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The research of simplified method of calculating wind and rain loads and its validation

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ABSTRACT

A simplified method is used to simplify the calculation of wind and rain pressures based on the equivalent basic wind speed and equivalent ground roughness coefficient. The first step is to calculate the sum of wind and rain pressures, and then equivalent basic wind speed and equivalent ground roughness coefficient can be obtained through the formulae of wind pressure and wind profile, at last the results of equivalent basic wind speed and equivalent ground roughness coefficient are fitted to obtain the fitting formulae. Response analysis of a transmission tower is performed with the consideration of wind and rain loads which are generated based on the simplified method and the integral formula respectively. It's validated that the proposed simplified method is feasible and can satisfy the accuracy requirement of practical engineering by comparing the results. The simplified method of calculating rain pressure can simplify the process which is very easy to apply rain pressure to structural design.

1. INTRODUCTION

Rain is one of the most common phenomena, and wind-driven rain (WDR), or driving rain, is rain that has a horizontal velocity component. WDR is one of the most important moisture sources affecting the hydrothermal performance and durability of building facades (Blocken et al. 2013). Rain intensities are often very large during typhoons or hurricanes, and many transmission tower-line systems have collapsed during severe gales and thunderstorms. Most researchers have attributed these collapse cases to wind loads, with few considering rain loads. Therefore, it has become necessary to study rain loads to understand both their effects on collapse cases and the mechanism acting on these structures.

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Choi (1993, 1994, 1997) has made major breakthroughs in the use of numerical simulations employing computational fluid dynamics (CFD) in WDR research, conducted based on a steady-state 3D wind flow pattern, and this method is used in the present study. Blocken and Carmeliet (2002) have extended Choi's simulation technique by adding a temporal component and developing a new weighted data averaging technique, allowing for the determination of both the spatial and temporal distribution of WDR. Unlike Choi's methods, which generally based on Lagrange frame to deal with raindrop motions by trajectory-tracking techniques, Huang and Li (2010) have presented a numerical simulation method based on a Eulerian multiphase model to estimate WDR intensity on building envelopes, which could save significant time during pre-processing and post-processing. By virtue of the Eulerian multiphase model, Huang's method could significantly reduce the complexity of evaluating WDR parameters, simplify boundary condition treatments and be more efficient at predicting the transient states of WDR, and its effectiveness has been validated through an example. Li et al. (2013) proposed a computational approach to simulate rain load based on the conservation of momentum and the wind tunnel test is performed indicating that the simulation results agree well with the experimental results. Fu et al. (2014) modified the existing rain load formula (Li et al. 2013), and both the numerical simulation and wind tunnel test were conducted which indicating that the modified formula is feasible and the rain load cannot be neglected.

Due to the complexity of existing rain load formula, it's necessary to propose a simplified method to calculate rain load for the convenience of structural design. In section 2, the mathematic models of wind and rain pressures are introduced, and section 3 proposes the methodology of simplifying the calculating process of rain load. In section 4 contrastive analyses of simplified method and integration formula of wind and rain loads are conducted based on a transmission tower model. Section 5 concludes the study.

2. MATHEMATIC MODELS OF WIND AND RAIN PRESSURES

Mean wind speed varying with altitude can be simulated by exponential wind profile:

$$V = V_{10}\left(\frac{H}{10}\right)^{\alpha} \tag{1}$$

Where V_{10} is the basic wind speed, H is the altitude, α is the ground roughness coefficient.

If the wind speed is V, the wind pressure yields:

$$P_w = \frac{1}{2}\rho_a V^2 \tag{2}$$

Where ρ_a is the air density taking 1.235 Kg/m^3.

The rain load for specific diameter can be calculated by the following equation (Li et al. 2013, Fu et al. 2014):

$$P_r = \frac{1}{6}\rho_r \pi d^3 n_h(d) V_h^{\ 3} \Big/ V_{term} \tag{3}$$

Where ρ_r is the density of raindrop taking 1000 Kg/m³, d is the raindrop diameter, $n_h(d)$ is the raindrop size distribution, γ is the velocity ratio, V_h and V_{term} denote the horizontal velocity of a droplet and the terminal velocity of a droplet in the vertical direction respectively.

Raindrop size distribution adopts Marshall-Palmer raindrop spectrum:

$$n(d) = n_0 \exp(-\Lambda d) \tag{4}$$

Where $n_0 = 8\times10^3$ (m^{-3}mm^{-1}) , $\Lambda = 4.1R_h^{-0.21}$ (mm^{-1}) , R_h is the rain intensity in mm/h.

Velocity ratio is the ratio of the horizontal velocity of a droplet and the corresponding wind speed, velocity ratio can be expressed as (Lin et al. 2013):

$$\gamma(H,d,\alpha) = \left(0.2373H^{-0.5008} - 0.0167\right)\left(\frac{d}{3}\right)^{0.8}\left(\frac{\alpha}{0.12}\right) + 1 \tag{5}$$

The terminal velocity of a raindrop with diameter d can be calculated by the following equation:

$$V_{term} = 9.40\times\left(1-\exp\left(-0.557\times d^{1.15}\right)\right) \tag{6}$$

In Eq. (3), V_h should adopt the terminal velocity of raindrop in the horizontal direction. The surface pressure acting on a structure can be calculated by the following equation:

$$w = \frac{1}{2}u_s\rho_a V^2 \tag{7}$$

Where μ_s is the shape factor.

The surface wind speed can be estimated as $\sqrt{u_s}V$ if putting u_s into V^2. When simulating the wind effect on a transmission tower, the wind flow acts on the front and rear elevations simultaneously. Hence, it can assume that the shape factor of front elevation is $0.5u_s$, then the terminal velocity of raindrop in the horizontal direction before impinging the transmission tower is $\sqrt{0.5u_s}\gamma V$. μ_s takes 1.34 for the tower body and 1.4 for the crossarm.

Consequently, the rain load acting on a transmission tower for any rain intensity can be obtained by integrating Eq. (3), and the Eq. (3) is named as integral formula of rain load. It's obvious that the integration is very complex, so it's necessary to propose a simplified method to calculate wind and rain loads for the convenience of practical application.

3. SIMPLIFIED METHOD OF CALCULATING WIND AND RAIN LOADS

The basic process is listed as below:

(1) The first step is calculating the sum of wind and rain pressures for the condition of ground roughness coefficient taking α, basic wind speed taking V_{10}, rain intensity taking R_h, and altitude taking H, then equivalent wind speed is derived with Eq. (2). If H is 10 m, the derived equivalent wind speed is the equivalent basic wind speed V_{10}^*.

(2) If α, R_h and V_{10} is fixed, the corresponding equivalent ground roughness coefficient α^* can be obtained by Eq. (1) with the results of the first step.

(3) The results of first and second step are fitted to obtain the fitting formulae of equivalent basic wind speed and equivalent ground roughness coefficient.

(4) The equivalent wind speed can be derived by equivalent basic wind speed and equivalent ground roughness coefficient, and then the sum of wind and rain pressures can be get by Eq. (2).

Based on the aforementioned process, the fitting formula of equivalent basic wind speed is derived:

$$\begin{aligned} V_{10}^* &= V_{10} + f_1(V_{10}) f_2(R_h) f_3(\alpha) \\ &= V_{10} + \left(V_{10}^2 + 0.355V_{10}\right)\left(\exp(0.0038R_h) - 0.93\exp(-0.013R_h)\right)\left(6.125\alpha + 4.305\right)\times 10^{-4} \end{aligned} \tag{8}$$

The difference of equivalent ground roughness coefficient and ground roughness coefficient is so small that it can be simplified that $\alpha^* = \alpha$.

The procedures to calculate wind and rain loads using equivalent basic wind speed and equivalent ground roughness coefficient are listed as below:

1. First it needs to calculate equivalent basic wind speed V_{10}^* and equivalent ground roughness coefficient α^* using Eq. (8) for one specific condition.
2. The second step is calculating the sum of wind and rain pressure P_{total} using V_{10}^* and α^* through Eq. (1) and Eq. (2).
3. Then the wind and rain loads acting on a structure can be simulated with shape factor u_s and projected area A: $F_{total} = u_s P_{total} A$.

4. CONTRASTIVE ANALYSES OF SIMPLIFIED METHOD AND INTEGRAL FORMULA OF WIND AND RAIN LOADS

In this section a transmission tower model is used to validate the feasibility of simplified method to calculate wind and rain loads. It is impossible to simulate the wind and rain loads at all points on the transmission tower in an actual simulation. Thus, the transmission tower is simplified to 34 nodes that are used to apply the wind and rain loads, and the number of nodes increases from the bottom to the top of the tower. A schematic of the simplified tower is illustrated in Fig. 1 and the finite element model of the transmission tower is illustrated in Fig. 2. The height of the tower is 254 m, with Q235 and Q345 steel used. The cross-sections of the tower members consist mainly of steel tube, although a few are made of angle steel.

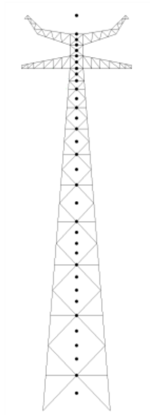

Fig. 1 Simplified transmission tower nodes

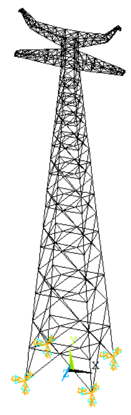

Fig. 2 Finite element model of transmission tower

The simulation parameters for fluctuating wind speed in this paper are as follows: (1) the power-law exponent is 0.12, 0.22 and 0.30; (2) the total time is 300 s, the time interval is 0.1 s, the cut-off frequency is 5 *Hz*, and the number of divided frequencies is 1024; (3) the horizontal fluctuating wind spectrum uses the Davenport power spectrum; and (4) the basic wind speed v_{10} is one of four classes: 10, 20, 30 or 40 m/s.

Six classes of rain intensities are employed: 0, 40, 80, 120, 160 and 200 mm/h, with the total number of conditions reaching 72. The vibration response of the transmission tower subjected to wind and rain loads is then calculated. The acquisition point of displacement is shown in Fig. 3. Due to the stochastic wind and rain loads, the tower displacement results for integration formula and simplified method are given as average values in Table 1 and Table 2 respectively. In Table 1, when α is 0.30 and v_{10} is 40 m/s, the maximum average displacement is 433.93 mm for rain intensity of 200 mm/h and 376.87 mm for pure wind, and the difference can reach 57.06 mm indicating that the contribution of rain load on the tower response cannot be neglected.

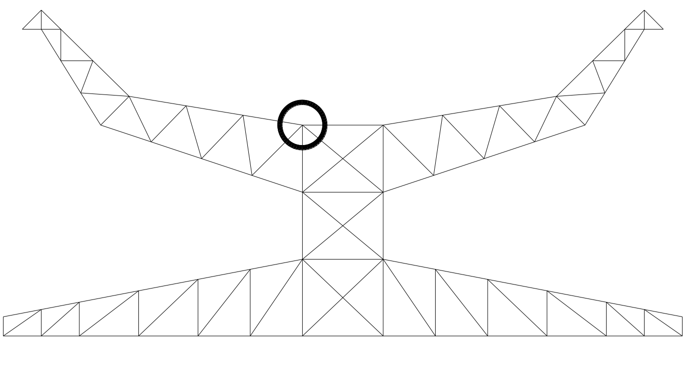

Fig. 3 Acquisition point of displacements

Table 1 Average tower tip displacements for integration formula

(1) α =0.12

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	7.9542	8.0087	8.0431	8.0731	8.1007	8.1266
20	31.672	32.108	32.384	32.624	32.844	33.052
30	71.202	72.675	73.603	74.414	75.158	75.858
40	126.54	130.03	132.24	134.16	135.92	137.58

(2) α =0.22

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	14.538	14.673	14.759	14.834	14.902	14.967
20	58.006	59.091	59.776	60.373	60.922	61.438
30	130.45	134.12	136.43	138.44	140.30	142.04
40	231.88	240.56	246.04	250.82	255.21	259.34

(3) α =0.30

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	23.599	23.881	24.059	24.214	24.357	24.491
20	94.253	96.508	97.931	99.173	100.31	101.39
30	212.01	219.62	224.42	228.61	232.46	236.08
40	376.87	394.91	406.29	416.22	425.35	433.93

Table 2 Average tower tip displacements for simplified method

(1) α =0.12

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	7.9542	8.0047	8.0391	8.0686	8.0968	8.1258
20	31.672	32.070	32.342	32.575	32.798	33.029
30	71.202	72.539	73.454	74.243	74.997	75.778
40	126.54	129.71	131.88	133.76	135.55	137.41

(2) α =0.22

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	14.538	14.641	14.712	14.773	14.831	14.891
20	58.006	58.824	59.383	59.864	60.323	60.798
30	130.45	133.20	135.09	136.71	138.26	139.88
40	231.88	238.39	242.86	246.73	250.43	254.28

(3) α =0.30

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	23.599	23.783	23.908	24.015	24.118	24.223
20	94.253	95.698	96.686	97.537	98.349	99.190
30	212.01	216.87	220.20	223.07	225.82	228.68
40	376.87	388.37	396.29	403.13	409.69	416.51

For comparing the two methods explicitly, the relative errors are calculated as given in Table 3. All relative errors are negative illustrating that the average displacements of simplified method is smaller than the results of integration formula, and it's obvious that the relative errors are so small that the maximum is only -4.02% indicating that the proposed simplified method to calculate wind and rain loads can satisfy the accuracy requirement of practical engineering.

Table 3 Relative errors of simplified method relative to integration formula

(1) α =0.12

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	0.00%	-0.05%	-0.05%	-0.06%	-0.05%	-0.01%
20	0.00%	-0.12%	-0.13%	-0.15%	-0.14%	-0.07%
30	0.00%	-0.19%	-0.20%	-0.23%	-0.21%	-0.11%
40	0.00%	-0.25%	-0.27%	-0.30%	-0.27%	-0.12%

(2) α =0.22

I (mm/h) / $V10$ (m/s)	0	40	80	120	160	200
10	0.00%	-0.22%	-0.32%	-0.41%	-0.48%	-0.51%
20	0.00%	-0.45%	-0.66%	-0.84%	-0.98%	-1.04%
30	0.00%	-0.68%	-0.98%	-1.25%	-1.45%	-1.52%
40	0.00%	-0.90%	-1.29%	-1.63%	-1.87%	-1.95%

(3) α =0.30

$V10$ (m/s) \ I (mm/h)	0	40	80	120	160	200
10	0.00%	-0.41%	-0.63%	-0.82%	-0.98%	-1.09%
20	0.00%	-0.84%	-1.27%	-1.65%	-1.96%	-2.17%
30	0.00%	-1.25%	-1.88%	-2.42%	-2.86%	-3.14%
40	0.00%	-1.66%	-2.46%	-3.15%	-3.68%	-4.02%

5. CONCLUSION

In this paper the simplified method to calculate wind and rain loads is validated. The simulation results show that rain load cannot be neglected. The relative errors are all very small indicating that the simplified method agrees well with the integration formula. The simplified method simplifies the calculating progress of wind and rain loads greatly which will promote the application of rain load in practical engineering.

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