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SOME COMPLICATIONS FROM MODELLING THE WIND FLOW OVER COMPLEX TERRAIN AT SMALL GEOMETRIC SCALES

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ABSTRACT

The significant issues which affect the accuracy of wind-tunnel simulations of the wind flow over complex terrain are discussed. Some theoretical guidelines which can assist the modeller to assess the consequences of choosing a small geometric scale are noted. However further work is needed to improve our understanding of the problem and to develop quantitative limits for accurate simulations.

INTRODUCTION

The effects of complex terrain on the wind flow close to the ground is of great importance for the estimation of wind loads on buildings and structures which are situated in hilly terrain. An understanding of these effects is also useful for other applications such as the prediction of wind energy resources, pollution dispersal estimates and for land management. Although there is a growing data base from reliable measurements over isolated hills such as the full-scale measurements (Taylor and Teunissen, 1987) and wind-tunnel model tests (Teunissen et al, 1987) over the Askervein Hill, there is very little information involving complex terrain. The chronic lack of reliable full-scale measurements of wind flows over complex terrain is due presumably, to the formidable practical difficulties associated with such a project. The dearth of practical, quantitative information on conditions in complex terrain is evident in the world of the practising engineer and mirrored in the national standards for wind loads such as NZ4203/4 (1992) and AS1170.2 (1989). These codes use crude wind-speed multiplying factors for topography which are based on limited experimental data from simple, isolated hills.

As a result of the lack of reliable prediction methods for flows over complex terrain, there has been a steady demand for wind-tunnel tests featuring sites in such surroundings. A fundamental task facing wind-tunnel users is to establish confidence in the accuracy of their wind-tunnel tests using reliable full-scale data through bench-mark testing. This has been done with single isolated hills such as Askervein hill over a range of model scales down to 1:2500 (Teunissen et al, 1987) and some modelling techniques have developed accordingly. In contrast, no such quantitative help is available for modellers of small-scale complex terrain models. There are however, several papers such as Britter (1982), Tieleman (1982) and Cermak (1984) concerning the theoretical issues involved in such simulations.

Successful modelling of complex terrain sites requires that there is sufficient terrain included in the model to ensure that the incident boundary-layer delivered by the wind tunnel at the upstream edge of the model is fully modified to the correct near-field profile by the time it reaches the site of interest. The only alternative is to impose the local low-level wind flow conditions directly on an isolated site model using grids, spires and fences. However, details of the local conditions would have to be known in advance and faithfully reproduced.

In addition to the problems of full-depth simulation modelling, the effects of scale on the accuracy of the wind flow over a complex terrain model in the wind-tunnel are not fully understood. Some attention to scaling problems for large-scale modelling has been reported by Zhao Y. Wang et al (1996) but the issues must be expected to intensify when scales of about 1:1,000 and smaller are contemplated. These issues relating to the geometric scale of the complex terrain model and the resulting accuracy of the modelled flow are the subject of this paper.

TOPOGRAPHIC MODEL

Model Size

In order to create an accurate near-field flow pattern over the area of interest, a sufficiently long fetch over the upwind terrain is required. For isolated hills this has not been a problem as the up-wind fetch is determined by the length of roughened floor required to generate a correctly scaled boundary-layer with the required level and size of the turbulence. However there is very little help when dealing with complex terrain where the boundary layer is modified in a unique way by the topography upstream of the site. In this case, a decision on the length of upstream fetch has to be made using a combination of past experience, some guess-work and consideration of the practical limitations. Of course some on-site wind-speed measurements with which to compare the modelled conditions would be invaluable in assessing the success of the model but such luxuries are very often not available. Many researchers such as the writer only have the use of relatively small wind tunnels and as a result, are under pressure to reduce the model scale beyond normal limits when confronted with a complex terrain simulation. Quantitative information on what constitutes an adequate length of upstream topography in order to ensure the correct site conditions is badly needed. The extent of the full-size area of interest and the working area of the tunnel will normally determine the maximum geometric scale of a suitable model.

Tunnel Blockage

The desired model scale should be chosen to keep the model sufficiently small in order to avoid significant tunnel blockage effects. The wind-tunnel roof should lie beyond the maximum height of influence of the model so that the deflected flow stream-lines over the hill model are unaffected by the roof. In practical terms, to achieve zero blockage the nominal (usually zero) pressure gradient evident along the empty tunnel should not be affected by the insertion of the model.

The down-wind length of the model is just as important as the vertical cross-section of the model. For negligible blockage over isolated hill models, Goh (1981) concluded that the roof height should be greater than 3 times the half-length of the hill (L). However, the presence of complex terrain along the wind path would complicate this rule. This is because extensive complex terrain would create a slower internal boundary layer above it which would tend to restrict the free-stream flow between the model and the roof to a greater extent than over an isolated hill.

Surface Accuracy

The accuracy of the height contours on the model is most important for the area immediately surrounding the site of interest but may be relaxed further away. At some point, the contoured topography could even be replaced with generic hills or blocks. There is little help available in defining the minimum distances from the site of interest for the optimum grading of topographic accuracy.

There have been a few comparisons between model and full-scale tests in complex terrain such as Meroney et al (1978) using a model scale of 1:5000 with the topography smoothed to 30m contour increments and Neal (1982) using 1:4000 scale with 40m increments. The models were constructed to a consistent accuracy over the whole model area. Both report high levels of success using these small-scale models as long as the affected region close to the surface is avoided.

PROBE POSITION

The accurate positioning of the measurement probe is of course vital for accurate measurements, especially when taken close to the surface in regions of high shear flows. Great care must therefore be taken to position the probe as accurately as possible during the initial setting-up in order to minimise this error.

Experience with the University of Canterbury's 1.2m x 1.2m Boundary-Layer Wind Tunnel showed the presence of additional position errors due to structural distortions during operation. These distortions are due to the traverser deflecting under the wind load from the (approx. 13 m/s) tunnel flow and causing the probe to move downwards and downstream. At the same time, the tunnel floor deflects upwards due to the negative gauge pressure (approx. -400 Pa) in the tunnel-working section. These relative movements have been observed by using an optical level from outside the tunnel working-section. Differential movement between the probe and the model surface was estimated to be within 1mm in both vertical and horizontal directions. Additional errors in position during the traverse due to the computer controlled drive and positioning system are normally considered to be negligible if the control and drive system is reliable. The consequences of any appreciable accumulated error in the position of the measurement probe would of course, become more significant as the model scale is reduced.

INCIDENT BOUNDARY LAYER

Boundary-layer Height

As for any wind engineering modelling project, the accurate representation of the full-scale flow speed and turbulence height profiles is required at the site of interest. This is normally achieved through the natural growth of the wind-tunnel boundary layer over an extensive upstream fetch. However, full boundary-layer simulation is only practical if the model scale is sufficiently small to avoid significant levels of tunnel blockage.

The ratio of hill height to boundary-layer height is an important modelling parameter which could be of use to determine the required height of the modelled boundary-layer for a full-depth simulation. For sites in flat, open terrain, the desired full-scale characteristics normally modelled are taken as those expected under the idealised situation of strong wind, neutrally stable conditions over flat, open terrain. Commonly used full-scale data which were first set out by Davenport (1960), have since been confirmed by Plate (1971), Cermak (1982) and others. They are similar to those quoted at the rough end of terrain category 2 in AS1170.2 (1989) (and with the ESDU 82026 (1993) except for the boundary-layer height). The theoretical gradient-wind height provided by the ESDU model lies between 750 - 2,800m for open country terrain (depending on the values chosen for the empirical constants). It is interesting that these maximum limits for the gradient height are significantly higher than the values available from earlier literature (~300m).

Under strong wind conditions, turbulence overturns and mixes the air sufficiently so that it becomes almost neutral and adiabatic up to some level. The upper limit of this level could theoretically be the gradient height. However, it is expected that neutrally-stable conditions throughout the full depth of the theoretical boundary-layer up to the gradient height is a rare phenomenon. Over significantly high hills and complex terrain which is often subjected to solar radiation, the atmospheric stability of even strong wind flows could become a significant parameter. A common situation would be when the upper limit is an inversion layer caused by stable stratification where the turbulence is weak. The upper limit of the neutrally-stable boundary-layer layer marking this inversion layer, is often considerably lower than the theoretical gradient height (Panofsky and Dutton, 1984). The existence of this low inversion layer can have a strong and persistent influence on the wind speeds in the boundary-layer below (Reid, 1995).

For this reason, not too much emphasis should be placed on the depth of the boundary-layer as a scaling parameter due to its sensitivity to atmospheric stability.

Boundary-layer Growth

Measurements taken at a constant height over a flat floor without a model installed would show a small but significant drop in flow velocity with distance down-wind due to the growth in the depth of the boundary-layer. A correction to nullify this effect which is extraneous to any topographic effects is worthwhile if there is a significant down-wind length over a complex terrain model. A suitable correction has been used by AES Canada for the Askervein hill tests (Teunissen and Flay, 1981). Its derivation assumes the growth of the boundary-layer depth, δ in a turbulent boundary-layer is given by,

$$\frac{\delta}{X} = 0.37 \ Re_X^{-\frac{1}{5}}$$

The boundary-layer profile is assumed to remain the same shape, defined by a power-law profile of power α, between the upstream reference position X_R and the local measurement position X_N. Rather than adjusting the height, a more simple but approximate correction, C can be derived for any height within the boundary layer which is added to the uncorrected flow speed at position X_N, where

$$C = U_R \cdot \left[1 - \left(\frac{X_R}{X_N} \right)^{0.8\alpha} \right]$$

Although the derivation of the correction is based on the flow over a flat surface without a model being present, the presence of the model hill during the actual tests is assumed to have no effect on the rate of boundary-layer growth. Tests in the tunnel over a flat roughened floor have confirmed the efficacy of this correction method.

Turbulence

A full-simulation model relies on the roughness and terrain of the upstream fetch to develop a suitable near-field boundary-layer and the required turbulence characteristics. The modeller has to make sure that the simulated near-field conditions are sufficiently close to those at full scale to ensure accurate results from the laboratory. For small-scale simulations, a limit defining when the length scales of turbulence are no longer appropriately modelled can be expected.

The turbulent structure in the surface layer of the boundary-layer over complex terrain is unlikely to be in equilibrium with the underlying surface (Tieleman 1982). It is therefore impossible to obtain appropriate roughness lengths and the friction velocities from locally observed mean wind profiles. The flat-plate flow models in equilibrium that are widely used to explain the behaviour of turbulent flows over complex terrain should therefore be interpreted with great care.

AERODYNAMIC ROUGHNESS

The conditions to ensure that sufficient turbulent energy is created to maintain turbulence levels in the boundary layer over the model rely on the surface roughness elements protruding through the laminar sub-layer into the main flow. An aerodynamically-rough surface also ensures that the flow behaviour is independent of the Reynolds number, $Re_x = U_0.X/\nu$. This is important as the flow similarity requirement of constant Reynolds number between full-scale and the model simulation is invariably violated. An indication proposed by Schlichting (1979) of whether or not such a flow-surface combination is aerodynamically rough is given by the roughness Reynolds number, $u_*k_s/\nu > 70$ based on the friction velocity, u_* and the sand roughness, k_s. If a direct relationship between the k_s and the surface roughness length, z_0 is assumed (say $k_s/z_0 \approx 25$, Teunissen et al, 1987), the condition becomes $u_* z_0/\nu > 3$. The ratio of k_s/z_0 does vary significantly with the size and spacing of the roughness elements so that the above roughness limit can only be taken as a guide. As the geometric scale of the model is reduced, k_s and z_0 should ideally be scaled by the same proportion. However, the effective roughness of the surface would eventually fall short of this criterion for an aerodynamically rough surface. For small-scale modelling, the boundary layer often lies in the transition range ($0.2 < u_* z_0/\nu < 3$), where fully turbulent flow is likely but cannot be guaranteed. However the magnitude of the turbulence-intensity profiles can indicate whether or not an adequate level of flow turbulence is present.

Schlichting (1979) also provides an alternative limit marking the independence of the surface skin friction coefficient from surface roughness effects. This uses an analogy based on pipe-flow criteria (Moody diagram), the Reynolds number, $Re_x = U_0.X/\nu$ and the relative roughness X/k_s for sand roughened plates (see figure 21.10 from Schlichting 1979). The limit for aerodynamically-rough flow is shown as a line of constant $U_0.k_s/\nu$. This information is reproduced by Cermak (1984) as an envelope of Re_x and X/k_s within which the surface drag coefficient of the model is independent of Reynolds number. This limit is easier to use as it uses physical rather than flow-based parameters such as u_*. However Britter (1982) recommends that the emphasis should be on u_*/U_0 and z_0/L (or U_0L/u_*z_0) rather than the Reynolds number for modelling flows over complex terrain.

When modelling the Askervein hill tests at a scale of 1:2500 (Teunissen et al, 1987), it was noted that in order to achieve a suitable roughness length, the model surface roughness had to be dis-proportionally large compared with its full-scale equivalent which violated the geometric scaling. This could become a problem at small scales if the individual roughness elements interfere with measurements taken close to the ground. The difference between surface roughness elements and small scale topographic features will also become more blurred as the model scale is reduced. The small scale features of the terrain would help to provide an apparent surface roughness that is sufficient to maintain aerodynamically rough flow. However, useful quantitative evidence and information to help the modeller on these roughness issues are currently not available.

FLOW SEPARATION

The correct simulation of the flow close to the ground over complex terrain relies on the correct modelling of any significant separated flows. In the absence of any significant density stratification, the occurrence of separation depends on the hill slope, the state of the boundary layer, the surface roughness and the existence of any salient ridges (Britter 1982). Just as in bluff-body flow, the Reynolds number Re_h based on the height of the model hills would be an obvious indicator of the flow's ability to represent the full-scale flow behaviour over steep slopes. Ferreira and Viegas (1995) supports this with experimental data and report a big change in flow conditions below $Re_h = 8 \times 10^4$ for their test set-up, based on changes in the drag coefficient. As a result, a minimum value of 10^5 for wind tunnel tests has been recommended. For small-scale models this limit would become a critical factor.

The onset of flow separation over the model is also affected by the level of surface roughness with rough surfaces promoting separation due to the relatively low levels of momentum in the flow close to the ground. This behaviour is in contrast with the flow around bluff bodies where rougher surfaces cause greater mixing of the flow momentum downwards towards the surface and the promotion of attached flows. The flow over complex terrain is no exception to this behaviour (Britter, 1982). The artificially high roughness successfully used by Teunissen et al, (1987) to maintain more realistic turbulence levels also was instrumental in achieving a more accurate representation of the separated flows over the rear side of the hill.

THERMAL EFFECTS

Normal wind-tunnel tests can only hope to simulate the strong-wind neutrally-stable atmospheric boundary-layer where mechanical mixing dominates over thermal effects. Britter (1982) suggested that it is unlikely that very strong winds will be encountered together with highly convective or very stable conditions. However, care should be taken when interpreting the results for wind energy applications where a substantial proportion of the energy is derived from medium wind speeds when thermal effects in complex terrain could be very strong. Such tests are also of little use when dealing with the strong winds generated by thunderstorms and tropical cyclones which are causing increasing interest and concern in many parts of the world.

Other climatic influences which could affect the accuracy of any model prediction includes density stratification, strong diurnal sea breezes, down-slope winds and mountain waves, and the blocking or channelling in valleys. These climatic influences would become increasingly significant as the scale of the model is reduced. It still remains unclear at what model scale these influences begin to reduce the accuracy of the modelling to an unacceptable level.

CONCLUSIONS

The need for basic research into the effects of relatively small model scales on the accuracy of simulated flows over complex, hilly terrain has been identified. Quantitative guidelines are needed to help the modeller choose the most accurate model configuration. Some of the more important issues involved include the necessary accuracy of the topographic model, the prediction of tunnel blockage errors, the minimum surface roughness length and use of small topographic features to maintain aerodynamically rough flow, and the accurate simulation of significant regions of separated flow. The unique problems of complex terrain modelling are intensified by the use of very small scale models and the effects of scale require further investigation.

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