COMPARISON OF WIND FLOW OVER A STEEP ESCARPMENT UTILISING CFD, WIND TUNNEL AND FULL-SCALE MEASUREMENT TECHNIQUES

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Abstract

Computational Fluid Dynamics predictions of wind flow perturbation over a tall steep escarpment are compared with full-scale and wind tunnel scale measurements. Three turbulence models are incorporated into the CFD study including the Standard k-ε model, Reynolds Stress model and Large Eddy Simulation.

Background

Previous full-scale and wind-tunnel scale measurements were performed on a large steep escarpment to verify code estimates of the 'topographic multiplier' and to investigate flow separation [2] [3]. The site chosen for the study was the Mt Dandenong escarpment in Melbourne. Cup anemometers and vanes were installed upon towers at the base and summit of the escarpment to measure wind flow perturbation over the topography, and the results were compared to a 1:1000 scale wind tunnel simulation. This paper will compare the results of the experimental work, for one wind direction, with a Computational Fluid Dynamics (CFD) model simulation utilising three different turbulence models.

CFD Modelling

CFD analysis of wind flow over the Mt Dandenong escarpment was performed using the commercially available software package Fluent. Fluent provides modelling capabilities for a range of incompressible and compressible, laminar and turbulent fluid flow problems. For all flows, Fluent solves the Navier-Stokes conservation equations for mass and momentum:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_i}+\rho g_i+F_i \tag{2}$$

where p is the static pressure, τ_{ij} is a stress tensor, and g_i and F_i are gravitational, acceleration and external body forces.

For flows involving heat transfer and convection, an additional equation for energy conservation is solved. Natural convection will play an important role in the perturbation of wind flow over the Mt Dandenong escarpment at low wind speeds while buoyancy forces dominate the inertial forces of the flow. At higher wind speeds that are normally of interest to the structural engineer, atmospheric stability effect will become less important. For this reason, a neutrally stratified atmosphere was assumed for the wind tunnel and full-scale measurements and the energy conservation equation was not solved for the current CFD study.

Fluent uses the pre-processing software package Gambit for geometry modelling and mesh generation. The boundaries of the model shown in Figure 1 and 3 are aligned along a 308° bearing and correspond with the section of escarpment modelled in the wind tunnel experiment [2]. A velocity inlet boundary condition was specified 5 km upstream of the escarpment crest approximating a category 3 [4] velocity profile. Zero pressure outlets were specified 3.5 km downstream of the escarpment crest and along a horizontal plane 3 km above ground level. The side walls were modelled as a symmetry boundary condition.

A 3D unstructured tetrahedral grid mesh was utilised for the current study to suit the relatively complex curved geometry of the modelled escarpment face and the desire to readily cluster cells in zones in regions of expected flow separation (Figure 1). A refined mesh was utilised around the crest of the Mt Dandenong escarpment since the prediction of separation due to an adverse pressure gradient depends heavily on the resolution of the boundary layer upstream of the point of separation.

Three turbulence models were investigated during the study including the Standard k-ε model, the differential Reynolds Stress model (RSM) and Large Eddy Simulation (LES). The transport equations used for the Standard k-ε model and the RSM are obtained from Equations 1 and 2 using a time averaging procedure known as Reynolds (ensemble) averaging.

The Standard k-ε model is a semi-empirical, eddy viscosity model in which the Reynolds Stresses are assumed to be proportional to the mean velocity gradients, with the constant of proportionality being the turbulent viscosity. The model adopts an isotropic description of the turbulence through this assumption and is thus not well suited for flows in which anisotropy of turbulence significantly effects the mean flow.

It has been demonstrated through previous full-scale and wind tunnel measurements (eg. [1]) that the perturbation of Reynolds stresses over steep hills and escarpments will result in highly anisotropic turbulence in which velocity and length scales vary with direction. The RSM computes the individual Reynolds stresses (UU, VV, WW, UV, UW, VW) and provides a better alternative for modelling anisotropic turbulence.

Both Reynolds averaging turbulence models can be used with either standard or non-equilibrium wall functions. Standard wall functions utilise a standard logarithmic type wall function whilst a non-equilibrium wall function provides a mean velocity that is sensitised to pressure gradient effects. For the current study, a standard wall function was used for the Standard k-ε model and a non-equilibrium wall function was assigned to the RSM.

LES is a developing turbulence modelling technique in which large eddies are computed in a transient simulation using a set of filtered Navier-Stokes equations. Filtering is essentially a manipulation of Equations 1 and 2 to remove only the eddies that are smaller than the size of the filter (usually the mesh size). Large eddies are resolved directly while small sub-grid eddies are modelled. Time-dependent simulation allows statistical properties of the flow to be obtained.

A comprehensive LES study is often computationally expensive requiring fine time step increments that should be roughly proportional to the eddy-turnover time. Nevertheless, a preliminary LES model was incorporated into the current study, for one time increment, to detect the presence of any large scale re-circulating flow over the escarpment, particularly in the lee of the escarpment crest.

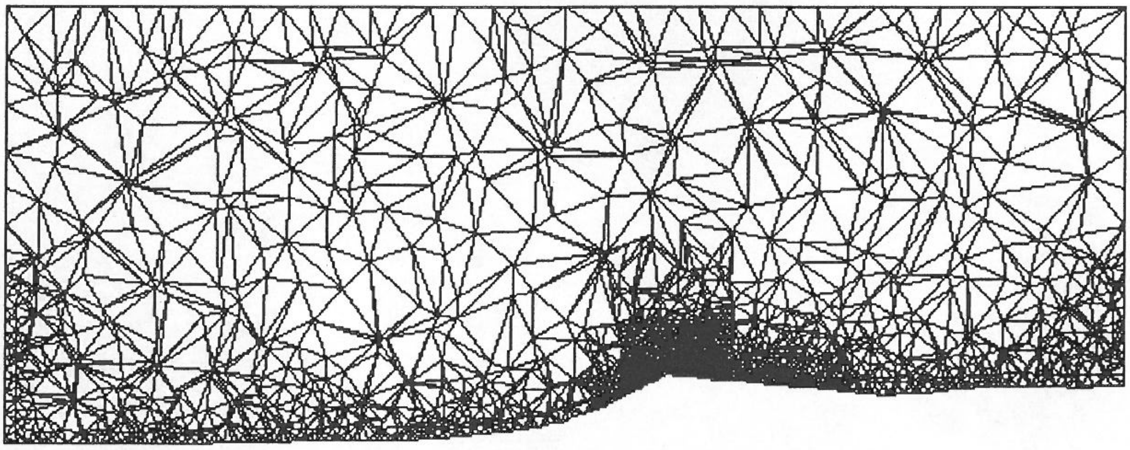


Figure 1 2D section of the unstructured tetrahedral mesh.

Results and Discussion

Normalised mean wind speed profiles above the crest of the Mt Dandenong escarpment (summit tower location) are shown in Figure 2. Both the measurements and CFD models clearly demonstrate separation of flow over the crest as is evident by the drop in wind speed magnitude below approximately 50 m. At elevations above the separation bubble, best agreement is found between the wind tunnel results and the LES turbulence model.

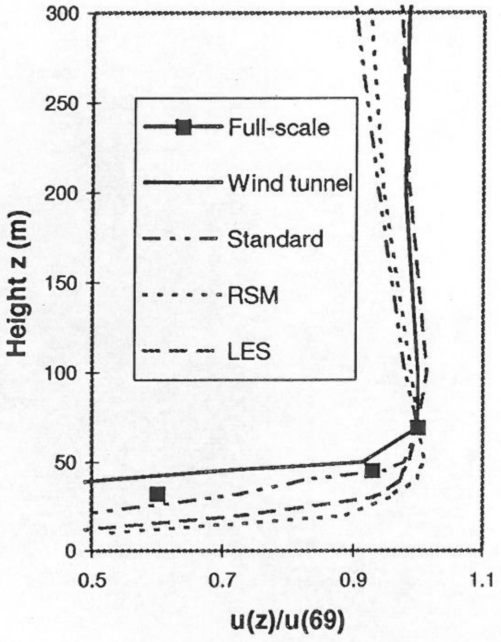


Figure 2 Vertical profile of mean wind speed above the Mt Dandenong escarpment crest.

Velocity gradients defining the shear layer across a vertical plane section following the 308° bearing are illustrated in Figure 3, as obtained from the RSM analysis. A stagnation in velocity is evident along the windward face of the escarpment followed by a rapid acceleration of flow over the crest.

Velocity vectors as obtained from an LES analysis are shown in Figure 4a, illustrating the rapid convergence of streamlines toward the escarpment crest followed by flow separation. Evidence of reverse flow within the separated shear layer at low elevations is shown in the 2D close-up view of Figure 4b. It is noted that of the three turbulence models used to simulate flow over the escarpment, only the LES model provided graphical evidence of flow reversal in the velocity vector diagrams.

Momentum and mass are mostly transported over the escarpment by the mean flow and large scale eddies. Large eddies tend to be dictated by the geometries and boundary conditions of the flow whilst smaller eddies are less dependent and tend to be more isotropic. Larger eddies with energy below approximately 1 Hz will be of most interest to the structural engineer designing typical summit structures to withstand the impact of wind loading (eg. transmission towers). The ability of the LES to *solve* macroscopic flow features and *model* small scale turbulence makes the method attractive for this purpose.

Conclusions

Computational Fluid Dynamics predictions of wind flow perturbation over a tall steep escarpment were found to compare well with the results from previous full-scale and wind tunnel scale measurements. Three turbulence models were incorporated into the CFD study including the Standard k-ε model, Reynolds Stress model and Large Eddy Simulation. The ability of the Large Eddy Simulation to *solve* macroscopic flow features and *model* small scale turbulence makes the method attractive for modelling wind flow over large hills and escarpments.

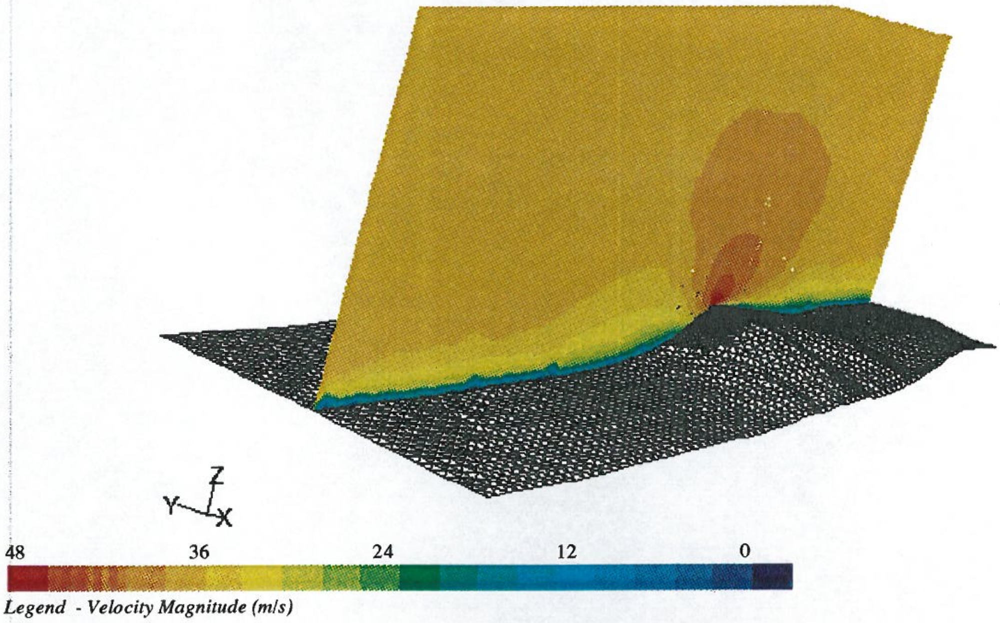
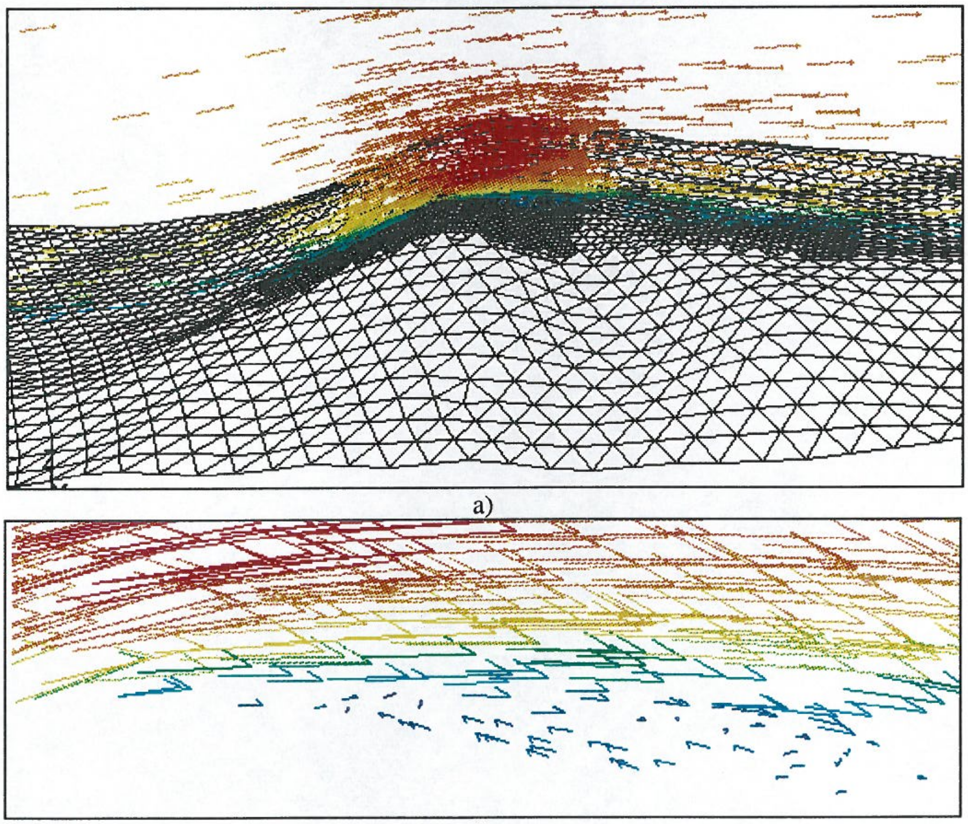


Figure 3 Velocity contours above the Mt Dandenong escarpment (wind flow in x direction).



a)

b)

Figure 4 Velocity vectors above the Mt Dandenong crest.

References

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