CHAPTER 30

Spilling breakers, bores and hydraulic jumps

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Quasi-steady breaking waves

On gently sloping beaches, almost all water waves break. After the initial breaking the water motion usually appears quite chaotic. However, for a moderate time, for example two or three times the descent time of the "plunge" in a plunging breaker, the flow can be relatively well organised despite the superficial view which is largely of spray and bubbles. If waves continue to break the breaking motion, or "white water" soon becomes fully turbulent and the mean motions become quasi-steady.

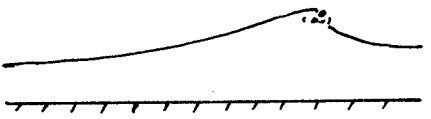
A reasonable definition of a quasi-steady wave is one which changes little during the time a water particle takes to pass through it. We exclude water particles which may become trapped in a surface roller and surf along with the wave.

At this stage in its development a wave on a beach may be described as a spilling breaker or as a bore. In fact, there is a range of these waves from those with a little white water at the crest to examples where the whole front of the wave is fully turbulent. In investigating the properties of such waves it is desirable to start by looking at the whole range of related motions. The most obvious extension is to the hydraulic jump; since, in the simplest view, it is equivalent to a bore but in a frame of reference moving with the wave. It is also an example where the mean flow is steady rather than quasi-steady. It takes little further imagination to see that a range of steady and quasi-steady breaking flows is more or less as follows:

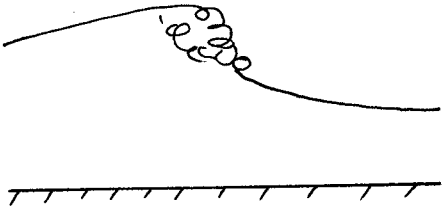
spilling breakers in deep water
spilling breakers in shallow water
bores
hydraulic jumps
flow below sloping weirs
waterfalls.

These are illustrated by sketches in figure 1. Within and between each example given there is a considerable variety of flows, not least, because of the differing physical sizes on which they may be realized, from a scale of a centimetre to a scale of ten metres. Other examples

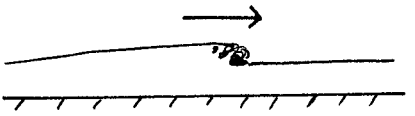
(a) spilling breaker (deep water)



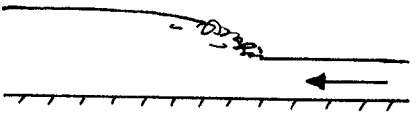
(b) spilling breaker (finite depth of water)



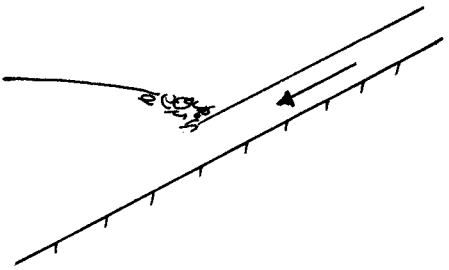
(c) spilling breaker/bore



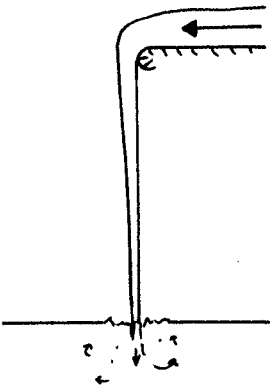
(d) bore



(e) hydraulic jump



(f) weir flow



(g) waterfall

Figure 1. A spectrum of quasi-steady breaking waves.

may be found; for example the white water at the bows of a ship.

Our aim is to increase understanding of the fluid motions in these waves. The only theoretical work on spilling breakers we are aware of is that of Longuet-Higgins and Turner (1974). They focus attention on the aerated surface roller falling down the front face of the wave. We started with ideas based on this model but after observing experimental waves modified our views, as described below. There is rather more work on hydraulic jumps (including a review paper by Rajaratnam (1967), some of which is discussed below.

Experiments and flow visualization

We have studied the motion and surface configuration of breakers, bores and hydraulic jumps in flumes with transparent sides. Photography and direct visual observation have been used. As well as observing entrained air bubbles we observed the motion of buoyant particles on small scale hydraulic jumps. This latter example induced some doubts about the importance of the downward flow in the surface roller of a hydraulic jump since the mean motion down the surface roller appeared to be very slight compared with the random motions. The scale of the flow observed was such that the roller had a height of a few centimetres, surface tension was important and there was only a small amount of aeration.

A few drops of dye in the roller of the hydraulic jump were very rapidly diffused and showed the extent of the turbulent motion. An attempt to minimise the effect of surface tension led us to a technique of flow visualization which enabled us to see the extent of the turbulent motion in propagating breaking waves as well.

The flow visualization method involves forming a layer of tiny bubbles on the free surface of the water. Best results are obtained by a layer which is rather less than a monolayer of bubbles. The bubbles are formed by adding detergent, we found a few parts per million to be satisfactory, to the water in a closed circuit flume. The flume is then run with air entrainment into the pump. This forms many bubbles of a diameter much less than a millimetre. When the pump is stopped the bubbles very slowly rise to surface and form a layer with clear water beneath.

When a breaking wave propagates over such a layer the bubbles indicate the motion of the surface layer of water after it is engulfed by the toe of the surface roller. The bubbles are sufficiently small that their rate of rise under gravity is almost negligible compared with the turbulent velocities. They give an indication of the extent of the turbulence, though it should be remembered that in liquids momentum diffuses much more readily than matter so that the turbulence may spread a little further than the bubbles. However, the spread of turbulence is not a diffusive but a convective process.

Visual and photographic observation, see figures 2 and 3, shows that the strong turbulence rapidly mixes the surface layer into an increasing

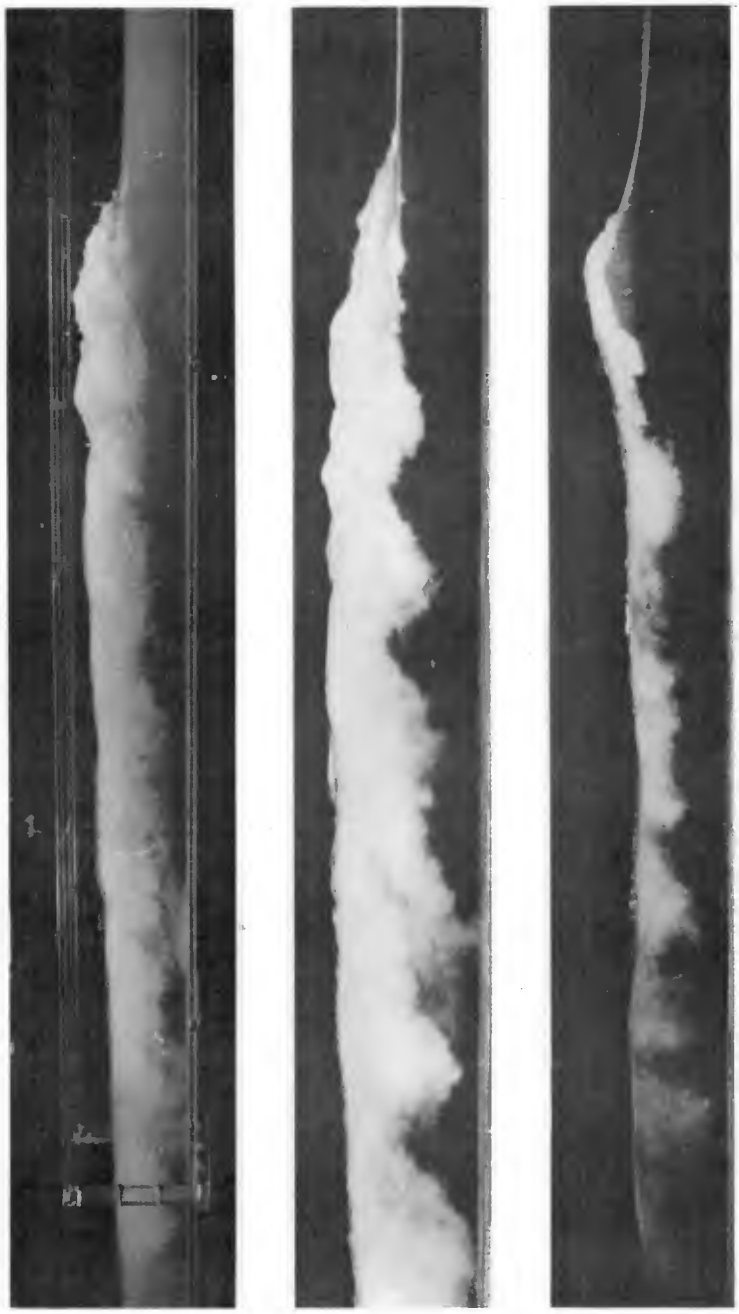


Figure 2. Visualization of the turbulence in propagating breaking waves - distant view.

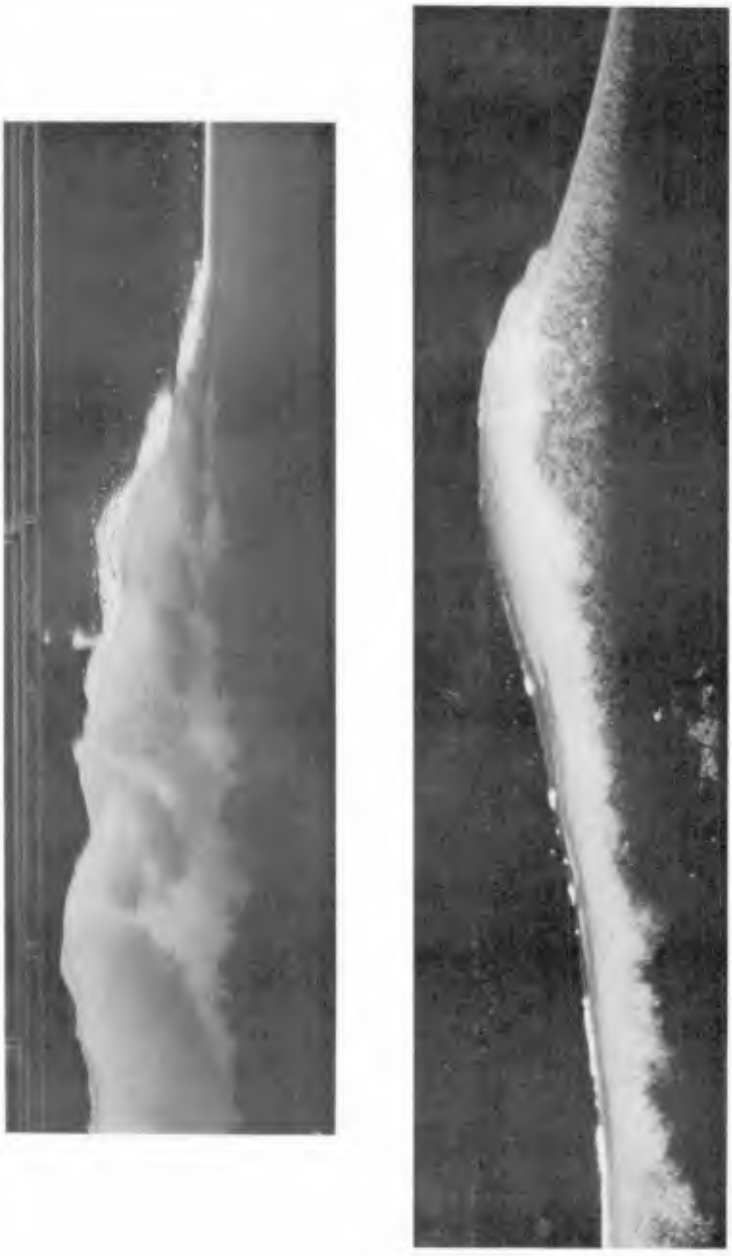


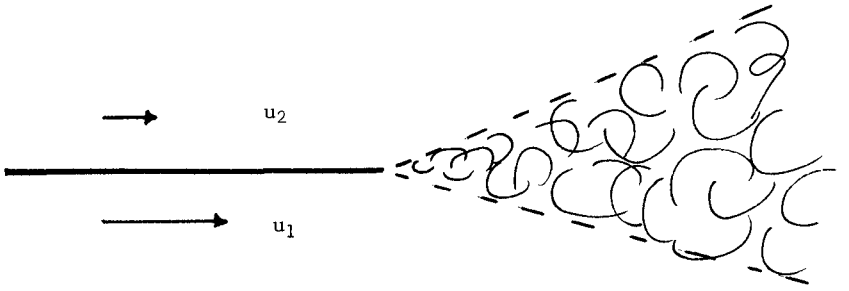
Figure 3. Visualization of the turbulence in propagating breaking waves - near view.

volume. This volume appears to commence from a point at the toe of the roller and forms a wedge which in an instantaneous view has "billows" on its under surface. For waves in moderate and shallow depths of water the turbulent region soon fills the whole depth. On the other hand, for deeper water, or for waves which are only just breaking, the breaking region is followed by a "wake" just below the free surface which only slowly thickens.

A model for the flow field

Our observations indicate that the surface roller does not play a dominant role in the dynamics of the wave. It is only a small part of the region of highly turbulent flow and is in no way separate from it. We consider that it acts as a trigger to initiate the turbulence. In many ways the initial volume of turbulent flow resembles a turbulent mixing layer.

A turbulent mixing layer occurs when two uniform parallel streams of velocities u_1 and u_2 are allowed to meet, for example by passing the end of a partition between them.



There have been numerous studies of turbulent mixing layers, some of which will be referred to shortly.

Consider the water motion in a frame of reference moving with the wave. The smooth water approaching the breaking wave has a velocity u_1 say. It means the toe of the surface roller which has a velocity u_2 which is not very different from zero. Mixing of the incoming water and the water already in the breaker ensues. The similarity to a mixing layer is enhanced by considering u_2 to be zero. There is then no need to have an upper fluid present except for that which is entrained into the mixing-layer. This small amount can be supplied by the reverse flow in the surface roller.

Alternatively, we note that for the toe of the surface roller u_2 is small and negative. In a true mixing layer u_2 is never quite as small as zero because there is always entrainment leading to a small adjustment of the velocity field. Thus if u_2 nominally equals zero

there is still some positive flow towards the mixing layer. In our imagination we can suppose u_2 to be nominally small and negative so that there is then no net flow towards the mixing-layer. This is the situation in a breaking wave.

A well documented property of turbulent mixing layers is that they spread linearly with distance in a wedge. The angle of spread depends largely on the velocity difference between the layers, however, for the case where u_2 is nominally zero there is a large scatter of recorded angles. See for example, Brown and Roshko (1974) which confirms the linear growth of mixing layers, and in figure 10 illustrates a scatter from 0.145 to 0.22 for one measure of the tangent of angle of spread with u_2 zero. The argument of the above paragraph indicates that for u_2 nominally equal zero, some small positive or negative values for u_2 might be more appropriate.

Another aspect of the flow in breakers which attracts attention is the air entrainment. This certainly leads to a lower mean density of fluid, but we consider this to be of secondary importance in the mechanics of the breaking wave. The eye, and camera, can only see one drop or bubble in any direction - vision beyond is obscured, thus it is very difficult to estimate the proportion of air and water. However, on the scale of 10 cm there is only a little air entrainment and yet breakers otherwise appear similar in structure to those on a much larger scale. Even with appreciable air entrainment the above mixing layer resemblance still holds. As Brown and Roshko (1974) show, by measuring mixing layers between helium and nitrogen, there are only quantitative differences when fluids of differing densities mix.

After the initiation of the turbulence it spreads until, at its upper boundary the effect of gravity becomes dominant towards the crest of the wave, and at its lower boundary interaction with the bottom becomes important. Exactly where these interaction regions are depends strongly on the type of breaking wave. Figure 4 is a sketch of these regions.

In the only case where there are measurements, the hydraulic jump, there is a considerable difference in the mean flow when a thick bottom boundary layer exists and when the flow is nearly uniform with depth, as is well shown by the work of Resch and Leutheusser, summarized in Resch et al (1976). This clearly indicates that these "interaction" regions can be important.

Behind the breaking region there is a long 'wake' in which the turbulence spreads, if the water is deep enough, and decays. The first part of this region is that which is most likely to be affected in a qualitative manner by entrained air.

Discussion

The model of flow in a quasi-steady breaker which is given above is not entirely new. We have found that Rajaratnam (1965) shows the

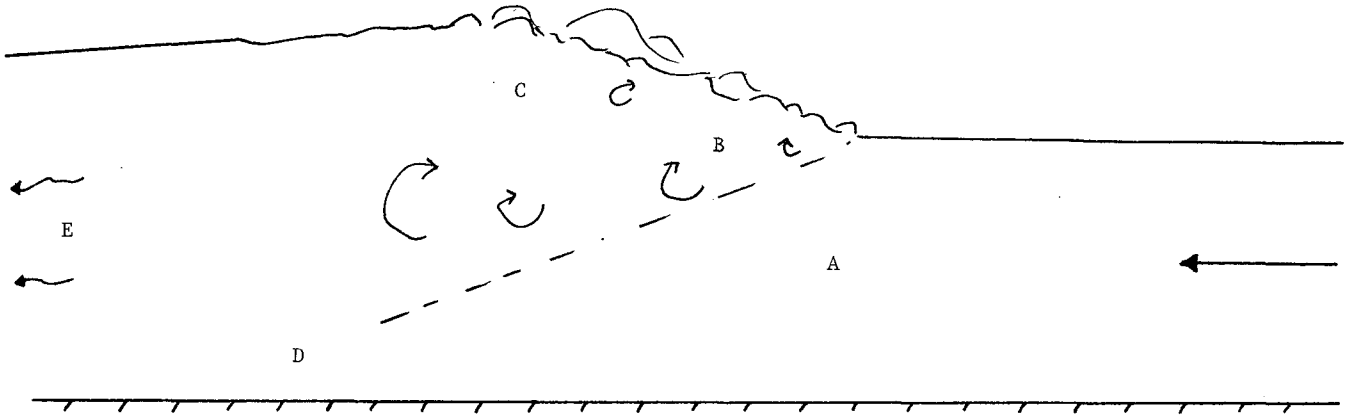


Figure 4. Model of quasi-steady breaking wave

A In flow region
B Mixing region
C } interaction regions { with gravity
D } { with bottom

E Wake, or decay, region.

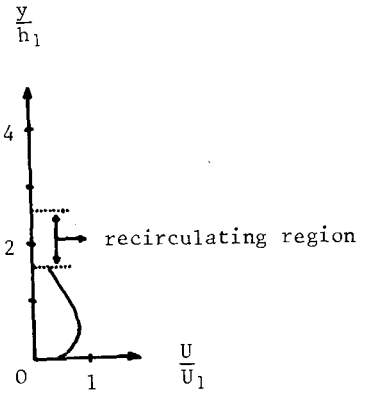
similarity between a strong hydraulic jump and a wall jet, and that Ogris (1975) has likened the hydraulic jump to a succession of vortices and also used the term 'mixing zone' to describe our 'mixing region' and our 'interaction regions'.

In studying any turbulent flow it is very helpful if it can be shown to be similar to other well known flows. Here we have made a hypothesis that flow in a breaking wave is in part like a mixing layer and part may be like a wake. Clearly it is important to assess the accuracy of this hypothesis with actual flow measurements since if the hypothesis proves reasonable then it will be of value in many studies relating to wave breaking such as air/sea interaction, sediment motion and wave forces on structures.

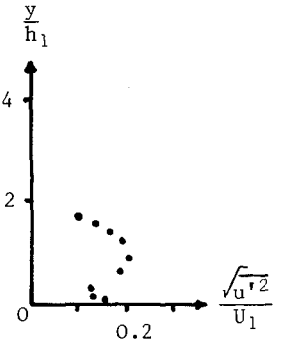
It is possible that some pressure and velocity measurements taken below breakers are of a quality to show the turbulent 'wake' of a spilling breaker, but we are unaware of them. This model of the wake from a spilling breaker is however supported by a laboratory investigation of sediment transport under waves (Nielsen et al 1978, final section).

Measurements of mean flow and turbulent fluctuations in hydraulic jumps are reported by Resch and others in a sequence of papers. Unfortunately they only consider very strong jumps. However, one can examine their weakest example which is for a Froude number of 2.85, that is a depth ratio of 3.6. The only measurements which appear to be relevant to our mixing layer hypothesis are those for a potential inflow at a distance of approximately 7 times the entry depth from the toe of the roller. These are shown in figure 5. From the measures of $\sqrt{u'^2}$ it appears that interaction with the bottom boundary-layer has already commenced. However, the upper part of the mean velocity profile does have an almost constant gradient as one finds through the centre of a mixing layer profile (eg Brown & Roshko, 1974, Fig 9) and the maximum intensity of $\sqrt{u'^2}$ is $0.19U_1$, which is not very different from the values for a mixing layer of around $0.17U_1$ found by several experimenters (see Champagne et al, 1976, figure 5). Examination of Resch and Leutheusser's figures for $\sqrt{v'^2}$ shows one very extreme point, in this profile only, so that we do not consider it reliable for comparison.

We hope this paper will help to stimulate further measurements and would particularly like to point out that it is possible to have quasi-steady breaking waves without air entrainment. The scale simply needs to be small enough. If the breaking front is of a height 1 to 2cm then, depending on the water quality and the particular type of wave, there may be no air entrainment and yet there is a very turbulent flow with all the other qualitative characteristics of a breaking. Without air entrainment laser-doppler anemometer measurements should be straight forward and able to show how far the ideas of this paper can be exploited.



(a) mean velocity profile from Resch et al (1976), figure 8.



(b) intensity of turbulent velocities in the mean flow direction from Resch and Leutheusser (1972), figure 5.

Figure 5. Velocity measurements in a hydraulic jump of depth ratio 5.6. h_1 and U_1 are the depth and mean velocity of the approximately uniform undisturbed flow. The measurements are at a point $7.2h_1$ from the toe of the surface roller.

We suspect that order of magnitude estimates from this model may be quite useful in some circumstances. For example to estimate the strength and scale of turbulence reaching the bottom from a bore on a beach, one could use results corresponding to a mixing layer with u_1=bore velocity, u_2=0 and thickness aproximately equal to the total height of the bore (note, bores on a beach only rarely have a depth ratio as great as 2, eg see Svendsen et al,1978). Alternatively if a spilling breaker is causing the turbulence, one might assume that at the wave crest the mixing layer had a width approximately equal to the height of the roller, then estimate the relative momentum deficit and patch this on to the corresponding wake flow, assuming the free surface represented a symmetric plane at the centre of the wake. When the wake half width equals the depth of water the turbulence affects the bottom.

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