INFLUENCE OF SEA SPRAY AND RAINFALL ON THE SURFACE WIND PROFILE DURING CONDITIONS OF STRONG WINDS

(*Research Note*)

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1. Introduction

Janin and Cermak (1988) have determined that airborne sediment in a wind tunnel substantially alters the low-level wind profile. This material apparently causes a reduction in wind speed since the pressure gradient force must accelerate both the air and the sediment, against the force of surface shearing stress.

In this brief paper, we explore whether atmospheric wind profiles would be expected to be modified during periods of high winds as a result of heavy rainfall or sea spray. Although there has been controversy regarding the effect of sediment load on pressure drop (e.g., Rangaraju, 1988), our assumption that the wind profile remains logarithmic is based on the physical modeling of Janin and Cermak (1988) in which even with sand loading in the atmosphere, the square root of the total kinetic energy profile remains logarithmic. This means that a given pressure gradient force can accelerate either air, or a combination of air and a suspended material but when suspended material is present, the actual air velocity will be less. This Note represents an extension of Janin's study of sediment to the suspension of water in the atmosphere. If the effect of the suspended water mass were significant, there could be substantial effects on the aerodynamic response of buildings and other structures in high winds.

2. Hypothesis

If the pressure gradient force is assumed to be the same with and without the water loading (e.g., rain droplets; sea spray) and in both cases the flow has reached a steady-state balance between the pressure gradient force and the surface shearing stress, then the kinetic energy as a function of height in the surface layer should be the same for both cases. Thus,

$$\rho_0 u_0^2 = \rho_a u_a^2 + \rho_w u_w^2 \tag{1}$$

where ρ_0 and u_0 are the density of the air and the velocity in the absence of suspended water; ρ_w and u_w are the density of the suspended water present per

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unit volume of air and the velocity of the water; and ρ_a and u_a are the density and the velocity of the air in the unit volume of air which contains the suspended water, respectively.

If the air and suspended water are assumed to be in equilibrium so that $u_a = u_w$, then Equation (1) can be rewritten as:

$$\rho_0 u_0^2 = (\rho_a + \rho_w) u_a^2.$$

Thus,

$$u_a = u_0 \left(\frac{\rho_0}{\rho_a + \rho_w} \right)^{1/2}. \qquad (2)$$

Since $\rho_0 \cong \rho_a$ because of the small volume affected by the individual water droplets and $\rho_w \ll \rho_0$, in general, Equation (2) can be rewritten as:

$$u_a \cong u_0 \left(1 - \frac{\rho_w}{\rho_0} \right)^{1/2}.$$

If the surface-layer wind profile in strong winds is assumed to be of the same form with or without water loading, then since:

$$u_0 = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \qquad (3)$$

with $z_o = 0.032\ u_*^2/g$; $z \geq 0.000015$ m, $\kappa = 0.35$ and u_* is the shearing stress (i.e., $\tau_0 = \rho_0 u_{*0}^2$; $\tau_a = \rho_a u_{*a}^2$ – where the droplets are not assumed to influence the shearing stress directly), then:

$$u_a = u_0(z) \left(1 - \frac{\rho_w}{\rho_0} \right)^{1/2} = \frac{u_{*a}}{\kappa} \ln \frac{z}{z_{0a}}. \qquad (4)$$

3. Results

Figure 1 presents the alteration of the surface wind profile due to different values of water loading (constant with height) and three values of the shearing stress.

With respect to sea spray, values of water loading would decrease with height. If sedimentation (and therefore, transfer of momentum) between different levels is ignored, Equation (4) would need to be modified such that:

$$u_a(z) = u_0(z) \left[1 - \frac{\rho_w(z)}{\rho_0} \right]^{1/2} \qquad (5)$$

If $\rho_w(z) = \hat{\rho} e^{-az}$, where a is likely on the order of $0.1\ \mathrm{m}^{-1}$ and $\hat{\rho}$ is the surface value of water loading, then the results shown in Figure 2 are obtained.

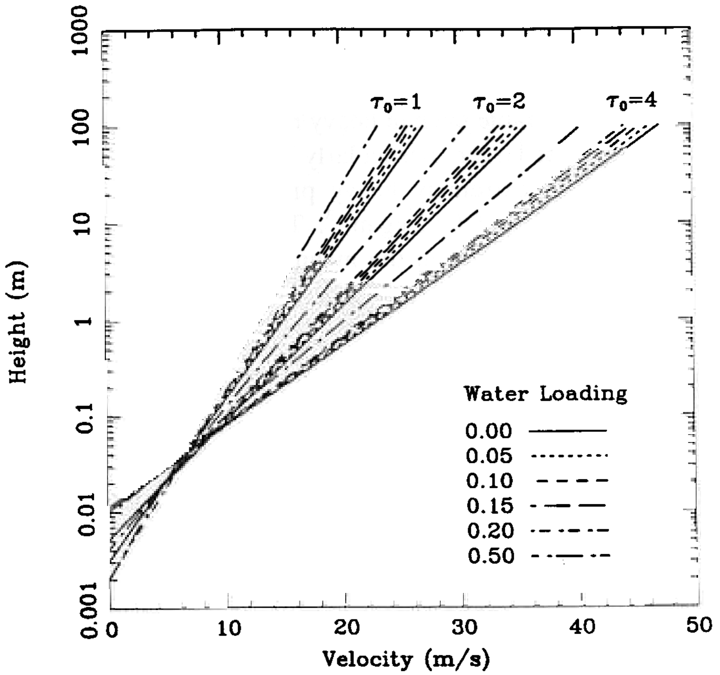

Fig. Velocity profile with respect to height as a function of stress (N/m^2) and water loading (kg/m^3).

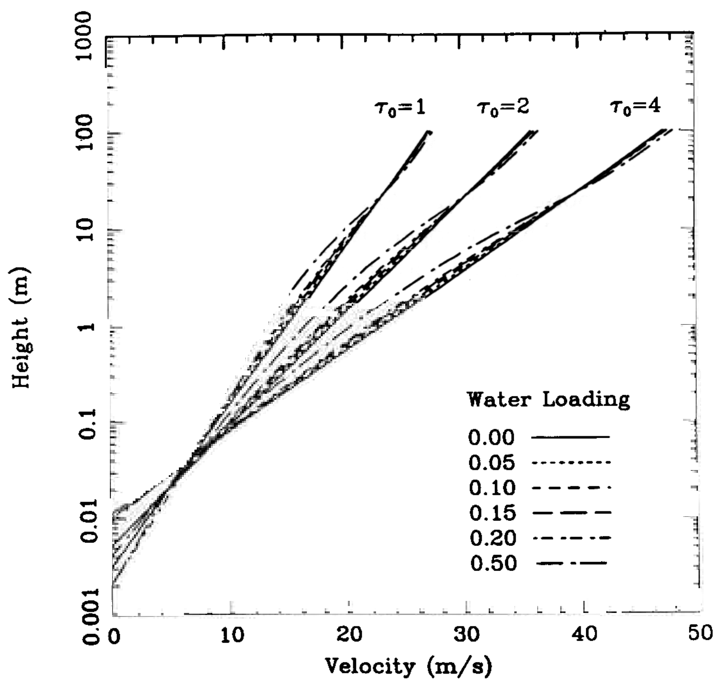

Fig. 2. Same as Figure 1 but the water loading is exponentially decaying with height.

Rainfall, in contrast, would have a uniform profile of water mass, although momentum would be transferred downward by the rainfall. Caldwell and Elliott (1972) showed that the mean wind profile change due to the transfer of momentum by rainfall is barely detectable even in heavy rain, although the effect on the stress distribution is somewhat larger, particularly in the lowest 10 m. Realistic values of rainwater density in extremely heavy precipitation events (e.g., a tropical cyclone) are on the order of 0.02 kg m^{-3}. Thus, under the assumptions stated above, the water loading effect on the mean wind profile is almost negligible as can be seen in Figure 1.

4. Conclusions

We have shown, through simple calculations, that the water loading effect on the surface-layer wind profile during strong wind conditions is negligible in rain water loading cases. However, this effect can be significant in white-cap sea-spray situations. When the water loading is large, which is most likely to occur near the sea surface when waves break, a 15% reduction of the near surface wind could be expected. Due to the exponential decay of sea spray loading with respect to height, the reduction of wind is minimal above 10 m. The conservation of kinetic energy is used in this calculation; however, in real situations, evaporation and advection of energy may be important. These effects are not considered in this study. The influence of the lower wind speeds with suspended water droplets on wind loading of structures needs to be examined. It would be expected that aerodynamic lift effects would be reduced from the equivalent wind profile without sea spray, while normal stresses would be in a somewhat different form since a portion of the kinetic energy is concentrated in droplets.

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References

Bagnold, R. A.: 1941, *The Physics of Blown Sand and Desert Dunes*, Methuen, London.

Caldwell, D. R. and Elliott, W. P.: 1972, 'The Effect of Rainfall on the Wind in the Surface Layer', *Boundary-Layer Meteorol.* **3**, 146–151.

Janin, L. F. and Cermak, J. E.: 1988, 'Sediment-Laden Velocity Profiles Developed in a Long Boundary-Layer Wind Tunnel, *J. Wind Eng. and Industrial Aerodynamics* **28**, 159–168.

Rangaraju, K. C.: 1988, 'Contribution of K. G. Rangaraju about the Paper: Sediment-Laden Velocity Profiles Developed in a Long Boundary-Layer Wind Tunnel, by L. F. Janin and J. E. Cermak', *J. Wind Eng. and Industrial Aerodynamics* **28**, 172–173.

Wipperman, F. K. and Gross, G.: 1986, 'The Wind-Induced Shaping and Migration of an Isolated Dune: A Numerical Experiment', *Boundary-Layer Meteorol.* **36**, 319–334.