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DEVELOPMENT OF VELOCITY AND SHEAR STRESS DISTRIBUTIONS IN THE WAKE OF A POROUS SHELTER FENCE

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SUMMARY

Results are presented of velocity and shear stress variation downstream of a shelter-fence of 50% porosity, taken under conditions of neutral stability in the atmosphere. Features of the results are the initial acceleration of the flow above fence height, and the persistence of wake effects to at least 50 fence heights downstream. In the far wake, both velocity and shear stress profiles conform to the self-preservation scales proposed by Counihan, Hunt and Jackson (1974), but their prediction of stress perturbation is an underestimate. The x^{-1} decay law for velocity perturbations is confirmed, but decay of Reynolds stress perturbation is even more rapid than the theoretical $x^{-3/2}$, in conflict with recent wind tunnel results.

1. INTRODUCTION

Despite early recognition that turbulence, and turbulent transport mechanisms, were likely to have at least as great an influence on shelter effectiveness as the mean flow field, few measurements of the turbulence characteristics behind shelter fences have been made until quite recently. The stimulus for recent interest, which has also fostered theoretical developments, is that the shelter-fence represents a simple and convenient example of a two-dimensional bluff obstacle. In practical terms, studies of shelter-fence wakes have applications to problems of turbulent wind interaction between structures, the dispersal of pollutants or spilt toxic material near buildings, aviation hazards, as well as the traditional agricultural areas of shelter, soil erosion and water conservation.

We first outline the salient features which are known to affect wind flow in the wake of barriers. Immediately behind a solid fence, there usually exists a recirculating eddy, bounded by the surface and a separation streamline which extends from the top of the fence to a re-attachment point downstream. Bradshaw and Wong [1] illustrate this for the case of a backward-facing step in a wind tunnel, and Ogawa and Diosey [2] for flow behind a barrier in the atmosphere. In each case, the re-attachment point was 6-7 fence heights downstream. This distance was also determined directly by Sheih *et al.* [3]. We shall refer to this as the separation region. Further downstream, the wake region steadily increases in depth and the flow accelerates until it must ultimately recover to a constant-stress logarithmic profile.

In agriculture, porous shelter-belts have been found to be overall more efficient than solid ones, striking a compromise between the amount of wind reduction at given height and the downwind distance for which it is effective. Raine and Stevenson [4] give a brief but useful review of this aspect. As a general guide, it seems that the 1/2 m windspeed behind a typical fence of 40-50% porosity recovers to about 80% of the upstream value at 20 fence heights downstream. Baltaxe [5] showed that, although separation is still present behind fences of porosity up to 25%, by the time porosity reaches 50% there is no evidence of a recirculating region.

Mulhearn and Bradley [6] illustrated the extreme sensitivity of the near-surface flow behind a shelter-fence to angle of attack of the incident wind and to fences of small aspect ratio. This sets a serious limitation on the acceptability criteria for field data, particularly turbulence measurements involving second and higher moments, such as Reynolds stress. For wind tunnel simulation on the other hand, it is critical to model correctly both mean and turbulent structure of the approach flow, and to maintain the similarity ratio between fence height h and surface aerodynamic roughness parameter z_o (Jensen [7]).

A theory for the wake behind a two-dimensional fence in a turbulent boundary layer has been given by Counihan, Hunt and Jackson [8], hereafter CHJ. It is valid downstream of the separation region where, in the wall region (W), the shear stress τ is constant with height and the total velocity u is given by

$$u = \left(\frac{\tau}{\rho}\right)^{1/2} \frac{1}{\kappa} \ln \frac{z}{z_o} \quad . \tag{1}$$

Here ρ is the air density, $\kappa(=0.4)$ is von Karman's constant and z is the vertical dimension. Away from the wall, in the mixing region (M), changes in mean velocity Δu and in shear stress $\Delta\tau$ are self-preserving and given by

$$\frac{\Delta u}{u_h} \frac{x}{h} = \hat{u} \frac{df}{d\eta} \tag{2}$$

$$\frac{\Delta\tau}{\rho u_h^2} \cdot \left(\frac{x}{h}\right)^{-\frac{3+n}{2+n}} = \hat{u}\, K^{\left(1 - \frac{1}{2+n}\right)} \frac{d^2 f}{d\eta^2} \quad \text{, where} \tag{3}$$

$$f = \eta^2 {}_1F_1 \left(\frac{2-n}{2+n}, \frac{n+4}{2+n}, \frac{-\eta^{n+2}}{(n+2)^2}\right) \quad .$$

${}_1F_1$ is the confluent hypergeometric function defined in Abramowitz and Stegun [9] p. 504. $\hat{u}$ is a velocity deficit parameter, x is distance downwind of the fence, u_h is the upwind mean velocity at fence height and n is the upwind power-law velocity exponent. The vertical scale $\eta = \frac{z}{h} (K \frac{x}{h})^{-1/(n+2)}$, and $K = 2\nu_o/u_h\, h$, where ν_o is a constant eddy viscosity in the relation

$$\Delta\tau = 2\rho\, \nu_o\, \partial u/\partial z \quad .$$

Profiles of velocity and shear stress perturbations in the mixing region should therefore collapse onto a single curve if scaled according to the self-preserving forms (2) and (3). These imply also that the maximum velocity perturbation falls off as $(x/h)^{-1}$ and that for Reynolds stress approximately as $(x/h)^{-3/2}$. The vertical displacement z_{max} of the maximum velocity deficit is approximately proportional to $(x/h)^{1/2}$. The theory in the wall region (W) predicts a decrease in τ, which should recover as $(x/h)^{-1}$.

The purpose of this paper is to report field data of the velocity and stress perturbations behind a shelter fence in the atmosphere under neutral conditions, against which to test the above predictions of CHJ.

2. EXPERIMENTAL DETAILS

Experiments were conducted at two locations. The first was the Division's field site at Bungendore (NSW) described in Bradley *et al.* [10]. For this work the site was ploughed and harrowed. Two 2 m diameter drag plates (Lynch and Bradley [11]) were installed 20 m apart along the line of the prevailing westerly wind as shown in Fig. 1 at DP1 and DP2. Midway between the drag plates, two 3-component sonic anemometers (S1, S2) were mounted on carriages on a special mast and could be rapidly and independently adjusted to any height between 1 and 5.1 m above the ground surface. A 4 m profile of 7 miniature cup anemometers (Bradley [12]) was mounted beside each drag plate at A2 and A3 and a third profile of 6 anemometers (A1) erected upwind of the forward drag plate. A 3-component Gill propeller anemometer (G) to provide wind direction and a profile of shielded psychrometers (P) were also located upwind. The unobstructed fetch consisted of about 400 m of the harrowed surface and a further 1 km of closely grazed pasture.

The fence consisted of sheep netting of mesh 0.15 × 0.15 m square into which were woven vertical slats of wood 1.2 × 0.08 × 0.01 m to form a 50% porosity barrier (see Fig. 1). It was in four sections, each of 25 m length which could be rolled up, removed and reinstalled with relative ease. The variation of downstream fetch was thus achieved by mounting it crosswind at various distances upwind of drag plate 1.

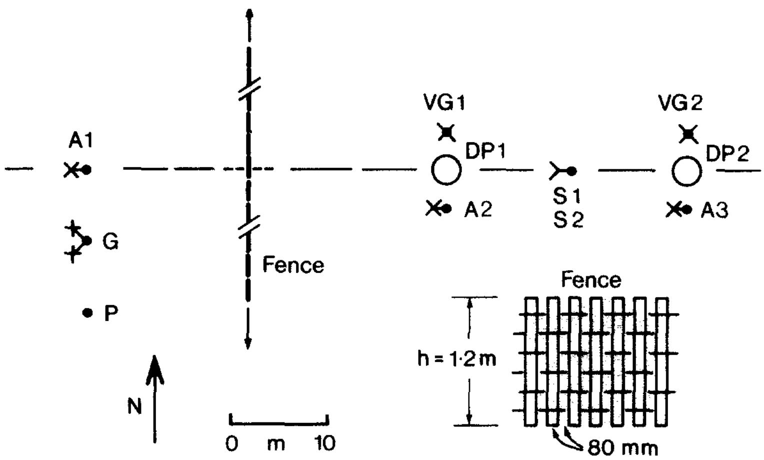

Fig. 1. Instrument locations at Bungendore field site. Fence details in inset.

Data were taken almost continuously on every occasion of good wind direction during an 8-week period from June-August 1976. One sonic was left at 5.1 m height as a reference, and the lower sonic was traversed over the height range 1.0 to 3.5 m, remaining at each level for about one hour. Several hours of data, sometimes covering a few days, were obtained at each fetch before the fence was moved. Thus we have a considerable body of data, comprising velocity and turbulence profiles and covering a wide range of thermal stability at a number of distances downwind of the fence.

Beside each drag plate, a single vertical Gill propeller (VG1, VG2) was mounted at 1.7 m height on a slim guyed pole to measure the mean vertical wind component with the minimum of flow distortion. In a subsidiary experiment, conducted during a few days of particularly consistent neutral conditions, a vertical array of such vertical propellers was mounted at heights of 1.0, 1.7, 2.4, 3.4 and 4.4 m to determine the streamline pattern in as much detail as possible both upwind and downwind of the fence. The behaviour of turbulence structure in the reference frame of streamline co-ordinates is discussed in a companion paper [13].

The second part of the experiment was conducted at Conargo (NSW) following an International Turbulence Comparison Experiment, described by Garrett *et al.* [14]. The drag plates and sonics were left as described in that report, but the fence was erected at various distances and appropriate angles around the drag plates according to the wind conditions. Little neutral data were obtained during this experiment, and the only results quoted here are certain drag plate measurements.

3. RESULTS

Data taken under conditions of neutral thermal stability are necessary to permit strict comparison with wind tunnel results and adiabatic theories. Such conditions are not particularly common in the atmosphere. The brief period of transition between daytime unstable and nocturnal stable conditions, which may well give small values of the Richardson or Monin-Obukhov stability parameters, is, in fact, a most unsuitable period for the purpose. It is a time of considerable and often chaotic non-stationarity with the collapse of the mixed layer, and strong vertical gradients of heat flux. Wake flows appear to be particularly susceptible to bouyancy effects.

For the present purpose, we accept conditions as neutral if at least four successive 15-minute periods have a Monin-Obukhov stability length lying in the range 100 m $\leqslant L \leqslant -20$ m. The asymmetry is due to our experience that the wake behaviour is more sensitive to slight stability than to slight instability. From a total of about 90 hours of data, about 25 hours satisfied this requirement, covering fairly well the range of height and fetch downwind of the fence.

The patterns of velocity and stress downwind of the fence were independent of wind velocity over the range 5-10 m/s. The logarithmic upstream wind profiles were extremely consistent with wind ratio $u_4/u_h = 1.195$ and drag coefficient $(u_*/u_h)^2 = 0.00410$, where u_4 is wind speed at 4 m and u_* the profile-derived friction velocity. Downstream profiles of wind velocity and Reynolds stress have therefore been normalised with u_4 and u_* respectively. The measured z_o was 2.0 mm during most of the experiment, but with early spring growth it suddenly increased to 3.0 mm. At Conargo, z_o was about 10 mm.

The profiles in Fig. 2 are the average of many 15 min runs at each fetch. Deceleration of the flow is evident 4h upwind. Immediately in the lee, driven presumably by the pressure drop across the fence, the velocity profile is almost uniform below the strong shear at fence height. Above this, the flow is also accelerated uniformly by the pressure perturbation, which does not generate additional shear immediately. At 4h downstream the shear layer has diffused, reducing further the wind speed at the surface and just above fence height. Further downstream, the profile gradually recovers towards the upstream condition, but retains a deficit of about 4% even at 50h.

Fig. 3 shows the development of Reynolds stress profiles downstream of the fence, as measured by the sonic system, normalised with the upstream friction velocity u_*. Each point on the profile represents at least 45 min of data, except those at 5.1 m, where the sonic remained throughout the profile and which therefore represent the average of a much larger number of 15 min runs, whose standard deviation is indicated by the error bars. Apparently, even at the greatest downwind fetch, the fence wake does not influence the Reynolds stress above about 4h. The x/h = 15 data are a small sample which, technically,

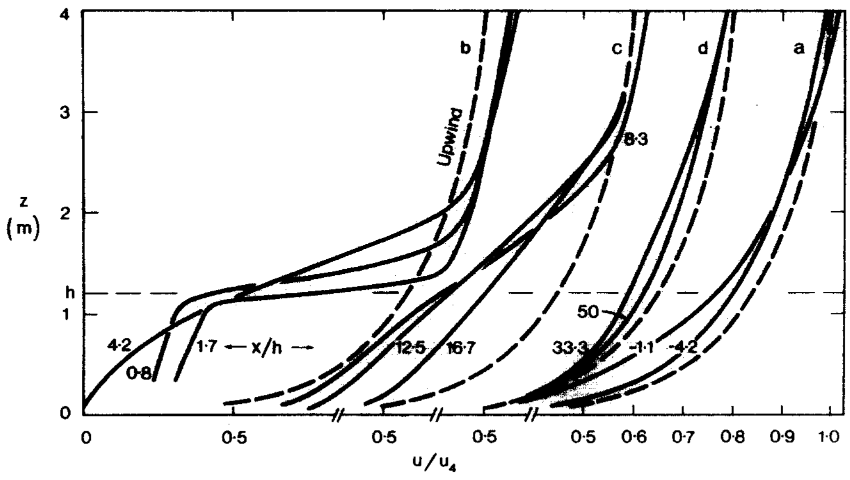

Fig. 2. Normalised velocity profiles at various distances x/h from the shelter fence: (a) upstream, (b) separation region, (c) and (d) wake region. Broken curves are the upwind logarithmic profile.

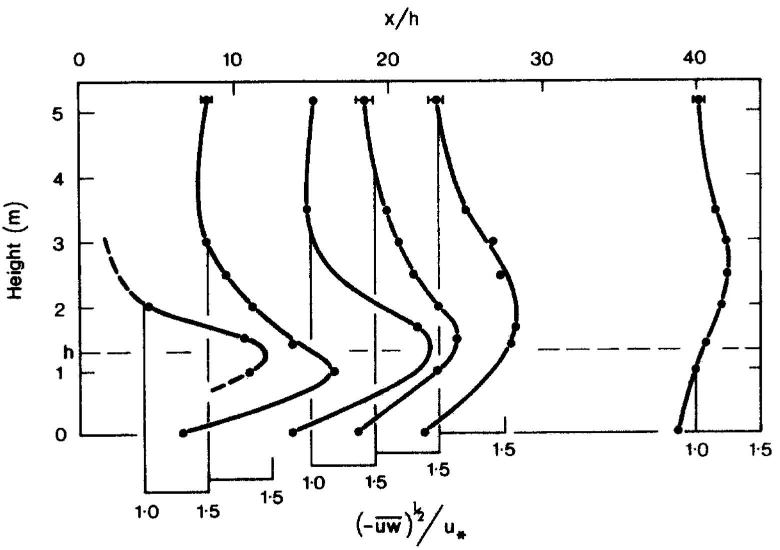

Fig. 3. Reynolds stress profiles downstream of shelter-fence referred to upstream friction velocity. Actual x/h positions of profiles may be obtained from key to Fig. 6. Surface values are interpolated from drag plate data in Fig. 4.

satisfied our neutrality criteria, but which was, in fact, a period of slow transition from strongly unstable to quite stable conditions, as discussed earlier.

In Fig. 3 the surface values of drag, u_{*s}, are interpolated for the particular fetch from the drag recovery curve, Fig. 4. Beyond 16h the recovery is slow and incomplete even after 50h. The Conargo data, obtained with a completely different drag plate installation, confirm this result. For the wind profiles beyond 25h, which had a substantial logarithmic lower section, it was possible to estimate the value of u_{*s} in the surface layer from equation (1). The results, again averaged over many runs, are also given in Fig. 4 and support the drag plate data.

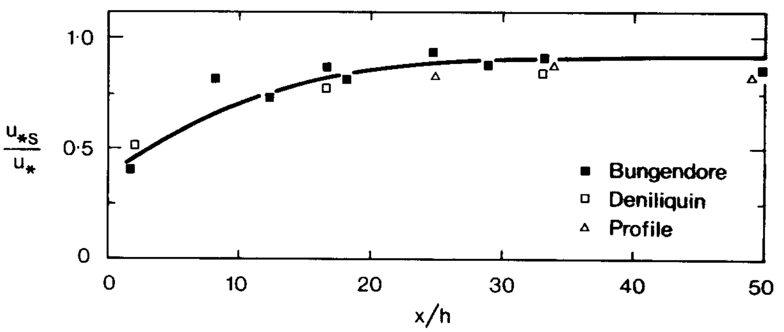

Fig. 4. Drag plate measurements of friction velocity referred to upstream value. Profile estimates are included for large downwind distances.

The incomplete recovery of surface drag, even after 50 fence heights, seems rather surprising. It does, however, receive some support from the wind tunnel measurements of Castro [15], whose Fig. 8 indicates velocity and stress perturbation profiles remarkably similar to those of Figs. 2 and 3. Dissimilarities between the two experiments are to be expected, of course. Castro used a solid barrier and a relatively rougher surface of $h/z_o = 78$ compared with about 600 at Bungendore, and his upstream wind tunnel flow exhibited substantial vertical gradients of shear and normal stresses.

4. COMPARISON WITH CHJ THEORY

It is first necessary to estimate the various parameters used in equations (2) and (3). The power n of the neutral upstream velocity profile is fairly close to the conventional value of 0.14. In CHJ, ν_o was taken as the upstream eddy viscosity at height h, but it was suggested that for porous windbreaks, the appropriate height should be $(1 - \phi)h$, where ϕ is the porosity, in our case 0.5. Hence the value $\nu_o = 0.5\kappa u_* z$ was used and the constant $\hat{u}$ fixed at 1.347 by forcing agreement between theory and data in the mixing region.

The result is shown in Fig. 5, which indicates that the non-dimensionalising scheme of CHJ appears quite reasonable at all distances in the outer part of the flow. It is obviously not valid in the region very close to the fence, and the acceleration above $\eta = 4$ is not predicted by the theory. The wall and

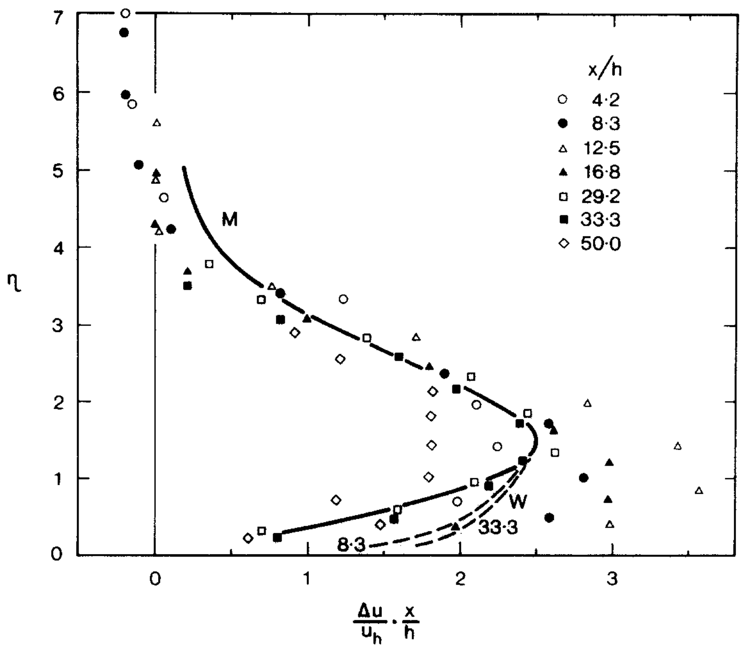

Fig. 5. Self-preserving velocity profiles. Solid line is CHJ solution for the mixing region (M). Broken lines are wall region (W) solutions at x/h of 8.3 and 33.3.

mixing regions have been matched at $\eta = 1.5$, but the wall theory predicts a much closer grouping of the velocity data for this range of x/h than is apparent in the experiments.

The CHJ non-dimensional grouping for Reynolds stress self-preservation (Fig. 6) also appears to collapse the data reasonably well for $x/h \geqslant 15$ in the mixing region, but the theory considerably underestimates the magnitude of the stress perturbation. Castro's [15] results also show this feature, although the discrepancy is not so severe. In his case, however, the $x^{-3/2}$ decay law is obviously invalid. We return to this point below.

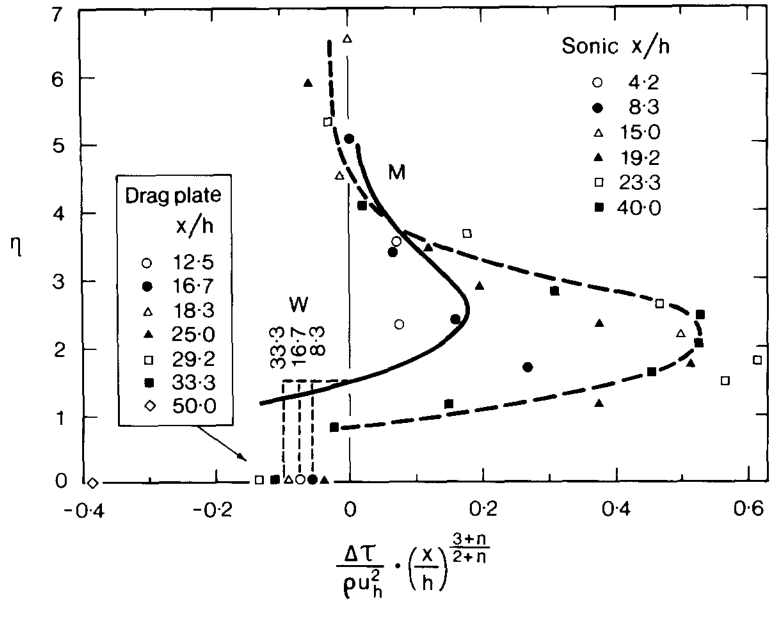

Fig. 6. Self-preserving Reynolds stress profiles. Solid line is the CHJ solution for the mixing region (M). Broken lines are wall region (W) solutions for x/h = 8.3, 16.7 and 33.3. Dashed line is an empirical fit to data for z/h ⩾ 15.0.

Parera [16] also compares wind tunnel results for solid and porous fences with CHJ theory. He finds that their parameter groupings collapse the velocity perturbation data quite well, but proposes an empirical equation as a better fit to the data than their mixing region theory. Like Castro, he finds that an x^{-1} decay law fits the Reynolds stress data better than the CHJ $x^{-3/2}$ prediction, and again proposes an empirical form.

In the wall region, the CHJ predictions agree remarkably well with the group of drag plate results over most of the wake region. However, the farthest point, at 50 fence heights downstream, appears anomalous, despite the supporting data referred to above and in Fig. 4.

It is useful to examine more closely the downstream development of the various quantities predicted by CHJ theory. A linear graph of $(\Delta u/u_h)_{max}$ against x/h indicates the x^{-1} relationship, which is generally agreed upon, and suggests a virtual origin for x/h, $x_o/h \approx 5$ downstream of the fence. Fig. 7 illustrates the x^{-1} decay of peak velocity perturbation for $(x-x_o)/h \geqslant 7.5$ and approximate agreement with the $x^{1/2}$ increase in z_{max}, although this is rather difficult to determine with any certainty for the rather broad Δu distributions at the largest fetches.

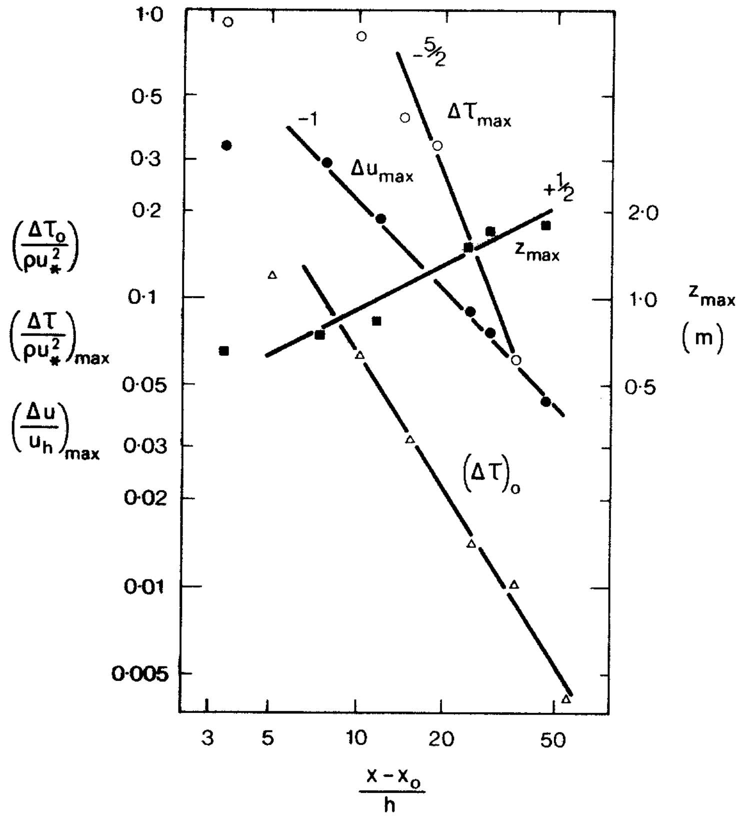

Fig. 7. Downstream decay of various quantities related to velocity and stress perturbation, as indicated. The lines have the slopes shown.

The Reynolds stress perturbation data do not agree with the x^{-1} decay results of Castro [15] or Parera [16]. In fact, they indicate an even more rapid decay rate than the predicted $x^{-3/2}$. Data for the decay of surface stress perturbation were taken from the smoothed curve through the drag plate measurements of Fig. 4. Even here the recovery of stress appears to be slightly more rapid than the predicted x^{-1} law.

5. CONCLUSIONS

We have presented a comprehensive set of wind and shearing stress perturbation data, taken downwind of a porous shelter fence under conditions of neutral stability in the atmosphere, for comparison with theory and with the results of wind tunnel experiments. It confirms that the perturbation profiles may be collapsed onto self-preserving forms by using the non-dimensional groupings proposed by CHJ. The velocity data conform well with the theory, but the shearing stress perturbations are considerably larger than predicted.

The problem probably lies with over-simplification in the use of an eddy-viscosity model. As Hunt (private communication) points out, the theory assumes the turbulence to be in local equilibrium, when it plainly is not. Near the surface, where $\partial(\Delta u)/\partial x$ is dominated by the strong shear stress gradient, this condition is closest to being satisfied which, Hunt suggests, may be the reason that the velocity field conforms reasonably well with simple theory. Agreement between the measured surface drag and the wall theory lends support to this argument.

The downstream decay of Reynolds stress perturbations appears to be more rapid than that of velocity perturbations, as CHJ theory predicts. This conflicts with wind tunnel results which find that both mean and turbulence quantities decay inversely with downstream distance. Both field and laboratory data on this point are subject to obvious limitations; the former by observational scatter and the latter by the limited depth of constant stress layer. In the immediate vicinity of the fence, wake theory cannot be expected to apply. The requirements for velocity self-preservation seem to support a virtual origin for the wake region at about 5 fence heights downstream, and universal stress and velocity perturbation profiles apply beyond a distance of 10-15h from the fence. Within this distance, flow acceleration is a feature of the region above fence height.

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