2nd to 21st storey in Hanoi. Building height H = 77.7 m; site size $D \times L$ = 24 m × 24 m. Duration time is 50 years [2].

Based on the author's algorithm has been presented, the Excel spreadsheet calculated the gust factor and wind load by two methods for three types of exposure A, B and C. The results for all floors are shown in Table 2 and Table 3.

Table 2. Gust factor G_k for the building from 2nd to 21st storey by two methods

Storey	Dynamic			Pseudo-static			Error (%)		
	A	B	C	A	B	C	A	B	C
2	1.003	1.006	1.010	1.006	1.009	1.011	0.28	0.34	0.16
3	1.012	1.020	1.031	1.017	1.026	1.032	0.54	0.59	0.06
4	1.025	1.041	1.062	1.032	1.048	1.059	0.69	0.66	-0.27
5	1.041	1.067	1.099	1.049	1.073	1.090	0.75	0.58	-0.75
6	1.061	1.098	1.141	1.068	1.102	1.126	0.71	0.37	-1.32
7	1.083	1.133	1.189	1.090	1.134	1.166	0.61	0.08	-1.91
8	1.108	1.172	1.240	1.113	1.169	1.209	0.46	-0.26	-2.48
9	1.135	1.214	1.294	1.138	1.207	1.256	0.28	-0.60	-2.99
10	1.163	1.258	1.351	1.164	1.247	1.305	0.10	-0.93	-3.42
11	1.193	1.305	1.410	1.193	1.289	1.357	-0.07	-1.22	-3.74
12	1.225	1.353	1.470	1.222	1.333	1.412	-0.21	-1.44	-3.94
13	1.257	1.402	1.531	1.253	1.380	1.469	-0.31	-1.59	-4.02
14	1.290	1.452	1.592	1.285	1.428	1.529	-0.36	-1.66	-3.97
15	1.323	1.503	1.654	1.319	1.478	1.591	-0.34	-1.63	-3.78
16	1.357	1.554	1.715	1.354	1.530	1.655	-0.26	-1.51	-3.47
17	1.391	1.605	1.776	1.390	1.584	1.722	-0.12	-1.28	-3.04
18	1.425	1.655	1.836	1.427	1.640	1.791	0.10	-0.96	-2.48
19	1.459	1.706	1.895	1.465	1.697	1.861	0.40	-0.55	-1.81
20	1.493	1.756	1.954	1.504	1.755	1.934	0.76	-0.04	-1.03
21	1.526	1.806	2.011	1.544	1.816	2.008	1.19	0.55	-0.15
22	1.559	1.855	2.068	1.585	1.878	2.085	1.69	1.23	0.83

Table 3. Wind load W_k^{tot}, kN acting on the k^{th} storey by two methods

Storey	Dynamic			Pseudo-static			Error (%)		
	A	B	C	A	B	C	A	B	C
2	146.4	118.8	71.4	145.8	119.6	71.2	-0.40	0.63	-0.28
3	162.6	136.5	88.6	162.4	137.7	88.2	-0.14	0.88	-0.37
4	174.3	149.8	102.1	174.3	151.2	101.4	0.02	0.96	-0.70
5	184.4	161.8	114.6	184.5	163.2	113.2	0.07	0.87	-1.18
6	193.8	173.3	126.7	193.9	174.5	124.5	0.03	0.66	-1.75
7	203.0	184.8	138.9	202.9	185.5	135.6	-0.07	0.37	-2.34
8	212.2	196.6	151.2	211.7	196.6	146.9	-0.22	0.03	-2.91
9	221.5	208.5	163.9	220.6	207.9	158.3	-0.40	-0.31	-3.42
10	230.8	220.8	176.8	229.5	219.3	170.0	-0.58	-0.64	-3.84
11	240.3	233.3	190.0	238.5	231.1	182.1	-0.74	-0.93	-4.16
12	249.9	246.0	203.5	247.7	243.2	194.6	-0.88	-1.16	-4.36
13	259.7	259.0	217.1	257.1	255.6	207.5	-0.98	-1.31	-4.44
14	269.5	272.1	230.9	266.7	268.4	220.8	-1.03	-1.37	-4.38
15	279.3	285.4	244.9	276.5	281.6	234.6	-1.01	-1.34	-4.20
16	289.2	298.8	258.9	286.5	295.1	248.8	-0.94	-1.22	-3.89
17	299.2	312.2	273.0	296.8	309.1	263.6	-0.79	-1.00	-3.46
18	309.1	325.6	287.1	307.3	323.4	278.8	-0.57	-0.68	-2.91
19	319.0	339.1	301.2	318.1	338.2	294.4	-0.28	-0.26	-2.24
20	328.8	352.4	315.2	329.1	353.3	310.6	0.08	0.25	-1.46
21	338.6	365.8	329.1	340.3	368.9	327.2	0.51	0.85	-0.58
22	348.3	379.0	343.0	351.8	384.8	344.4	1.00	1.52	0.39

Comment: From the calculation results, it can be seen that the pseudo-static method gives the results in accordance to TCVN 2737:1995 for exposure A and B (error less than 2.0%). Particularly for exposure C, the result is more different (error less than 4.5%).

4. Conclusion

Through the presented problem, the authors have proposed a formula to determine the gust factor according to the pseudo-static method, to determine the wind load on the high-rise buildings. The calculation of wind load according to the pseudo-static method is quite simple, with the results compared to the results calculated by the direct dynamic method with small error, confirming the reliability of the proposed formula. Therefore, it is possible to use the formula proposed by the authors in the determination of the wind load on a high-rise building in Vietnam.

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ÁP DỤNG PHƯƠNG PHÁP GIẢ TĨNH TÍNH TẢI TRỌNG GIÓ LÊN NHÀ CAO TẦNG TẠI VIỆT NAM

Tóm tắt: *Bài báo trình bày phương pháp tính toán tải trọng gió lên nhà cao tầng theo phương pháp động lực học trực tiếp (theo tiêu chuẩn hiện hành của Việt Nam TCVN 2737:1995). Đồng thời, dựa vào quy trình thiết kế của C. Dyrbye và S. O. Hansen, nhóm tác giả đề xuất công thức xác định hệ số giật cho nhà cao tầng với các tham số gió (profile gió, chiều dài rối, độ rối, mật độ phổ) theo TCVN 2737:1995. Thực hiện ví dụ số theo công thức đã đề xuất để tính toán hệ số giật và tải trọng gió.*

Từ khóa: Tải trọng gió; nhà cao tầng; phương pháp giả tĩnh; hệ số gió giật.

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