WIND FLOW OVER ESCARPMENTS

CHOI E.C.C.

Division of Building, Construction & Engineering, CSIRO

ABSTRACT It has been known for a long time that wind loading on structures is strongly affected by topographic effects. However it was only in the past decade that systematic research was being carried out to tackle this problem. Experimental measurements and analytical solutions are being studied. This paper looks at wind tunnel results of flow over (steep) slopes and escarpments and their comparison with analytical solutions.

Introduction

The mean profile and turbulence characteristics of wind flow over hills and escarpments are complicated. However such information is vital to design engineers. In the past decade wind tunnel studies and on site measurements over different terrain features have been carried out[1],[2],[3]. Parallel to experimental studies numerical solutions[4] and analytical solutions are investigated[5]. The analytical solution proposed by Jackson and Hunt provides the only basic analytical theory and is often being used. However the theory applies only to low hills and escarpments with smooth slopes. The present paper looks at flow patterns over large sharp slopes and the deviation of experimental results from the analytical solutions.

Analytical Solution

For non separated turbulent boundary layer flows over a low slope, Jackson and Hunt[6] proposed that the flow can be divided into an inner layer and an outer layer. The inner layer is associated with large changes in shear stresses. The outer layer behaves closely to that of irrotational flow and can be approximated by potential flow theory. The velocity perturbation can be expressed by the following equation

$$\Delta u(x,z) = \frac{h}{L} . \sigma(x,z) . u_0(L) \qquad 1$$

Δu(x,z) = incremental speed-up at height z above the local surface and at horizontal distance x from centre of slope (as shown in figure 1).

h = height of ramp or escarpment.

L = characteristic length of ramp.

σ(x,z) = shape function of the ramp, and

$$= \frac{1}{2\pi} . \ln\left(\frac{\left(\frac{x}{L}+\frac{1}{2}\right)^2 + \left(\frac{x}{L}\right)^2}{\left(\frac{x}{L}-\frac{1}{2}\right)^2 + \left(\frac{x}{L}\right)^2} \right)$$

$u_0(L)$ = the upstream reference velocity at a height of L, and

$$= \frac{u_*}{k} \ln\left(\frac{L}{z_o}\right)$$

u_* = upstream frictional velocity.

z_o = roughness length.

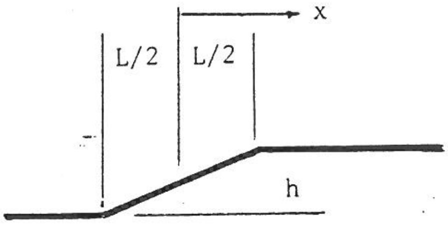

Figure 1 Line diagram of ramp

Experimental Studies

Experimental study of wind flow over two-dimensional ramps and escarpments was carried out in the Hong Kong University boundary-layer wind tunnel. The boundary-layer was generated by using roughness elements and grids. The slope and top of the ramp was also covered by the same roughness elements so as to eliminate any effect due to change in terrain roughness. Slope angles studied in the experiment varied from 30 degree to 90 degree and with three slope heights for each slope angle. Velocity measurements were taken by hot wire anemometer at different heights over the crest of the ramp and also downstream of the crest at fixed intervals.

Result and Discussion

The analytical solution proposed by Jackson and Hunt applies only to low and smooth hills where $h/L << 1$ and $L/z_o >> 1$. In many practical situations the slopes are large and steep where these conditions are not true. Slopes investigated in the present wind tunnel study also fall under this category. A comparison of the results are as follows.

Figure 2 shows typical plots of the speed-up $\Delta u(x,z)/u_o(z)$ over the top of the ramp. Point A is located at the crest of the ramp. In general the speed-up effect is strongest at point A and decreases downstream. For steeper slopes the area downstream of the crest at levels close to the ground shows negative speed-up values indicating the flow separation zone.

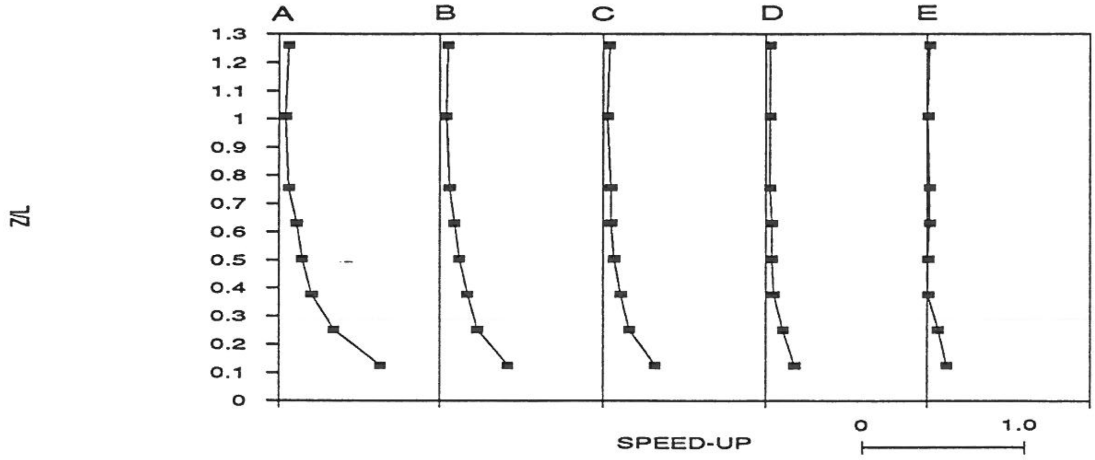

Figure 2 Speed-up for 30 degree slope

To test the applicability of equation 1 to the experimental data, the theoretical shape function and the shape function as deduced from experimental data are plotted in figure 3. These values are calculated for point A where the speed-up effect is strongest and flow separation is below the lowest measuring point. It can be observed that the theoretical values are good prediction of experimental result over the lower and central portion of the curve. The theory under estimated the result at large values of z/L.

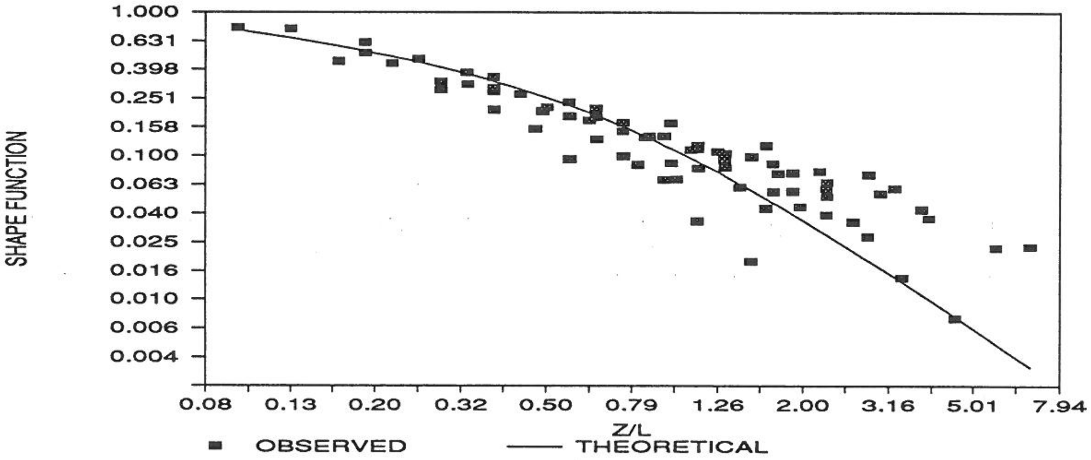

Figure 3 Theoretical and observed shape functions.

To have a better perception of the effect of speed-up, the incremental speed-up $\Delta u(x,z)$ is non-dimensionalized by the undisturbed wind speed $u_o(z)$. This non-dimension speed-up factor (s) is expressed as follows.

$$s = \frac{\Delta u(x,z)}{u_o(z)} = \frac{h}{L}.\sigma(x,z).\frac{\ln L/z_o}{\ln z/z_o} \qquad 2$$

The speed-up factor (s) is further normalized by the ram slope (h/L) and in Figure 4 both the theoretical and observed values are plotted. The curves show similar trend of variation as in figure 3. It is also observed that a straight line can reasonably be fitted to the experimental data. The following equation was obtained using least square fitting method.

$$\frac{\Delta u(z)}{u_o(z)} = 0.107\frac{h}{L}\left(\frac{z}{L}\right)^{-1.1} \qquad 3$$

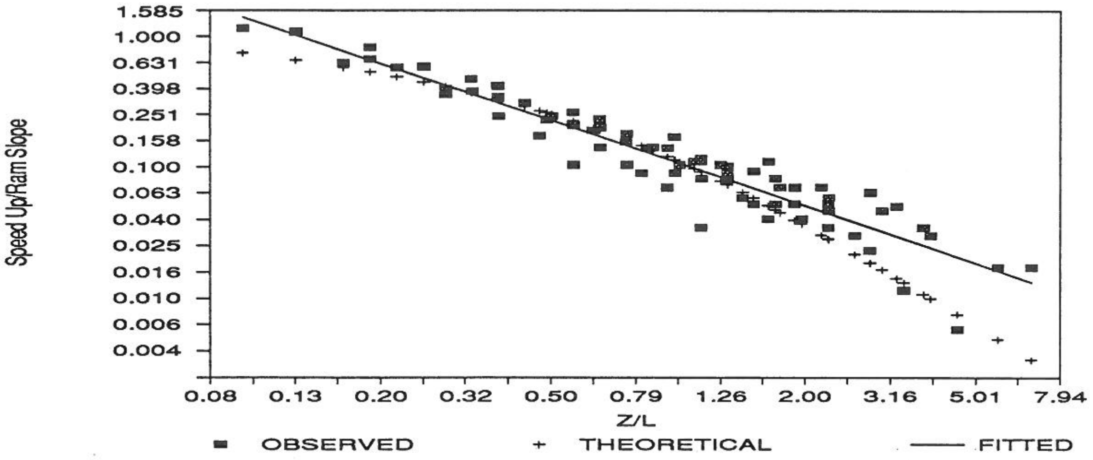

Figure 4 Theoretical and observed speed-up.

On further investigation it was noted that the power of z/L was affected by the angle and size of the slope. For the smaller slope the power was about -1.25. For the larger slopes it ranged from -1.03 to -0.96. Thus it seemed reasonable to assume a value of -1.0 for large slopes (the other constant was also recalculated to be 0.115). With this assumption, equation 3 can be re-written as follows.

$$\frac{\Delta u(z)}{u_o(z)} = 0.115\frac{h}{L}\left(\frac{z}{L}\right)^{-1} = 0.115\frac{h}{z} \qquad 4$$

Equation 4 suggests that speed-up at the crest of large slopes is a function of z/h only. To test the validity of this equation the observed speed-ups for the 90 degree escarpments are plotted against the predicted values using equation 4. As shown in figure 5 the points lie reasonably on the 45 degree straight line. Speed-up values are also calculated using the mean wind speed topographic multiplier from AS 1170.2 and plotted on the same graph. It seems for large speed-up situations the observed values are larger than those predicted by the code.

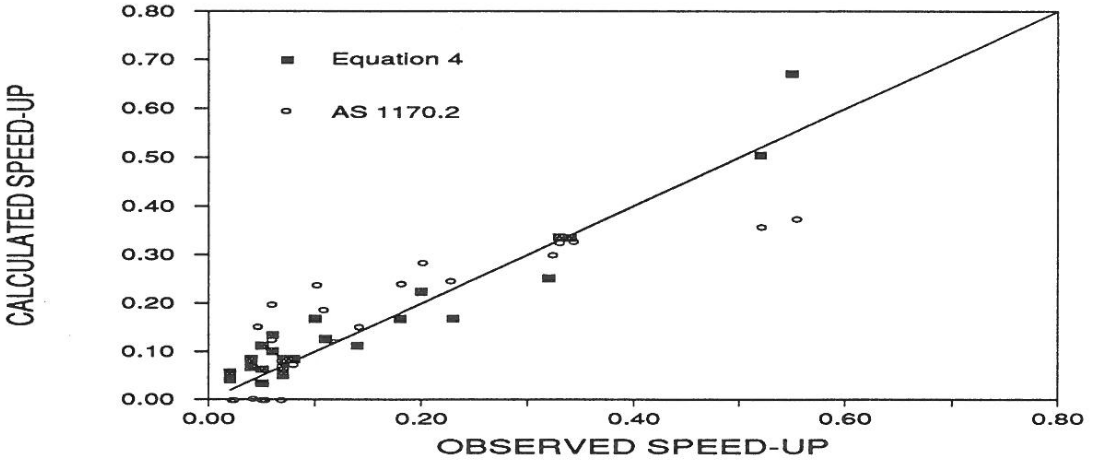

Figure 5 Observed and predicted speed-up for 90 degree escarpment.

Discussion

An experimental study of the phenomenon of wind flow over escarpments is carried out. The effect of escarpment height and slope angle on speed-up factor is investigated. The analytical solution proposed by Jackson and Hunt compares favourably with the experimental result. However for large slopes at large z/L values the speed-up factor can better be approximated by equation 3.

For the cases studied the speed-up factor at the crest is not affected by the slope angle for slopes greater than say 30 degree. It is a function of z/h only.

References

[1]Jensen N.O. : J. of Wind Engg. & Ind. Aerody., 15, pp. 243-251, (1983).

[2]Bowen A.J. : Proceedings Fifth International Conference on Wind Engg., Pergamon, 1, pp. 161-172, (1979).

[3]Teunissen H. W. : J. of Wind Engg. & Ind. Aerody., 15, pp. 271-286, (1983).

[4]Deaves D.M. : J. of Wind Engg. & Ind. Aerody., 6, pp. 89-111, (1980).

[5]Jackson P.S. : Proceedings Fourth International Conference on Wind Effects on Buildings and Structures, London, pp. 33-40, (1975).