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Investigation of Speed-up in Atmospheric Boundary Layer Flow Over Two-dimensional Complex Terrain

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Abstract

Pressure driven horizontally homogeneous atmospheric boundary layer flow has been numerically modelled using Reynolds Averaged Navier–Stokes (RANS) equations with a Shear Stress Transport (SST) turbulence closure. The flow over full scale two-dimensional isolated and consecutive sinusoidal hills has been studied. Different hill slopes and shapes have been simulated to investigate the effect of hill profile on wind speed-up. Turbulent kinetic energy, mean velocity values and the rapid distortion theory have been used to estimate the standard deviation of turbulent velocity fluctuations to offer a prediction of the three-second gust wind speed in accordance to usual automatic weather station measurements. Results from the computational study were similar to measurements made using a 1:500 scale model of the numerical environment in a boundary layer wind tunnel. It was found that above the crest, the Australia/New Zealand Wind Loading Standard (AS/NZS 1170.2) standard predicted lower wind speed-ups up to heights about half the hill height, compared to computational fluid dynamics (CFD) simulations for isolated hills with a shallow slope ($\phi < 0.45$). Conversely, the AS/NZS 1170.2 standard accurately predicted wind speed-ups for isolated hills with steeper slopes ($\phi \geq 0.45$). The ASCE standard failed to predict gust speed-up values across all heights above the crest. Similar characteristics as with isolated hills was found when testing a more complex consecutive hill profile. The AS/NZS 1170.2 standard failed to predict large separation zones found in the lee of isolated hills. Results suggest that the topographical section of the current AS/NZS 1170.2 standard needs revision.

Introduction

Estimating wind forces on structures, utilisation of wind power, observations at meteorological stations, dispersion of pollutants and many other phenomena are significantly affected by airflow over complex terrain. Topographic features, such as hills and ridges, can significantly increase the effects of extreme weather by increasing near-surface wind speeds that result in larger structural loads. Miller et al. [15] showed that even the low-lying topography of the Bermuda Islands, which rise to a maximum elevation of $76m$, will cause a significant increase in wind speed and therefore the structural load. The first numerical and theoretical studies to investigate the effects of low topography on airflow relied on techniques of asymptotic matching, where the equations of motion are linearised [5, 12, 13, 19]. However, on steep hills, assumptions of linearity do not apply due to the complicated behaviour of surface flow and flow separation. To fully describe the flow field a numerical model is required to solve the non-linear equations of motion [14]. Through the use of CFD codes and wind-tunnel measurement, non-linear models have shown to offer good predictions of wind speed-up and separation zones [2, 3, 5, 7].

In the complex terrain of a country like New Zealand, the hill-shape multiplier is an important factor in the calculation of design wind speeds in order to achieve a safe level of structural design for buildings. Recently, predictions from seven different wind loading standards have been reviewed and compared against full-scale measurements of wind flow over complex terrain [10]. It was found that the current methods provided in these standards to estimate the wind speed-ups do not adequately account for the effects of land features that are more complicated than the smooth single-hill shapes that are considered in the standard. Applying the method provided in the standards to more complicated hill situations could seriously under- or over-predict the correct design wind speeds in such complex terrain. This paper is aimed at remedying this undesirable situation by investigating the wind-speed up at the crest of hills in complex terrain through numerical and experimental methods.

Methodology

Two-dimensional CFD models of simplified hills were developed for atmospheric boundary layer (ABL) flow with conditions consistent with category 2 terrain roughness (AS/NZS 1170.2 [1]). For this study, the commercial code *ANSYS/CFX* 17 was employed. Two-dimensional steady RANS equations are solved using an element-based finite volume method. A SST turbulence closure was chosen due to it exhibiting a good similarity to reality [16]. High-resolution discretisation schemes have been used for both the advection and turbulence terms. In both the wind tunnel and the ABL, the airflow is predominantly generated by horizontal pressure differences. Therefore, to aid in comparison between experimentation, simulation and field studies a pressure-driven numerical approach was taken. This was achieved by implementing an adapted mathematical model of the ABL in strong winds offered by Deaves and Harris [9] in the derivation of the mean inlet profiles [18]. To model the ABL, inlet conditions were set using equations (1) to (3) for mean wind velocity ($\overline{U}$), turbulence kinetic energy (k) and the specific rate of dissipation (ω) respectively [16, 18].

$$\overline{U}(z) = \frac{u_*}{\kappa}\left(ln\left(\frac{z}{z_0}\right) + C_{U1}\left(\frac{z}{H}\right) + C_{U2}\left(\frac{z}{H}\right)^2 \dots \right. \\ \left. \dots + C_{U3}\left(\frac{z}{H}\right)^3 + C_{U4}\left(\frac{z}{H}\right)^4\right) \quad (1)$$

$$k(z) = u_*^2\left(C_{k1} + C_{k2}\left(1-\frac{z}{H}\right)^2 + C_{k3}\left(1-\frac{z}{H}\right)^4 \dots \right. \\ \left. \dots + C_{k4}\left(1-\frac{z}{H}\right)^6\right) \quad (2)$$

$$\omega(z) = \frac{k(z)}{\kappa u_* z}\left(1 + (1+C_{U1})\left(\frac{z}{H}\right) + (1 + C_{U1} \dots \right. \\ \left. \dots + 2C_{U2}\left(\frac{z}{H}\right)^2 + (1 + C_{U1} + 2C_{U2} + 3C_{U3})\left(\frac{z}{H}\right)^3\right) \quad (3)$$

H is the domain height, κ is Von Karman's constant, u_* is the friction velocity ($U_{ref}(10m) = 10ms^{-1}$), z is the height above local ground, and the aerodynamic roughness length is $z_0 = 0.02m$ (Category 2 terrain [1]). All coefficients have been calculated through semi-analytical and CFD methods [16, 18]. With equations (1) to (3) set at the inlet, symmetry planes for the top and sides of the computational domain, a zero-gauge pressure outlet condition and an appropriate rough-wall treatment for the ground surface, the modelled profiles will be equivalent at the inlet and outlet of the computational domain, producing a pressure driven horizontally homogeneous ABL [18]. It is essential to ensure that the inlet boundary conditions are combined with an appropriate rough-wall treatment to achieve the correct ABL profiles. In *ANSYS/CFX* 17 an equivalent sand-grain size (k_s) is used to model the aerodynamic roughness. Blocken et al. [4] defines the relationship between z_0 and k_s as,

$$k_s = 29.6 z_0 \tag{4}$$

Blocken et al. [4] also states that there are four requirements that should be satisfied simultaneously when the aerodynamic roughness is expressed as an equivalent sand-grain size,

1. High mesh resolution at the surface;
2. The roughness height lies within half of the wall-adjacent cell;
3. The relationship between sand-grain size and aerodynamic roughness must be known;
4. A horizontally homogeneous ABL is required.

The first requirement is essential for all CFD simulations, however, in this study it is limited by the second requirement. In this study the first layer thickness (vertical height of the wall-adjacent cell) is at least twice the height of the equivalent sand-grain size. Using equations (1) to (4) the third and fourth requirements have been satisfied. The dimensions of the computational domain have been chosen in such a way that the flow becomes fully developed both upstream and downstream of the hill, and produces no blockage effects. Hill profiles have been modelled as simple shapes defined by equations (5) and (6).

$$f(x) = \frac{H}{2} cos\left(\frac{\pi \phi x}{H}\right) \tag{5}$$

$$\phi = \frac{H}{2L_u} \tag{6}$$

where ϕ is the the hill slope and L_u is the characteristic hill length. Figure 1 depicts the dimensions of the computational domain with a representative isolated hill. Numerical uncertainty and mesh refinement were quantified through the implementation of the Grid Convergence Index (GCI) method described by Celik et al. [8]. The mesh refinement study was conducted using the $\phi = 0.45$ hill alongside three different mesh resolutions; the number of elements in each mesh were $N = 87173, 41625$ and 24288. The result of a mesh refinement study was a mesh with ≈ 87000 elements that gradually increase in size from the bottom to the top of the computational domain (figure 2).

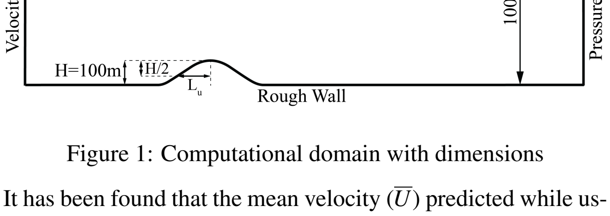

Figure 1: Computational domain with dimensions

It has been found that the mean velocity ($\overline{U}$) predicted while using RANS equations differs from the mean (in time) magnitude of the velocity or mean speed ($\overline{W}$) [17]. Therefore, equations offered by Popiolek [17] have been used to estimate the mean speed values ($\overline{W_e}$) and the standard deviation of speed (σ_e) using equation (7) and (8) and mean values predicted through CFD simulations.

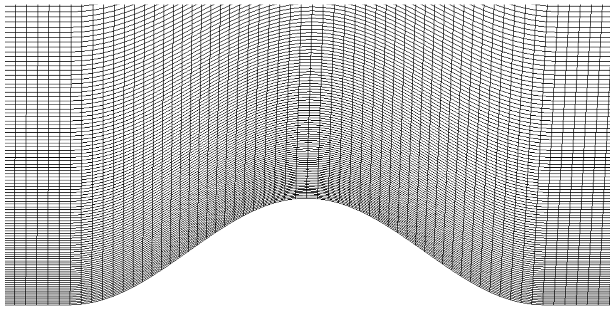

Figure 2: Refined computational mesh

$$\overline{W_e} = \begin{cases} \overline{U} - 0.036k^{0.5} + 0.797\frac{k}{\overline{U}} - 0.179\frac{k^{1.5}}{\overline{U}^2} & if\ \frac{k^{0.5}}{\overline{U}} < 1.592 \\ 0.287\overline{U} + 1.226k^{0.5} & if\ \frac{k^{0.5}}{\overline{U}} \geq 1.592 \end{cases} \tag{7}$$

$$\sigma_e = \overline{U}^2 - \overline{W_e}^2 + 2k \tag{8}$$

To allow for comparison against current wind loading standards, the gust wind speeds upstream and at the crest have been approximated through the use of the estimated wind speed and standard deviation of speed and rapid distortion theory [6] in equation (9) [11, 15],

$$U_{gust} = \begin{cases} \overline{W_e} + g\sigma_e & \text{Over flat terrain.} \\ \overline{W_e}\left(1 + gI_u\left(9/5 - 4S/5\right)^{0.5}\right) & \text{Above a 2D crest.} \end{cases} \tag{9}$$

where g is a peak factor, I_u is the turbulence intensity and S is the mean speed-up. Measurements were made in the boundary-layer wind-tunnel at the University of Auckland at a nominal scale of 1:500. The model tested was two-dimensional, extending across the full width of the wind tunnel perpendicular to the flow. The wind-tunnel test section is 20 m long, 2.5 m high, and 3.6 m wide, and the reference wind-tunnel speed at a height of $20mm$ ($10m$ in full-scale) above the floor was $6.56ms^{-1}$. The same terrain category that was used in the CFD simulations was also replicated for the wind-tunnel tests. A cobra probe was used to measure the vertical wind-speed profiles.

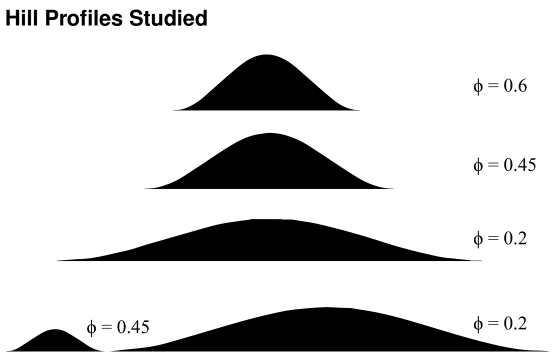

Figure 3: Hill geometries used in CFD simulations (The profiles here are not shown to scale)

Three isolated two-dimensional full-scale hills of varying slope ($\phi = 0.2, 0.45, 0.6$) were modelled with a hill height of $H = 100m$. Additionally, as this study primarily focused on testing the limits of the current AS/NZS 1170.2 wind-loading standard, a fourth hill was modelled; this hill was a simplified version of the Belmont Hill in Wellington studied by Flay et al [10] with the first hill being half the height of the second ($H = 50m$ *and* $100m$). Figure 3 shows the tested hill profiles. Wind tunnel measurements where made with an isolated two-dimensional hill of $\phi = 0.45$.

Results

The fine mesh results were used in all CFD studies as, found through the GCI method, the relative error is in an acceptable range and the relative extrapolated error is very small (table 1).

	U_{crest} at $z = 10m$
$e_a^{21}(\%)$	6.28
$\mathrm{GCI}_{fine}^{21}(\%)$	0.727

Table 1: Results of mesh sensitivity analysis for an isolated hill of $\phi = 0.45$ $H = 100$

Wind speed-up is equal to the the ratio of wind speed above the crest of the hill divided by the reference wind speed at the same local height above the ground some distance upstream where the flow is unaffected by the hill. The gust speed-up at the crest of each hill obtained from two-dimensional CFD modelling and wind tunnel testing is compared against the AS/NZS 1170.2 and ASCE standards in figure 4. At higher slopes ($\phi = 0.45$ and 0.6), the current AS/NZS standard is in agreement with the predicted values and those obtained through wind tunnel testing. Conversely, at a lower slope ($\phi = 0.2$) the AS/NZS standard failed to accurately predict the speed-up caused by the hill. It severely under-predicts the near surface ($^z/_H = 0$ to 3) wind speed-up with a maximum difference of 0.2 between the standard and predicted CFD values. This is significant due to wind loads being dependent on the velocity squared. The largest wind speed-up predicted was $S_{gust} \approx 1.7$ at $z/H = 0.1$ on hills with a slope of $\phi \geq 0.45$. The wind speed-up profile predicted for hills of $\phi \geq 0.45$ does not vary significantly with increasing hill slope. This characteristics is predicted by the AS/NZS 1170.2 standard. The ASCE standard is seen to under-predict gust speed-up across all heights above the crest.

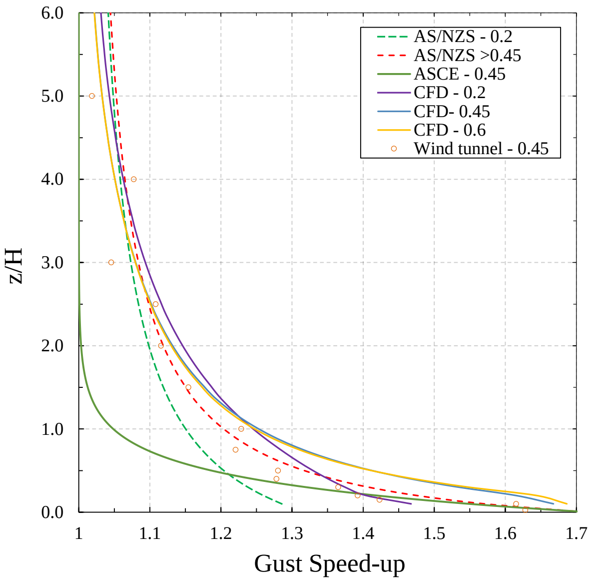

Figure 4: Gust speed-up profiles: showing results from the wind tunnel test, CFD simulations, AS/NZS 1170.2, and ASCE for a hill of height $H = 100m$. The test type is followed by the hill slope in the legend.

When looking at the consecutive hills case, the upstream hill (hill 1) does not appear to affect the gust speed-up profile of the downstream hill (hill 2) compared to their respective isolated hill cases. Figure 5 shows the gust speed up profiles over the consecutive hills against the AS/NZS 1170.2 standard, it can be seen that similar behaviour to the isolated cases is exhibited. Unlike the consecutive hill tests of [7], this may be due to the first hill not producing a significant increase in the turbulent kinetic energy at the second hill and so the gust speed-up remains unaffected. A likely reason for this is the small size of the first hill. The contour plot of turbulence kinetic energy in figure 6 highlights how the turbulent kinetic energy generated by separation in the lee of the first hill does not significantly propagate to the second.

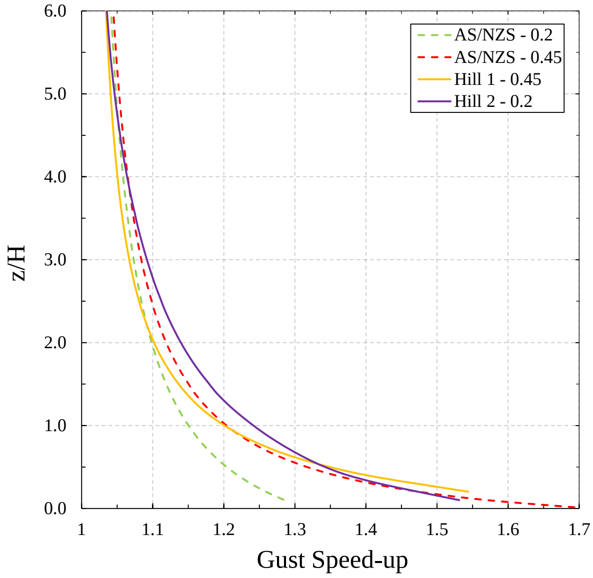

Figure 5: Gust speed-up profiles over consecutive hills. The test type is followed by the hill slope in the legend.

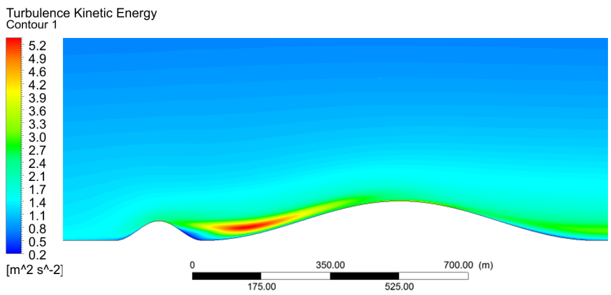

Figure 6: Turbulent kinetic energy contour plot of consecutive hills

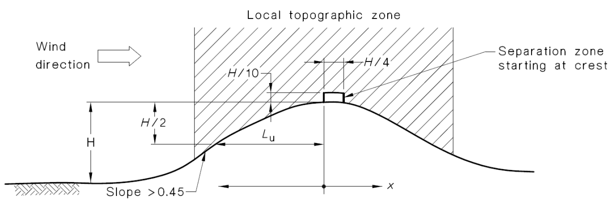

Figure 7: Separation zone for hills and escarpments having an upwind slope greater that 0.45 [1]

The AS/NZS 1170.2 standard states that flow separation starts at the crest for hills of slope $\phi > 0.45$ and reattachment occurs $H/4$ downstream (figure 7)—25m downstream of the crest for a 100m high hill. However, as shown in figure 8, separation and reattachment occur approximately at 80m and 472m downstream of the crest respectively. This predicted separation zone exceeds the limits of the current standards definition suggesting this characteristic needs revision.

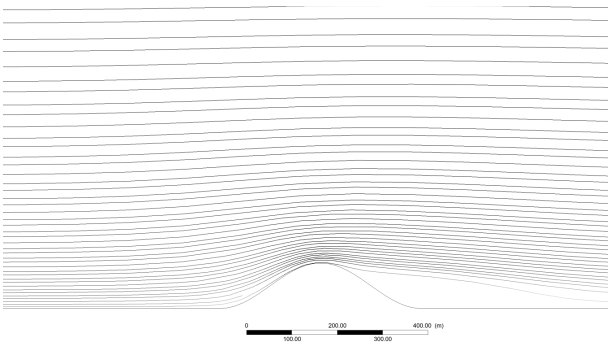

Figure 8: Streamlines showing the separation zone predicted using CFD for an isolated 2D hill with $\phi = 0.45$

Conclusions

The current AS/NZS 1170.2 standard predicts the gust speed-up over isolated hills with a slopes of $\phi \geq 0.45$ with good accuracy. It correctly assumes a constant gust speed-up profile for hill slopes of $\phi \geq 0.45$ and produces profiles of a similar shape to those predicted in this papers numerical study. However, When tested against a hill slope of $\phi = 0.2$ the standard failed to accurately predict the gust speed-up in the near surface region ($z/H = 0$ to 3). When calculated using the standard, speed-up values close to the surface deviated by up to 0.2 when compared against CFD results. This would lead to under-designed buildings not suitable for their environment. When testing consecutive hills where the upstream hill is steeper and smaller than the downstream hill, there was no change to the gust speed-up profiles at the crest of either hill and CFD results exhibited similar characteristics to isolated hills when compared to the AS/NZS 1170.2 standard. Additionally, the standard incorrectly states that flow separation originates at the crest of the hill for all slopes of $\phi \geq 0.45$. CFD results show that separation occurs further downstream from the crest. Due to these conclusions the topographic section of the AS/NZS 1170.2 standard may need revision.

Acknowledgements

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