VELOCITY FIELD IN A STEADY BREAKER

by

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ABSTRACT

An experimental investigation is described of the velocity field in a steady, spilling-type breaker, generated on a steady current by a submerged hydrofoil. Velocities have been measured with a laser-doppler system, and analysed with respect to mean and rms-values as well as Reynolds stresses. The results indicate that the turbulent flow field downstream of the initiation of the separation at the surface resembles that in a turbulent wake.

INTRODUCTION

Peregrine and Svendsen (1978) have proposed a model for the flow field in a class of steady and quasi-steady breaking flows such as hydraulic jumps, bores, and spilling breakers. They concluded from visual observations that the turbulent flow, immediately following the breaking, resembles a turbulent mixing layer, which arises because the smooth flow from upstream meets the relatively slowly moving water in the toe of a surface roller. This roller, which is small compared to the region of high-intensity turbulence, is believed not to play an important role in the dynamics of the wave, other than that it triggers the turbulence.

In Peregrine and Svendsen's model, the region of turbulent flow following breaking is supposed to spread downstream and downward as in a mixing layer; at some distance downstream the upper region becomes affected by gravity, and for waves in shallow water the lower region by the bottom. Still further downstream there is a so-called wake or decay region.

The usefulness of a model such as this is that it enables one to describe the main features of the turbulence induced by breaking in terms of better known classes of turbulent flows. However, the model is partly hypothetical. It is based on visual observations, which are largely qualitative. A more quantitative verification is still needed. It is the purpose of the present study to contribute to such verification, through the measurement and analysis of the mean flow, the turbulent intensities, the turbulent shear stresses, and their decay with distance downward and downstream.

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The contents of the paper are as follows. The experimental arrangement and procedure are described first. This is followed by a presentation of the main results. These are subsequently discussed and compared with the model of a turbulent mixing layer and a turbulent wake. The conclusion is that the observed flow field appears to be predominantly like a turbulent wake.

This proceedings paper is kept rather brief. A more extensive presentation will be given in a forthcoming paper.

EXPERIMENTAL ARRANGEMENT AND PROCEDURES

Flow conditions

As stated in the introduction, the purpose of the present study is to investigate the turbulence induced by a breaking water surface, with special reference to the model proposed by Peregrine and Svendsen (1978) for the flow field in a class of steady or quasi-steady breakers. A partial check of the validity of that model can be obtained in a breaker in which the mean (non-turbulent) motion is steady. Such type of flow was used in this study, because its investigation is experimentally much simpler than that of non-steady flows, while at the same time it should yield useful information about the flow characteristics in quasi-steady breakers.

We have set out to obtain a steady breaker, which should be relatively unaffected by a bottom boundary layer, and the geometry of which should resemble that of a spilling breaker or a post-breaking bore on a beach. We have created such a flow condition by inserting a hydrofoil below the free surface of a steady flow in a laboratory flume (Fig.1).

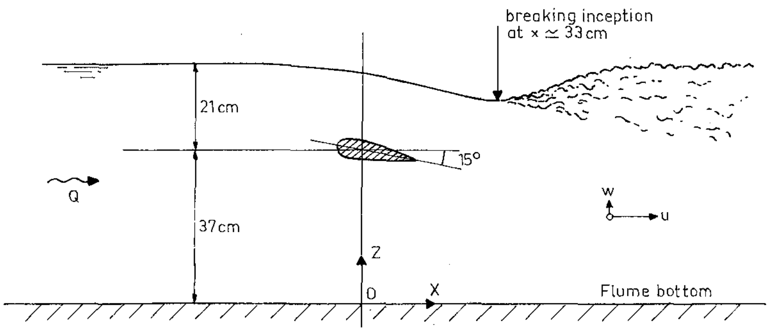

Fig.1 - Sketch indicating flow condition and definition of reference frame

Under these conditions, there is no need for the entire upstream flow to be supercritical, or even to have a Froude number near 1. We could therefore choose a relatively large depth (larger than the critical depth for the given maximum discharge), so as to obtain an extensive region in which the post-breaking turbulent flow near the free surface would not be affected by the proximity of the bottom. The maximum discharge in the flume is 0.50 m^3s^{-1}, and the flume width is 0.80 m; the corresponding critical depth is 0.34 m. The experiments were performed with a mean undisturbed flow depth (h) of 0.58 m.

Our ultimate interest is in "full-size" breakers, with high Reynolds numbers and intensive air entrapment. We have therefore chosen for as large dimensions and discharge as could be achieved in the available flume, so as to minimize scale effects. These experiments will be referred to as "full scale". The cross-sectionally averaged undisturbed flow velocity in these runs was 1.08 ms^{-1}. In addition, a few measurements were made in a so-called "half scale" run, which was a Froudian model of the full-scale situation, with a length scale of about 1:2, with the purpose of obtaining insight into possible scale effects. The numbers given in the following refer to the full-scale experiments.

The hydrofoil was chosen to have a relatively full profile. A NACA 6024 profile was used, with a maximum thickness of 4.8cm and a chord of 20.0 cm.

In preliminary runs, the depth of the center of the hydrofoil below the undisturbed mean water level (d) and its angle with respect to the horizontal (α) were varied, in order to find conditions which appeared suitable to our purpose (as described above). For the values of mean depth and discharge mentioned above, useable flows were obtained for values of d from about 0.15 m to 0.30 m, and for values of α from about 5° to 20°. The final full-scale experiments were performed with d = 0.21 m and α = 15° (see Fig.1).

Velocity measurements

Velocities were measured by means of a laser-doppler velocity (LDV) meter. Such meter works on the principle of measuring the Doppler frequency shift of a laser beam scattered by small particles in a moving fluid. It measures some average velocity value for a volume with a characteristic linear dimension of the order of 1 mm. In what follows these dimensions are ignored, and we shall refer to the measurements as "point" measurements.

The LDV system which was used operates in the reference beam mode. Laser beams were transmitted transversely through the flume (through the glass-panelled side-walls) and the water in it. The components radiating and detecting the signals were mounted in a fairly rigid frame over the flume, to maintain proper alignment. This frame could be moved in its entirety, along the flume as well as vertically.

If no light scattering is detected by the laser-doppler system, the output signal contains no information about the flow velocity. This situation is called "signal drop-out". In this experiment, the signal drop-out is most often induced by air bubble interruption of the laser beam near the breaking surface. The occurrence of drop-outs was accounted for in the data analysis.

The LDV system is capable of measuring two velocity components in one point simultaneously. We have measured the downstream component (u) and the vertical component (w, positive upward).

The outputs of the LDV were recorded simultaneously in an analog magnetic tape recorder (Bell Howell adr 1000). The recording time was 2 minutes per measurement point.

The velocity signals (u,w) were separated in their mean values $(\bar{u},\bar{w})$ and the fluctuations about these means, $(u',w') = (u,w) - (\bar{u},\bar{w})$. (Here and in the following, an overbar denotes a time average.) Estimates of $\bar{u}$, $\bar{w}$, $u'_{rms} \equiv (\overline{u'^2})^{1/2}$, $w'_{rms} \equiv (\overline{w'^2})^{1/2}$ and $\overline{u'w'}$ in all the measurement points were obtained using standard analog equipment. The procedures which were used in the analyses will be described in more detail in a forthcoming paper.

RESULTS

Measurements of (u,w) have been made in a number of points in the central verticals of flume cross-sections, at various distances (x) downstream of the center of the hydrofoil. The minimum distance used was x = 0.33 m, in the cross-section of the toe of the breaker (Fig.1). The maximum distance was 4 m. It was believed that beyond that too much bottom influence would occur.

A number of points in each vertical were used, with a height (z) above the flume bottom varying from 0.21 m (the minimum possible with the frame supporting the LDV apparatus) to somewhat below the free surface, where the signal drop-outs were judged to become too severe. Measurements were also made in the undisturbed flow, i.e. in absence of the hydrofoil.

The results have been plotted in two ways, vz. as a sequence of vertical profiles, and as isolines in the x,z-plane. For brevity, only the profiles of $\bar{u}$, u'_{rms} and $\overline{u'w'}$ are given here (Figs. 2, 3 and 4), as well as isolines of $\overline{u'w'}$ (Fig.5).

Data points of the full-scale experiments are indicated by crosses, and those of the half-scale experiments by open circles. The latter points have been scaled up from the measured values. The lengths have been multiplied with a factor 2. With a strict Froude scaling, the velocities should have been multiplied with a factor $2^{1/2}$. In fact, the ratio of the actually measured upstream mean velocities was used, which was about 1.6. The difference is due to a mal-adjustment of the discharge.

The full-scale data points have been connected by full-drawn straight-line segments for purposes of visualisation.

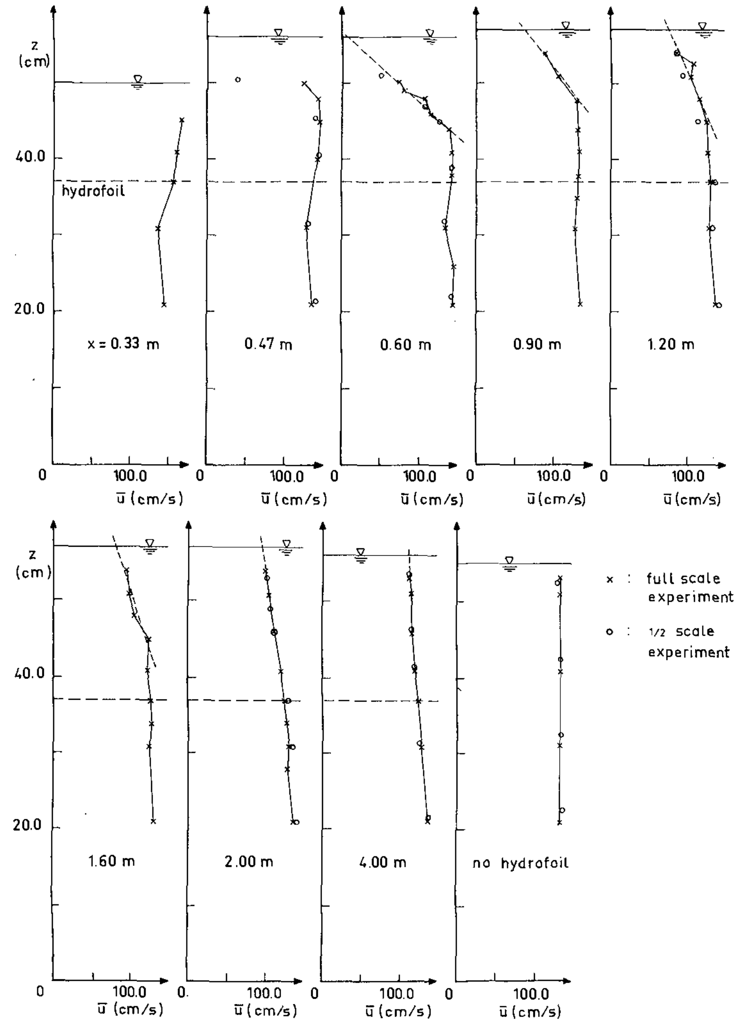

Fig. 2 - Vertical profiles of $\bar{u}$ in sections at various distances downstream of the hydrofoil. The dashed lines in the upper part indicate linear extrapolations. The profile in the lower right hand corner is for the flow in absence of a hydrofoil.

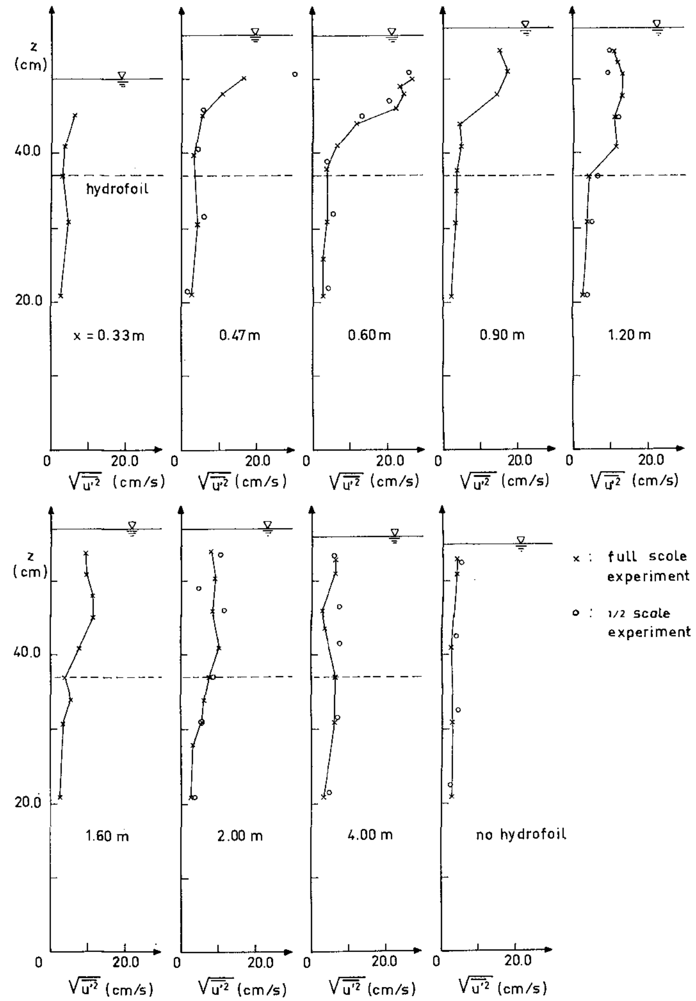

Fig.3 - Vertical profiles of $\sqrt{\overline{u'^2}}$ in sections at various distances downstream of the hydrofoil. The profile in the lower right hand corner is for the flow in absence of a hydrofoil.

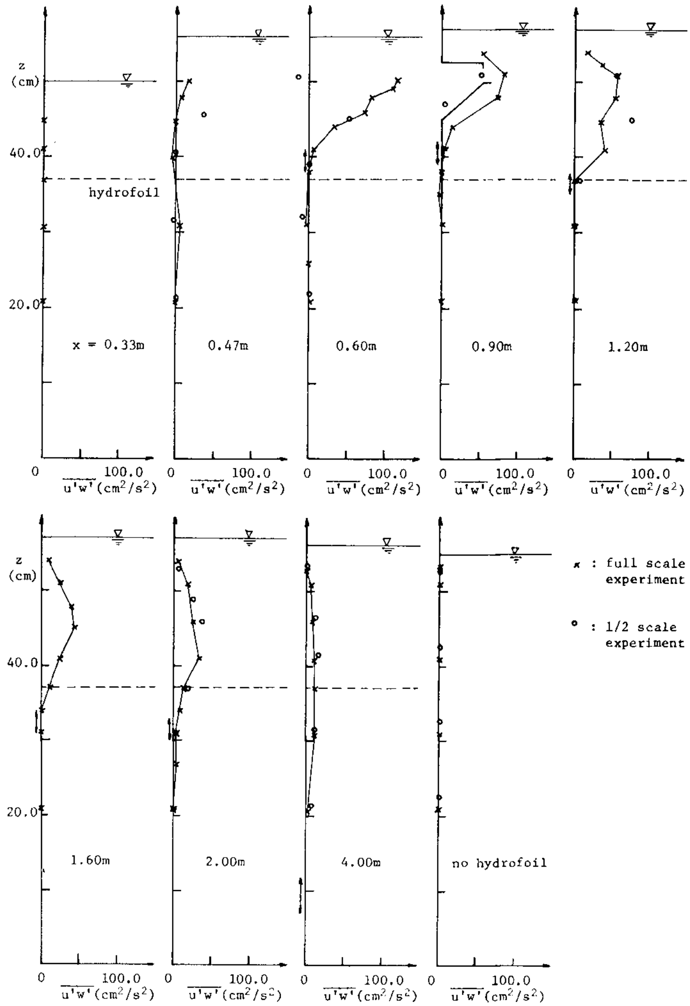

Fig.4 - Vertical profiles of $\overline{u'w'}$ in sections at various distances downstream of the hydrofoil. The profile in the lower right hand corner is for the flow in absence of a hydrofoil.

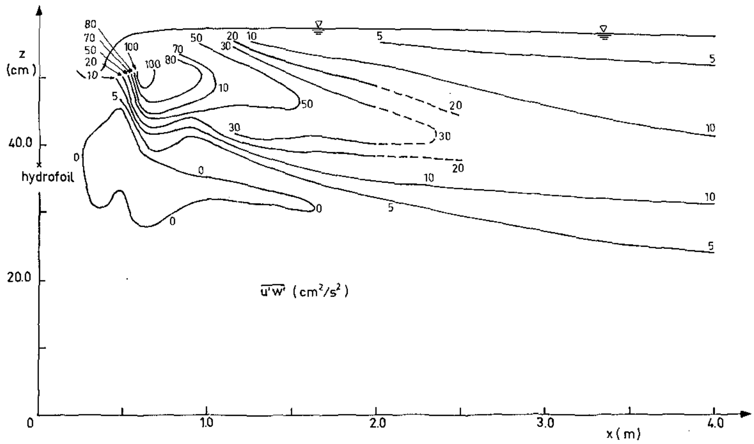

Fig.5 - Lines of constant $\overline{u'w'}$ values downstream of the hydrofoil

DISCUSSION

General trends

The half-scale results are in general in good agreement with the full-scale results. Significant deviations are present in all three profiles at x = 0.47 m, and in the $\overline{u'w'}$ - profile at x = 0.60 m as well. This matter has not been pursued in the present study, so that no conclusions concerning scale effects can be drawn other than that these appear to be absent in the region downstream of the cross-sections mentioned above.

The profiles in the lower right-hand corner of the Figs.2 through 4 refer to the undisturbed flow conditions. It can be seen by inspection that the corresponding mean-velocity profile (Fig.2) is virtually uniform in the upper part of the flow, while the turbulent shear stresses there do not deviate visibly from zero, when drawn on the same scale as the profiles for the flow with a hydrofoil (Fig.4). This indicates a virtual absence of any influence of a bottom boundary layer in the upper flow region.

It is clear from Fig.2 that the profiles of $\bar{u}$ in the presence of the hydrofoil exhibit a strong defect near the breaking surface. This defect penetrates into the deeper region of the flow with increasing distance downstream, while at the same time it diminishes in magnitude. However, even at x = 4 m it is still clearly present, as can be seen by comparing that profile with the one for the flow in absence of the hydrofoil.

At the most upstream cross-section , a slight velocity defect can be discerned at a height $z \backsim 0.3$ m, which is an indication of the wake generated behind the hydrofoil.

Fig.3 shows that the turbulence has its greatest intensity near the toe of the breaking surface, from where it decays downward and downstream. At $x = 4$ m, the station farthest downstream, it is still significantly in excess of its value in the undisturbed flow. The wake of the hydrofoil shows up in Fig.3 as a slight excess of u'_{rms}.

The quantity $\overline{u'w'}$, which is proportional to the turbulent shear stress, has significant non-zero values only in a fairly well-defined upper layer downstream of the toe of the breaker. It is virtually zero in the cross-section of this toe ($x \backsim 0.33$ m); no evidence of a wake behind the hydrofoil is present in this profile.

Altogether, the results shown in the Figs.2 through 5 clearly indicate the presence of a region of relatively high shear on top of a more or less undisturbed flow. The thickness of the shear layer increases in the downstream direction, while the mean-velocity defect and the turbulent intensity and shear stress decrease.

Comparison with wake and mixing layer

In the classical theory of turbulence a number of freely evolving shear flows has been studied, such as mixing layers, jets and wakes. In this section, the question will be considered to which extent the observed flow is similar to one of these.

A mixing layer forms the transition between two uniform parallel flows of different velocity, while a jet and a wake can be seen as laterally limited regions of velocity surplus and velocity deficit, respectively, relative to the undisturbed flow. In a mixing layer the cross-stream variation in mean flow velocity is constant in the downstream direction (if the two external flows have a sufficient lateral dimension), while this quantity decreases downstream in jets and wakes.

It follows from the above that the flow observed in our experiment, which is characterized by having a velocity deficit with respect to the undisturbed flow, which deficit is decreasing downstream, is qualitatively most nearly like a flow in a wake. This can be checked quantitatively, or at least semi-quantitatively, by estimating the values of some characteristic parameters and their variation downstream, and comparing this with the corresponding results for a typical wake flow. This is done in the following. We have also concluded some theoretical results for a mixing layer, since this was taken by Peregrine and Svendsen as a model for the initial phase of the post-breaking flow.

The quantities to be considered in the comparison are the mean velocity defect ($\bar{u}_d$), a characteristic value for the turbulent velocity magnitude (u'), and a lateral length scale (l).

Asymptotic theoretical relations have previously been derived between these quantities and their variations downstream, assuming a high Reynolds number (Re) and a nearly parallel, self-preserving flow, away from bounding surfaces. The results are asymptotic in the sense of $Re^{1/2} >> 1$ and $l << L$, in which L is a longitudinal length scale, as well as in the sense that only the far field is considered, sufficiently far downstream from the physical origin of the shear layer, so that the flow has settled down to self-preservation. Some such results, taken from Tennekes and Lumley (1974), have been collected in Table 1, in which the symbol $\sim$ indicates a proportionality, and $\tilde{x} = x - x_o$ is the downstream distance to some reference point $x = x_o$. (This point is near the physical origin of the shear layer. However, a theory for self preserving flow in the far field cannot predict the location of $x = x_o$ in terms of the details of the physical origin of the shear flow, since by definition a self preserving flow has no "memory" of those details.)

Table 1 - Downstream variation of characteristic parameters in free shear layers

	Mixing layer	Plane wake
$\bar{u}_d$	const.	$\sim \tilde{x}^{-1/2}$
l	$\sim \tilde{x}$	$\sim \tilde{x}^{1/2}$
$\tilde{u}'$	$O\{(l/L)^{1/2}\}\bar{u}_d$ = const.	$O(\bar{u}_d) \sim \tilde{x}^{-1/2}$

Experimental values of $\bar{u}_d$, $\tilde{u}'$ and l were determined as follows. The mean velocity defect was calculated as $\bar{u}_d = \bar{u}_1 - \bar{u}_f$, in which $\bar{u}_1$ is the value of $\bar{u}$ in the lowest point of measurement ($z = 0.21$ m), and $\bar{u}_f$ the value of $\bar{u}$ at the mean free surface eleveation , as estimated by linear extrapolation of the upper part of the measured profile (see Fig.2). For $\tilde{u}'$ the maximum value of u'_{rms} in the vertical profile was taken, and l was defined as the depth of the shear layer, from the mean free surface elevation down to the region where there is a fairly abrupt transition between the region of high shear above and the more or less homogeneous flow beneath. The locations of these transition zones were estimated from the vertical distributions of $\overline{u'w'}$; they have been indicated in Fig.4 by vertical arrows.

The most upstream cross-sections where meaningful estimates could be made were $x = 0.60$ m for $\bar{u}_d$ and l, and $x = 0.90$ m for $\tilde{u}'$ (see Figs. 2, 3 and 4).

For a comparison of the observed downstream variations of $\bar{u}_d$, $\tilde{u}'$ and l with the theoretical ones, it is necessary to have an estimate of the location of the reference point for the downstream distance, $x = x_o$. This point is expected to be near the point of initiation of breaking, $x = x_b \cong 0.33$ m (see Fig.1). A more exact estimate is not necessary if one considers points far downstream ($x-x_o >> |x_o-x_b|$), but since our measurement points may not fulfill this condition it is worthwhile to allow x_o to differ from x_b.

A value of x_o can be determined so as to optimize the fit of the data points to some theoretical model. We have not done this numerically; we found by visual inspection that $x_o = 0.5$ m gives results (see Fig.6) which appear to be consistent with the asymptotic theory for a plane wake: u_d and u' both vary approximately as $(x-x_o)^{-1/2}$ and l varies approximately as $(x-x_o)^{1/2}$ (excluding the most upstream measurement of l). Based on these results, we conclude that the flow downstream of the breaking surface is not only like a wake flow in a qualitative sense, but also in a more quantitative sense.

A quantitative comparison of our observations with the theoretical model of a mixing layer was not attempted in view of the observed downstream decrease of u_d and u', which is absent in the classical mixing layer model.

CONCLUSIONS

Measurements have been made of horizontal and vertical velocities, including turbulent fluctuations, in a steady mean flow with a breaking surface, similar to a so-called spilling breaker in shallow water. These measurements have given rise to the following conclusions:

(1) A region downstream of the initiation of breaking can be recognized in which the flow evolves as in a free self-preserving turbulent wake. This conclusion rests on the observed downstream variation of mean velocity defect, turbulence intensity, and shear layer thickness.

(2) The region mentioned in (1) is bounded above by the free surface, which is more or less horizontal because of gravity. The lateral (= vertical) spreading of the shear layer occurs mainly in the downward direction. The flow can therefore be compared to that in one half of a symmetric wake.

(3) The measurements of the flow in the region mentioned in conclusion (1) appear to be free of scale effects if scaled up according to Froude's law.

(4) If -as hypothesised by Peregrine and Svendsen (1978)- there exists a region immediately downstream of the initial breakpoint, in which gravity is unimportant, and in which the flow is similar to that in a mixing layer, then such region is small compared to the overall vertical dimensions of the breaker. The model of a mixing layer does not appear to be useful for the prediction of the downward and downstream spreading of the turbulence induced by the breaker, over distances of the order of the breaker height or layer.

ACKNOWLEDGEMENTS

One of us (S.) thanks the Delft University of Technology for granting him a Research Fellowship.

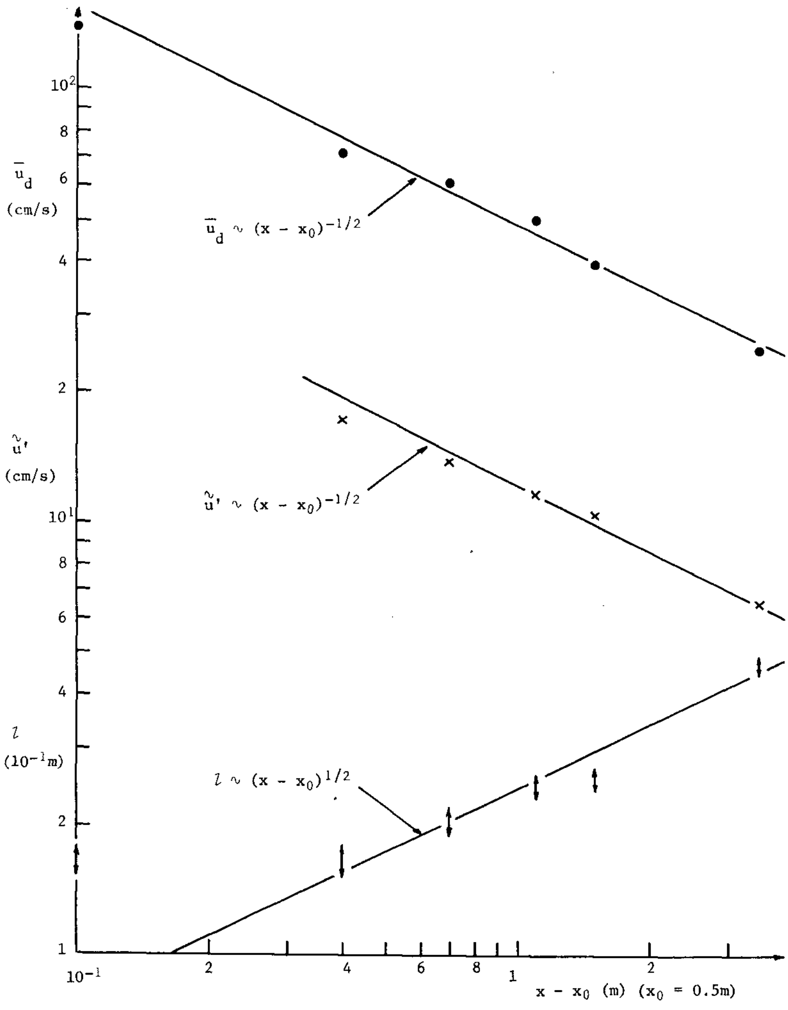

Fig.6 - Variation of flow parameters with distance downstream, for x_o = 0.5 m. Mean velocity defect (●), turbulent intensity (×) and layer thickness (↕). The straight lines indicate proportionalities to $(x-x_o)^{\pm 1/2}$.

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