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WATER-WAVE IMPACT ON WALLS

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■ **Abstract** The more violent impacts of water waves on walls create velocities and pressures having magnitudes much larger than those associated with the propagation of ordinary waves under gravity. Insight into these effects has been gained by irrotational-flow computations and by investigating the role of entrained and trapped air in wave impacts. This review focuses on the results of theoretical work, making particular note of the value of considering pressure impulse, and highlights the aspects that are poorly understood.

1. INTRODUCTION

Since the first harbors were built, perhaps about 4000 years ago, there has been a need to protect areas of water, and land, from the wave action of the sea. Protective structures such as breakwaters and sea walls need to be sufficiently robust to withstand the most violent impacts of the waves, and it is these violent impacts that are the main focus of this review.

Precise measurements of pressures in violent wave impacts were not possible until electrical signals from piezo-electric probes could be used in the 1930s. Prototype measurements by De Rouville et al. (1938) and the careful experiments by Bagnold (1939) and Denny (1951) laid foundations for all subsequent work.

The pressures measured are much greater than would be expected from the parameters associated with the incident wave: wave height, H; water depth, h; gravity, g; and water density, ρ. Pressures can easily exceed $10\rho g(h + H)$. The corresponding effects on velocity and the upward splash may be seen in Figure 1. Further, details of the pressure record show great variability for nominally identical waves. However the pressure integrated with respect to time, the pressure-impulse, shows greater consistency. Similarly, the total force measurements have great variability compared with the total impulse on the wall.

Bagnold (1939) observed that the pressures were greatest when the amount of air trapped by the wave as it meets the wall is least, but not zero. He developed a theoretical model based on one-dimensional flow of a "piston" of water compressing an air cushion.

Subsequent experiments have benefited from improvements in instrumentation, particularly recording methods, and have generally confirmed Bagnold's observations. Among papers reporting such results and field measurements we note Richert (1968), Blackmore & Hewson (1984), Witte (1988), Kirkgöz (1991, 1995), Hattori et al. (1994), Bullock et al. (1999), and the two substantial projects, Monlithic Coastal Structures (MCS) and PRObabilistic design tools for VERtical Breakwaters (PROVERBS), funded by the European Union's Marine Science and Technology (MAST) program (see Oumeraci et al. 2001).

The typical behavior of water waves at a wall is described in Section 2. This is followed by a section on what has been learned from inviscid, irrotational, incompressible flow computations that reproduce the violent peak pressures (Section 3). The insights obtained from using a simpler pressure-impulse model are described in Section 4. Sections 5 and 6, respectively, introduce our present awareness of the effects of entrained and trapped air as well as three-dimensional effects. This account depends heavily on work at Bristol, England.

2. GENERAL DESCRIPTION OF WAVES AT A WALL

There are a large number of parameters that affect waves at a wall. The incident waves can range from gentle regular waves to a steep multidirectional sea. The waves are often significantly affected by the seabed topography in front of the wall. The mean water depth at the wall is important, and at tidal sites this is always varying. The structure of the wall: smooth, rough, perforated, block work, sloping, curved, etc., also influences the impact of a wave.

We are especially interested in the impact of the wave crest. Thus for simplicity many of the possible complexities of the wave field, and wave evolution on the approach to a wall, are not discussed here. On the other hand the shape of the wave as it meets the wall does have a strong influence on its impact, so we omit one of the more important aspects of wave impact by ignoring the way in which the shape of the wave develops. The three-dimensional nature of waves is only discussed briefly.

Another important parameter is the water depth at the wall. This can vary, from the base of the wall being exposed in the wave troughs, to the case where the crest of the wall is near the mean water level and it is overtopped by much of each wave. Both of these properties may hold when the wave height is larger than the wall height, and all cases are of interest. However, we assume that neither of these two extremes applies. For the most part we make the further simplification that the wall is vertical and smooth and that the seabed is horizontal immediately in front of the wall.

For sufficiently gentle incident waves, linear wave theory gives a good description. The waves are perfectly reflected, and if they are regular a standing wave pattern results. However, waves do not need to be very steep before the pressure on the wall becomes affected by second-order effects. These are most evident when the water is relatively deep compared with the wavelength. Longuet-Higgins (1950) noted that the second harmonic fluctuating pressure does not decay with depth. This is essentially due to the asymmetry between crests and troughs. The crests are higher and sharper than the depth of the troughs, so each time a crest forms, i.e., twice per cycle, there is an elevation in the water's center of mass, which must be generated by a force on the bed. Otherwise, the wave pressures are primarily sinusoidal.

For steeper waves that are still smooth and reflecting another feature in the time variation of pressure becomes evident. Beneath the wave crest a pressure minimum occurs so that there are two pressure maxima for each crest impact. This is most easily interpreted by considering the case where the extreme wave crest is thin and narrow, almost a vertical sheet of water. The water at the crest is projected upward and appears to be nearly in free fall. Thus a higher pressure is needed to provide the pressure gradient to accelerate water upward. Then, at the maximum upward excursion of the water it is exerting little or no pressure on the water below. As it falls down it must be decelerated, and the resulting pressure gradient is again supported by a higher pressure. These features are illustrated by an experimental record in Figure 2. Comparable theoretical results for the force on a wall from incident solitary waves of different heights is given in Figure 7*a* of Cooker et al. (1997).

For incident waves close to the limiting steadily traveling waves, pressure records beneath the wave crest become asymmetrical, as may also be seen in Figure 2. A higher pressure develops to generate the upward jet. However, the maximum pressure is only a few times that associated with the wave and water depth parameters, $\rho g(h + H)$. At this point it is worth noting that, as is illustrated

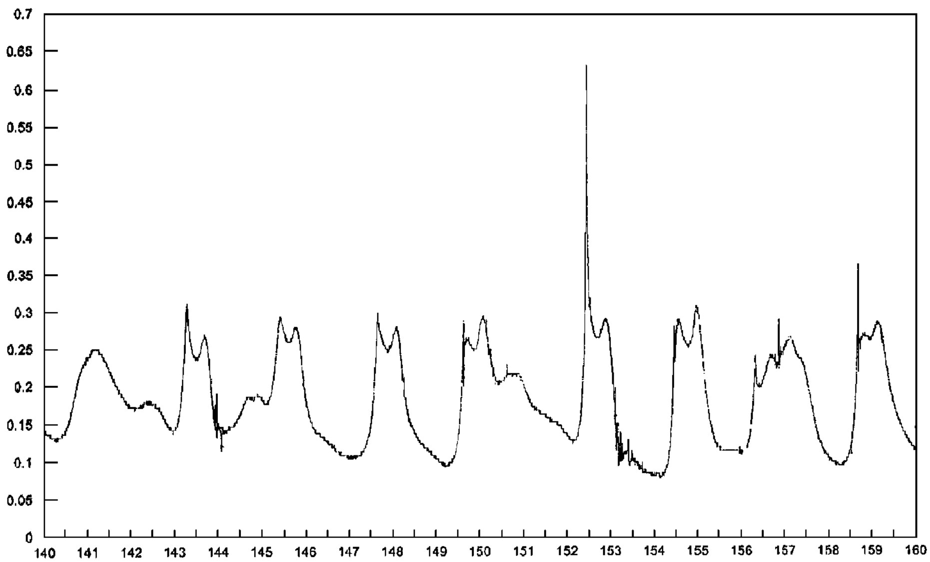

Figure 2 A record of pressure versus time for waves at a wall in a wave flume (courtesy of W. Allsop, H.R. Wallingford).

below, violent wave impacts are very sensitive to the shape of the incident wave just before impact. Thus the mean water level and the still water level may be less relevant than the water depth immediately in front of the wave crest, usually the water depth at the trough, and the total depth of water beneath the wave crest. The expression $(h+H)$ is best interpreted here as the maximum water depth at the crest.

For steep unsteady waves, a multitude of incident wave shapes is possible of which those associated with wave breaking are the most relevant. The greatest water speed generated by a freely traveling water wave occurs when the crest of the wave overturns, generating a jet of water as the wave breaks. This can lead to a water speed as much as two or three times $[g(h+H)]^{1/2}$. The existence of a wall in front of such a wave can interfere with the breaking process at any stage. The most dramatic interaction between wall and wave occurs when their interaction is close to the inception of overturning (described in more detail in Section 3). This interaction can lead to water velocities many times greater than $[g(h+H)]^{1/2}$.

If a crest has already developed a forward jet, then it may trap an air pocket as it strikes the wall. Similarly if the wave has fully broken, then the air-water mixture at its turbulent front meets the wall. In both cases the trapped and entrained air influences the dynamics. Also, in storm conditions the amount of entrained air persisting in the water can be significant. Aspects of trapped and entrained air are discussed below.

From a practical point of view for designers of sea walls, breakwaters, or other structures, the required quantities are often the total force, or impulse, and, sometimes, the maximum pressure arising from wave impacts together with their probability of their occurrence. Although in this review we suppose the wave properties prior to impact are known, it should be noted that achieving repeatable violent impacts is remarkably difficult to obtain even in experiments with periodic incident waves. Part of this variation is due to turbulence left by breaking waves, but this is aggravated by the sensitivity of the pressure to details of the wave's shape.

In Figure 3 the pressure record of one violent wave impact is shown. The sharp impulsive peak of maximum pressure is the prominent feature. For reliable recording of such peaks high sampling rates, 10 kHz or more, are needed. We look at the following aspects of these peak pressures in Section 3.

Following the peak pressure in Figure 3 there is some oscillation in pressure before the main bulk of the pressure record continues. As one might expect from the discussion above, a weak secondary peak is seen before the wave crest leaves the wall. The physical effects that predominate in creating these features are as follows:

1) For the peak pressure the inertia dominates; the timescales involved are too short for any gravitational influence. In the laboratory violent peak pressures act for times of approximately 1 millisecond, and peak duration ranges from 10 to 100 milliseconds in the field.
2) Subsequent oscillations in pressure are still too rapid for much gravitational influence and can be attributed either to an irregular shape of the incident

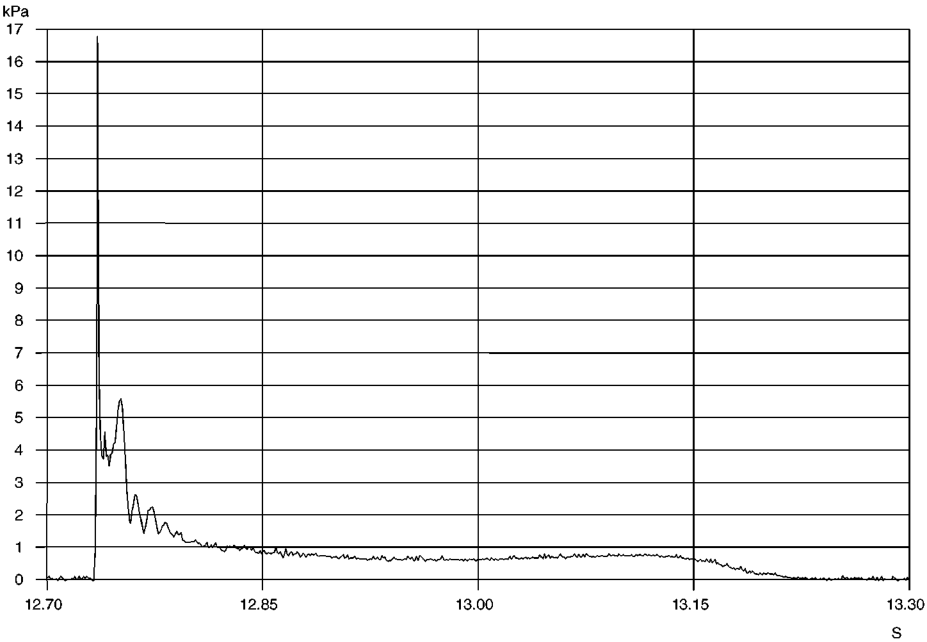

Figure 3 Pressure measurements from the impact of one wave in a Plymouth University laboratory flume (courtesy of M. Walkden, Bristol University).

wave crest or to the effects of trapped and entrained air. In two-dimensional laboratory experiments on a rigid wall, well-defined oscillations are not uncommon and are clearly related to pockets of trapped air.

3) The major part of the remainder of the wave profile is similar to that noted above for steep nonviolent waves and is thus due to hydrostatic pressure of the wave crest as modified by the water's vertical acceleration, its deceleration giving the final minor peak of pressure. Hence the pressure field is dominated by gravity and is thus related to wave propagation and reflection; a topic discussed in detail for the solitary wave by Cooker et al. (1997).

In the PROVERBS project the type of profile illustrated in Figure 3 was often seen in measurements and considered to be the typical impact profile. It was nicknamed the "church roof" profile.

3. VIOLENT PRESSURE PEAKS

The most violent pressure peaks are much higher than any pressures associated with wave propagation and the influence of gravity, thus investigators recognized early that normal water-wave theories could not explain such peaks. By using solitary waves, Bagnold's (1939) carefully conducted experiments that eliminated much of the variability of natural and regular waves. He demonstrated that the highest pressures occurred when the least amount of air was trapped. Bagnold recognized the importance of the inertia of the impacting wave. Although much of his discussion of the phenomenon is perceptive and useful today and is the foundation on which all subsequent work has been developed, we can now see that he gave too much attention to the effect of the trapped air for the most violent waves.

Theoretical study of the wave impact process has been able to gain little from the traditional theories of water waves. It is only in recent decades that accurate numerical modeling of overturning water waves has been realized, starting with Longuet-Higgins & Cokelet (1976). Such a numerical approach was first applied to steep waves at a wall by Cooker & Peregrine (1990b) using an extension of the boundary integral method of Dold & Peregrine (1986) (see also Dold 1992); the surprising results of which are described below.

The irrotational-flow computations describe a large amplitude wave that in the absence of the wall would have just started overturning when reaching the wall's position. The wave approaches the wall at a position where the wave would have a nearly vertical front face, and an almost "flat" impact on the wall might be expected. However, the wall stops water in the lower part of the advancing wave so that the wave trough fills up and the water level at the wall rises more rapidly than if the wall were absent. Indeed, the water level at the wall accelerates so fast that the height of the vertical face of the wave is rapidly reduced and the free surface moves as if converging toward a point (see Figures 4 and 5).

At some point during the surface convergence, water close to the wall accelerates even faster, at over $1000g$ in the example illustrated, and a vertical jet forms. The high accelerations require correspondingly high pressure gradients, over $1000\rho g$,

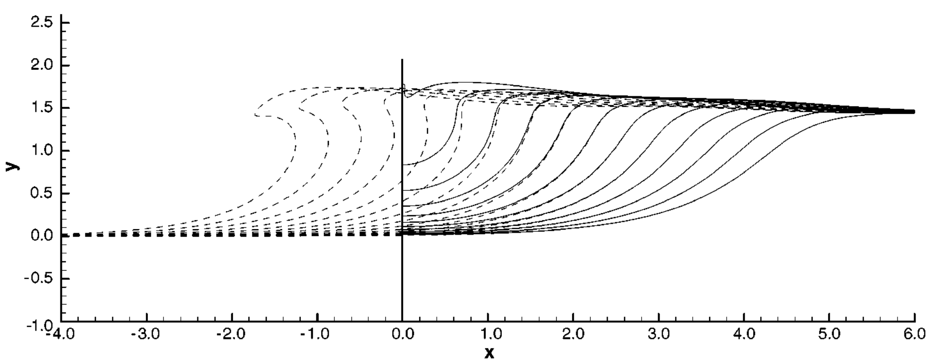

Figure 4 A steepening wave approaching a wall: surface profiles at equal time intervals. Space units are in terms of the initial depth at the wall. Broken lines show the wave's evolution in the absence of the wall. The wave moves from right to left (courtesy of G. Hu, Bristol University).

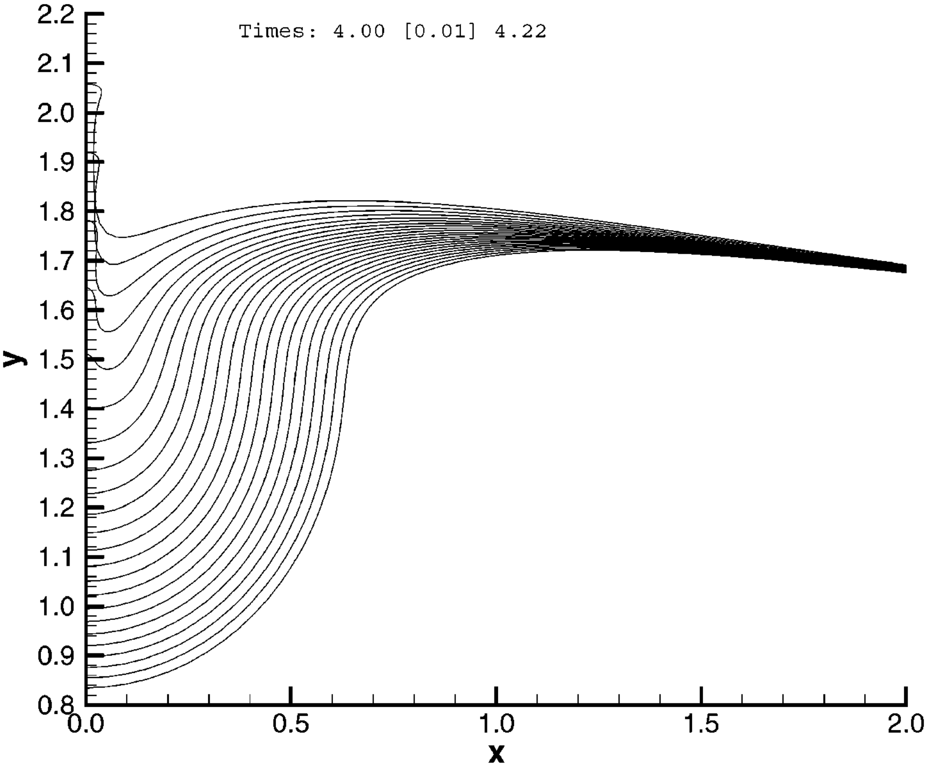

Figure 5 Detail of wave profiles close to the wall for the wave of Figure 4. Successive profiles "focus" toward the point where a jet forms (courtesy of G. Hu, Bristol University).

and, in this case, high pressures well over $10\rho g(h + H)$. The remarkable feature, compared with previous expectation, is that very violent pressures occur without any actual impact on the wall but with a smooth irrotational flow. We have called this phenomenon "flip-through."

Further computations of flip-through show that the smaller the region into which the free surface "focuses," the smaller and more violent is the resulting jet formation. Clearly the overturning crest of the wave can meet the wall before a jet forms, thereby trapping an air pocket. Again, the smaller the trapped-air pocket is, the greater the nearby water pressures at impact are, in line with Bagnold's observations, but the air pocket is not essential for the high pressures and violent motions (see Figures 6 and 7 for pressure fields with and without a trapped-air bubble). Bagnold (1939) did observe that the water level at the wall and the wave crest are converging. Remarkably similar fluid motion has been observed in laboratory experiments by Chan & Melville (1988). For the most violent impact measured on

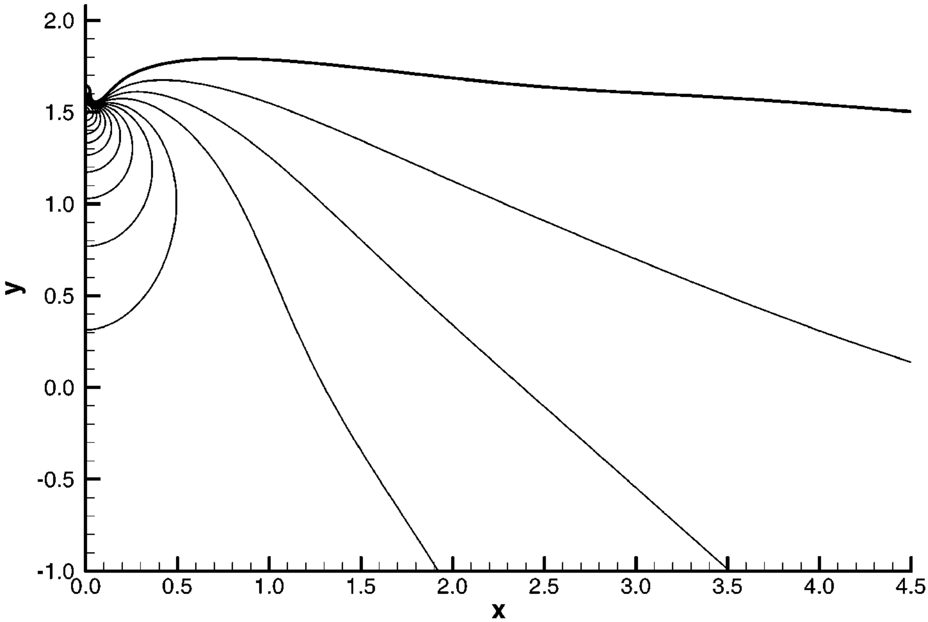

Figure 6 Computed pressure field at flip-through for the wave of Figure 4 (courtesy of G. Hu, Bristol University).

a vertical wall, they describe from viewing their high-speed film, "It is observed that wave impact occurred through the focusing of the incident wavefront onto the wall; that is through the convergence of the wave crest and the surface intersection point at the wall."

The only qualitative difference in the experiment from a computed flip-through is that the thin high-speed jet rapidly breaks up into drops due to the effects of air and/or surface roughness and surface tension resulting in entrainment of small bubbles. The initial computations of Cooker & Peregrine (1990b) and the experiments of Chan & Melville (1988) involved very different incident waves. Cooker & Peregrine used a large shallow-water wave that steepened due to the higher portion overtaking the front of the wave, whereas Chan & Melville used the frequency dispersion of deep-water waves to focus wave energy into a breaking wave event. Also, the "wall" described by Chan & Melville was a vertical plate that did not penetrate to the bottom of the wave tank. These differences and a range of more recent computations show that flip-through, when it does occur, is independent of the global geometry and dynamics and is a local phenomenon.

The localization of the highest pressure, both in space and time, means that in the laboratory the area of a pressure transducer may be too large to accurately catch the pressure peak. On the other hand, a small area of high pressure, versus the total area affected by enhanced pressures, may be less important for a coastal

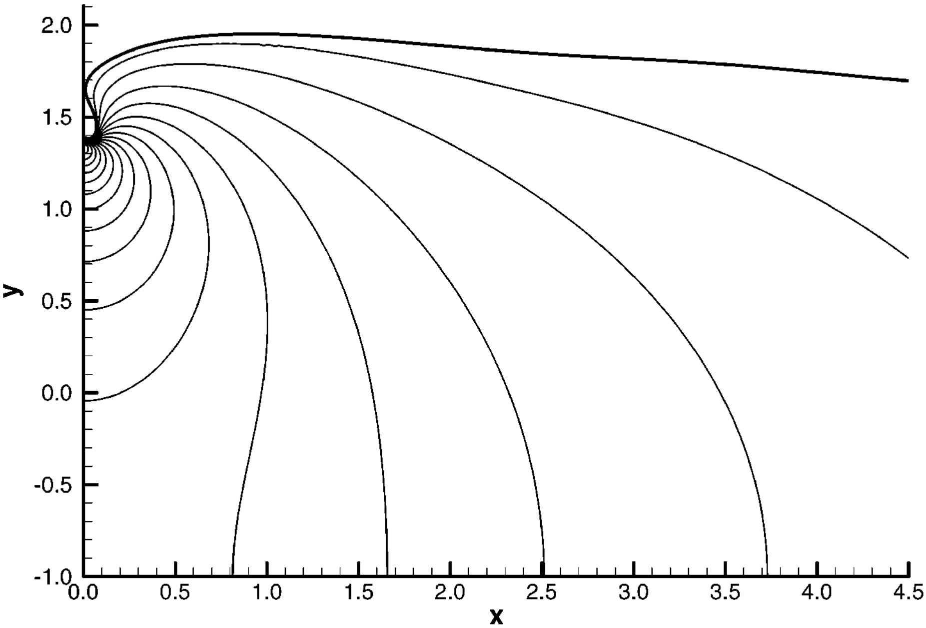

Figure 7 Computed pressure field of a wave with a small trapped-air pocket with hydrostatic pressure subtracted (courtesy of G. Hu, Bristol University).

structure. However if there are cracks, or weak points in a structure, such high pressures could threaten its integrity.

For the mathematical model used here, i.e., irrotational inviscid incompressible flow with no effects from the air, there may be no upper limit to the maximum pressure if the free surface can "focus" to a small enough region. Similar high pressures that result in high-speed vertical jets can occur even more dramatically in axisymmetric flows, as discovered experimentally by Longuet-Higgins (1983) and studied in greater detail by Zeff et al. (2000). The most violent possibility might be when a minute bubble is formed as a vertical jet at the wall and an overturning jet from the wave form simultaneously. Such matters are the subject of ongoing investigation but are unlikely to be directly relevant to practical flows.

The flow near the point of maximum pressure is of practical interest however. This point moves up the wall, but if one takes a frame of reference that moves with this point, the flow becomes relatively simple. Water impinging on the wall forms a high-speed jet, and water enters the jet so rapidly that the flow near the pressure maximum is almost steady in this reference frame. This can be illustrated by a comparison of the pressure contours with the case of steady jet impact (for analysis see Gurevich 1965) in Figure 8 [see also the filling flow described by Peregrine & Kalliadasis (1996, Figure 2) in which the jet formation region is also moving].

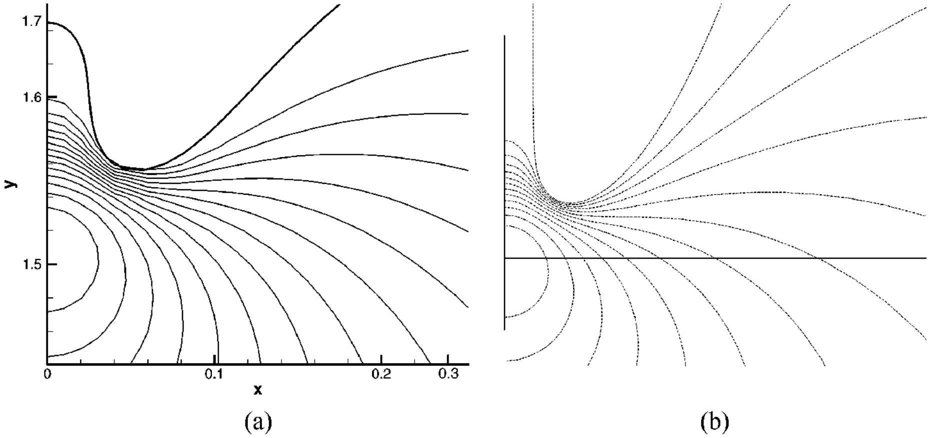

Figure 8 (*a*) Pressure field near the pressure maximum of Figure 6 (courtesy of G. Hu, Bristol University). (*b*) Pressure field near the pressure maximum of colliding equal jets converging at 7° (courtesy M. Cooker, University of East Anglia).

In practice, these localized high-pressure events can be disrupted by disturbances that are small on the scale of the incident wave but are of a size similar to the peak-pressure region. Examples of such disturbances are small surface waves and roughness of the vertical wall. In the laboratory only the first breaking/impacting wave in an experiment has a perfectly smooth water surface and even then there is appreciable variability.

Although the peak pressure may be disrupted and modified in any particular example, the general field as shown in Figures 6 and 7 is likely to be little affected. This pressure field is of greater importance for the design and integrity of structures because it provides the forces, impulse, and turning moments acting on any structural element. In essence, once the point of maximum pressure is known, the pressure field has a simple pattern, which decays with distance from the maximum to the near hydrostatic pressures at a distance of approximately twice the water depth. Using the concept of pressure impulse, Cooker & Peregrine (1990a) used these properties, apparent in the full computation of flip-through, to make a much simpler approximation to the pressure field.

Whereas the pressure provides the force on the wall, the pressure gradients are also of relevance because they provide a force on any object protruding from the wall or resting on the bed. Cooker & Peregrine (1992) discuss this topic and indicate that the force directed away from the point of peak pressure that is given to such objects can be larger than the drag force resulting from the water's motion in the opposite direction. Because the force on an object due to a pressure gradient is proportional to the object's volume, whereas drag is proportional to its cross-sectional area, this pressure-gradient force is especially important for larger objects that are near the impact.

4. INSIGHTS FROM THE PRESSURE-IMPULSE MODEL

Bagnold (1939) and others, e.g., Richert (1968), demonstrated that the impulse given by a wave is much more consistent than force or pressure in measuring the impact of a wave. This has led to the use of pressure impulse, which is the time integral of pressure through the impact, just as impulse is the integral of the force. Pressure impulse is

$$P(\mathbf{x}) = \int_{\text{before}}^{\text{after}} p(\mathbf{x}, t)\mathrm{d}t.$$

Here we consider impact to be only due to the violent peak, not the total time that the wave crest spends at the wall. Thus the weight of the water that gives hydrostatic pressure is not included (illustrated in Figure 7). By assuming that the very short timescales permit neglect of both nonlinear terms and viscosity, the equation of motion simplifies to

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \nabla p = 0,$$

which upon integration in time gives

$$\mathbf{u}_{\text{after}} - \mathbf{u}_{\text{before}} = -\nabla P.$$

The further assumption of incompressibility gives $\nabla^2 P = 0$, which must be solved in an appropriate domain.

The boundary conditions for $P(\mathbf{x})$ become $\partial P/\partial n = 0$ on any rigid stationary impermeable surface that is wet before and after impact, and $P = 0$ on the free surface, when pressure is measured relative to atmospheric pressure. The "forcing" term for pressure impulse comes from the stretch of the boundary that was dry beforehand and is then "hit" by water. Here we suppose the approaching water has a velocity component of U toward an impermeable wall and has zero flow through the wall, i.e., $\partial P/\partial n = -\rho U$, where the normal is toward the water.

Even without any further analysis one can see where earlier attempts to model impact with one-dimensional models can be improved. Zero pressure impulse along the free surface gives a strong constraint on the pressure-impulse distribution.

This integration over the flow field evolution loses all detail in the impact region, which can either include direct impact of water or a very rapid rise of water level. Thus, Cooker & Peregrine (1990a) also simplified the wave shape, considering a semi-infinite horizontal strip of water of depth H with the impact region being some fraction of its contact with the vertical wall. This enables derivation of a simple Fourier-series solution (illustrated in Figure 9).

One result is that for a uniform impact velocity U the total impulse cannot be greater than $0.54\rho UH$ per unit length of wall, which occurs when the whole depth of the water is involved in the impact. This relatively small impulse from the impact of a semi-infinite volume of incompressible water is entirely due to the

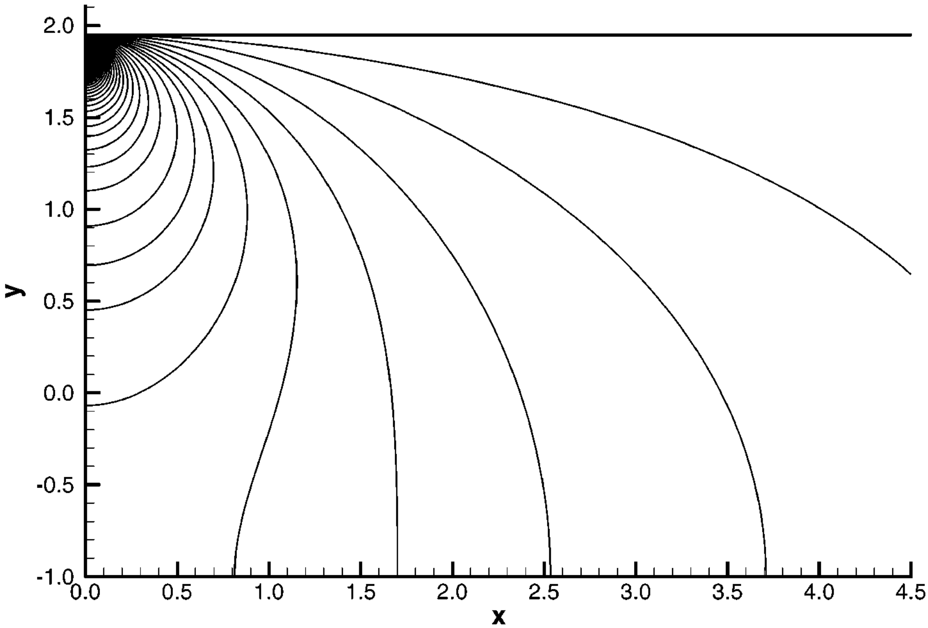

Figure 9 Pressure-impulse field for comparison with Figure 7 (courtesy G. Hu, Bristol University).

effect of the constant pressure at the free surface. It also indicates that the shape of the wave at distances more than 0.5*H* from the wall is not very important, which also encourages the use of much simplified wave shapes. Cooker & Peregrine (1990a, 1995) give several examples. Experimental studies confirming the value of the pressure-impulse approach are described by M.A. Losada, F.L. Martin, & R. Medina (unpublished report) and Chan (1994) who shows that the concept is useful within its limitations.

Many features of impact are revealed by pressure-impulse solutions. If the area of a two-dimensional impact on the upper part of the wall is small compared with the water depth, then the decay of pressure with depth below the impact region is rather slow. Cooker & Peregrine (1995) showed that pressure impulse decays logarithmically with depth down the wall for an infinite water depth, leading to an infinite total impulse on the wall. However, in practice, water is of finite depth, although some modern caisson breakwaters are in water of depth many times the maximum wave heights usually encountered. In addition, although there are many cases of impact where wave crests are parallel to the face of breakwaters or sea walls, the transverse extent of a simultaneous violent impact is limited in reality.

Wood & Peregrine (1998) describe results of pressure-impulse modeling of three-dimensional wave impacts. For example, for an impact height equal to one third of the water depth, the middle of the impact region becomes approximately two dimensional on the wall when length of the impact region is approximately four times the water depth.

One of the more important features to emerge from a range of pressure-impulse solutions is that the effect of a given impact, i.e., a given impact velocity and area, can be enhanced by the proximity of rigid boundaries. This contrasts with the ameliorating effect of the zero pressure impulse at the free surface. This is easily understood if one thinks in terms of a plane rigid wall forming a "reflecting" plane for an image impact, as is the usual method of images for dealing with point sources. Examples of enhanced impact effects include impacts due to sloshing in a container. These impact effects can be aggravated by "filling flow" effects (Peregrine & Kalliadasis 1996) in an almost full container. Similar effects also occur for the "partial containment" of vertical impact on a projecting platform, beneath the deck of a pier, or beneath offshore platforms (Wood & Peregrine 1996) (illustrated in Figure 10).

Where the bed is highly porous, as in many cases where rubble or armor units form a berm in front of a breakwater, the pressure-impulse distribution has been modeled by Wood & Peregrine (2000), showing that the "image" effect of a rigid impermeable boundary is then very considerably diminished.

An estimate of the pressure field is readily made from the pressure-impulse field if the duration of the violent impact, Δt, can be estimated. Most measured violent pressure peaks appear to give time traces that are almost triangular so that the maximum pressure is $2P/\Delta t$. Impact duration clearly increases with the physical size of the waves, but no detailed quantitative study has been made. Appropriate scaling from laboratory to ocean waves is still an uncertain matter for violent impacts.

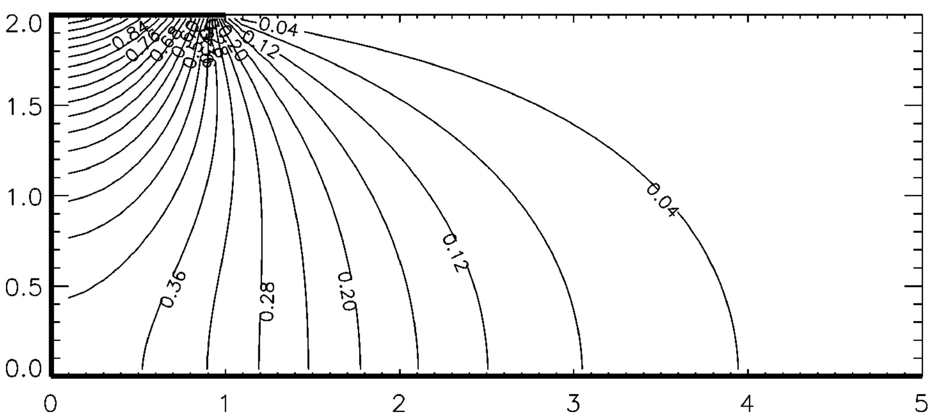

Figure 10 Pressure impulse due to vertical upward impact on a projecting platform for two-dimensional flow (courtesy D. Wood, Oslo University).

5. TRAPPED AND ENTRAINED AIR

It is easy for an overturning wave to trap a pocket of air against a wall. For laboratory waves, the compressibility of the air can give rise to two important features: an increase in the duration of the pressure peak, with related reduction of peak pressure, and oscillations of pressure following the peak. These oscillations can sometimes be sustained long enough for a musical note to be heard (D.H. Peregrine, personal observation).

By using a simple linearized model of a semicircular air pocket, Topliss et al. (1992) found the free modes of acoustic oscillation. These frequencies compared well with experimental measurements when the dimensions of the air pocket were taken from corresponding video pictures. Zhang et al. (1996) directly modeled numerically the trapping of an air pocket by a two-dimensional irrotational flow. An effective model of jet impact against the wall enabled continued computations to show an oscillation of appropriate period.

When video of an air pocket is viewed, it seems remarkable that such simple theoretical models give a reasonable value for these oscillations because the initial air pocket rapidly breaks up into smaller bubbles. Such break-up is to be expected because while the air pocket is being compressed the water surface is slowing down so that the higher pressure is in the air. A pressure gradient in this direction promotes Raleigh-Taylor instability. If the wave impact is violent, then this instability can grow very rapidly and break up the air pocket. However, the compressibility of the air is not affected by its volume being disrupted and broken into bubbles.

It is the compressibility of air-water mixtures that makes scaling from laboratory to prototype difficult. The effect of even a small volume fraction of air in water greatly increases its compressibility. From a fluid-dynamic view point, this is best demonstrated by the variation of the velocity of sound. At atmospheric pressure, just 1% of air gives a velocity of sound of 120 m s^{-1} and as low as 30 m s^{-1} for 20% of air. These values are for adiabatic pressure fluctuations, ignoring the effects of surface tension and other factors that are likely to be unimportant in wave impact.

For large ocean waves at a breakwater, there is always a substantial entrainment of air, which results from the breaking of previous waves as well as the air that is “captured” by each individual wave. Measurements by Lamarre & Melville (1992) and Bullock et al. (1999) show a wide range of air-volume fractions.

In addition, there is a significant difference between salt- and freshwater. As was well demonstrated by Scott (1975, 1976), the modal size of bubbles in saltwater (typical diameters less than 1 mm) is much smaller than those in freshwater ($\sim$5 mm in diameter). This means bubbles persist much longer in saltwater, thus leading to higher volume fractions of air. This effect is now known to involve, among other things, the hydration properties of the ions (Weissenborn & Pugh 1996). Although there is a reluctance to use saltwater in laboratory equipment because of its corrosive properties, a set of experiments at Plymouth University were measured with fresh- and saltwater successively in the same flume (Bullock et al. 2001). Even at their relatively small scale a significant difference was found.

Peak pressures were reduced by ~10%, whereas the total impulse did not differ greatly.

The general impression is that the effect of air is to "cushion" the most violent impacts. Hence, in scaling from laboratory to prototype, some appropriate reduction factor should be found for pressures and forces. Normally, Froude scaling is used for wave problems where length and timescales are modified by accounting for gravity, which is intrinsic to the incident waves' propagation. This usually leads to estimates of prototype forces that are much larger than is considered realistic—but this view must be tempered by difficulties experienced in maintaining the long-term integrity of most structures directly exposed to ocean waves. If compressibility is to be included, then no simple scaling can be expected.

The effect of compressibility in a correspondingly violent flow has been evaluated. The filling flow of Peregrine & Kalliadasis (1996) gives a very high pressure for the case of a flow entering a confined space that is almost full before the flow encounters the far end. The initial incompressible model is extended to the compressible case by Peregrine & Thais (1996), who used the simplest equation of state for air-water mixtures. Two different pressures were evaluated: the peak pressure, which appears to be directly related to the flip-through peak pressures described in Section 3, and a general contained pressure, which is likely to be comparable with the pressures below the impact region, such as those modeled by the pressure-impulse method. These pressures are reduced by increasing the air fraction but in differing ratios: The peak pressure is reduced more than the background pressure. Bullock et al. (2001) find that these results are consistent with their experimental findings for wave impact.

Although impacts with significant compressibility effects do not fit the simple pressure-impulse model described above, it is still instructive to consider them in the context of that model. Consider the compressibility of trapped air. The water may still be approaching the wall with velocity U; but if trapped air is at the wall, it takes time for the air to be compressed and then re-expand, which is likely to extend the duration of the impact peak. Also, the water does not lose its wall-normal velocity component, but instead rebounds. This "bounce-back" implies an elastic collision between water and wall that leads to an increase in the impulse imparted to the wall. This increased impulse is estimated and compared with experimental measurements by Wood et al. (2000). The example shown in Figure 11 is typical. The measured pressure impulse is greater than that which results from the simple pressure-impulse calculation and compares reasonably well with the "bounce-back" results. In these examples, which use the incoming wave velocity measured in the experiments, the main pressure peak was only just violent enough to be separated from the gravity-affected part of the pressure. Even so, there is clear support for the hypothesis that "bounce-back" occurs and increases the impulse imparted to the wall.

As with simple mechanical impact, there is an energy loss associated with inelastic impacts. A simple calculation (Cooker & Peregrine 1995) demonstrates that this also applies in the pressure-impulse model. For the purely inelastic

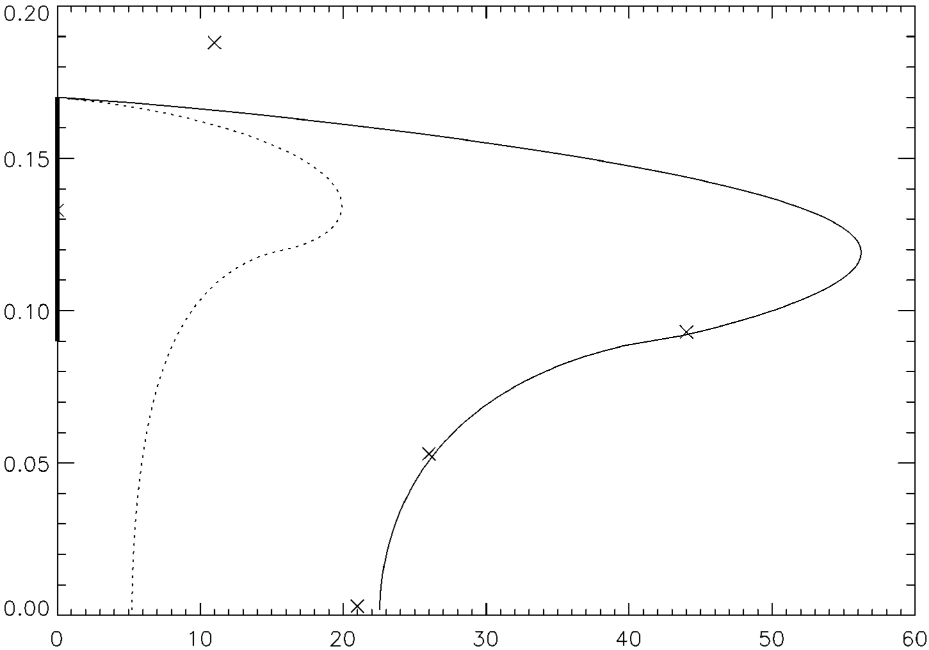

Figure 11 The curves show pressure impulse as a function of height, with and without "bounce-back." The heavy line is the impact region. The crosses are experimental measurements (courtesy of D. Wood, Oslo University).

impact of flip-through, it seems clear that much of the "lost" energy is concentrated into the upward jet because the irrotational-flow computations are energy conserving. In other cases, even with the rebound of compressed air, there is still "lost" energy. Most of the energy goes into the upward jet/splash and, when there is direct impact on the wall, into the break-up of air pockets, thereby causing intense turbulence.

Another approach to the trapped-air case is to suppose that compressibility effects are not important, as might be the case for small waves in the laboratory, and simply take the air pocket to be incompressible, but, of course, with the density of air instead of water. Calculations on this basis (A. Porter, private communication) give a significant reduction of pressure impulse when compared with the case where the air is replaced with nonimpacting water. This case can only reasonably apply when the air pocket is so small that its oscillation period is much less than the impact duration. Thus very small air pockets may reduce impact strength in such a case, which appears contrary to several experimental reports dating from Bagnold (1939) to present. However, as noted earlier, small volumes of trapped air may indicate a wave impact that is close to the flip-through case and is thus violent owing to the "surface focusing" of its inertia.

On the other hand, a somewhat unusual example of trapped air in an impact shows an unexpectedly large effect produced by an air pocket. As described by Walkden et al. (2001), heavy overtopping of a breakwater with a low crest can lead to a significant impact of water from the wave onto water behind the breakwater. Thus, although this is not a direct impact on the breakwater, it is much more confined. This impact eliminates much of the effect of zero pressure impulse at the free surface and hence exerts significant impulse on the rear of the breakwater.

In the experimental part of the study by Walkden et al. the falling water was shown to have trapped a large air pocket just above the water closest to the breakwater. Initially the theoretical pressure-impulse model was evaluated with the pressure in the air pocket equal to atmospheric pressure. However, experimental pressure measurements close to the free surface indicated a much higher impulse. Good agreement between theory and experiment was obtained when the pressure impulse at the air pocket–water interface was set equal to 80% of that attributed to the falling water. Such a high pressure impulse occurring in the air pocket is surprising and merits further investigation of air-pocket dynamics.

6. THREE-DIMENSIONAL EFFECTS

Much of the discussion up to this point is for the idealized two-dimensional case that is usually modeled in laboratory flumes and for which some theoretical progress has been made. In the real three-dimensional world at the edge of an ocean, many aspects of the fluid dynamics may differ, so we reconsider some of our assumptions.

Real waves may be irregular and three dimensional. We have invariably referred to wave crests but at times even that may be inappropriate. In our focus on the most violent impacts, it is appropriate to be concerned with waves that are breaking or are about to break, and wave breaking is normally associated with wave crests. However, when a wall is in shallow water, for example, if the mean water level is close to the base of the wall, the details of incident wave motion are very strongly affected by the bed, which often has a relatively steep slope. In such cases, a much wider variety of flows can occur, especially when waves take the forms of surging, or collapsing, breakers. Three-dimensional aspects of wave impacts can generally be expected to reduce the forces and pressures when compared with two-dimensional impact because peak pressures become more localized. However, there are aspects of three dimensionality that may act to enhance wave impacts. The most obvious of these is when there is some wave focusing and an incident wave crest is concave toward the wall when viewed from above. This leads to a greater focusing of the wave's inertia, as with axisymmetric flows. Hence peak pressures can be enhanced. Often, damage to breakwaters recurs in the same place, which may relate to wave focusing by offshore topography, although greater wave height may be more important than curved crests.

There is an experimental indication that waves with an angle of incidence that is only slightly off the wall normal may lead to more severe conditions. Whillock

(1987) found that in experiments with an angle of incidence less than 15° there were higher pressures than for the same waves at normal incidence. If waves are long crested, this could be related to the speed of each crest along the wall. If a crest has speed c and is incident at an angle θ to the wall normal, the crest position on the wall has a speed $c/\sin\theta$. This speed is unbounded as $\theta \to 0$. Normally this is just a phase speed and bears no relation to water velocity. However, as is well known, for normal wave breaking, overturning water must gain a velocity at least slightly greater than the speed of the crest. Thus if the wave breaks along the wall, the water might gain velocities comparable with this large along-wall phase velocity.

7. DISCUSSION

It is clear that the fluid mechanics for many wave impacts on walls can be described well by the traditional water-wave model of irrotational, inviscid, incompressible flow. For two-dimensional fully nonlinear problems, computation with boundary-integral methods is efficient and can easily cover a wave's evolution during its final approach to a wall. In addition, its extension to describe a trapped-air pocket has been demonstrated.

Computation of three-dimensional examples requires substantial computing resources but has been demonstrated for a number of interesting cases not directly connected with wave impact (Grilli et al. 2001, Xue et al. 2001, Liu et al. 2001).

The most intriguing feature in the fluid dynamics of wave impact is the violent flip-through where, without any true impact, a high-speed, vertical jet emerges from a small region of high pressure. This phenomenon can be given a wider context: It may occur at any rigid boundary over which the free surface moves because gravity is unimportant in this part of the flow, so the "wall" need not be vertical. Indeed, on beaches of moderate slope, flip-through does appear at the parametric boundary between waves that do not break and waves that form "collapsing" breakers.

The most natural wider context for the vertical-wall case is that of standing waves, which need not necessarily be purely periodic but may be considered in a more generalized unsteady sense, noting that mathematically the wall is just a reflecting plane. Although there is much recent activity studying standing waves making jets (Longuet-Higgins 2001, 2002; Longuet-Higgins & Dommermith 2001; H. Bredmose, M. Brocchini, D.H. Peregrine, L. Thais, submitted), there is much yet to be learned about jet formation. Other works directed at this topic include Longuet-Higgins's (1993) solution with a singularity as well as the considerations by Peregrine & Prentice (1994) and Cooker (2002) of "initial" conditions related to the focusing of the free surface that happens in flip-through.

From a practical point of view, the apparently unbounded pressures from flip-through impacts are less important because it is clear that surface roughness, of the waves or the wall, limits the surface focusing that can occur. Combining this with the great sensitivity of flip-through to wave shape, and the natural variations of the incident waves, provides support to the growing use of probabilistic methods in design. This was the major theme of the PROVERBS project whose report, Oumeraci et al. (2001), provides a wider context to this problem. However, greater understanding of the mechanics of flip-through and its sensitivity to disruption is needed before a good quantitative probabilistic assessment of the importance of the extremely high localized pressures can be made.

Away from the small region of very high pressures, the pressure-impulse approach has provided greater insight into the general properties of wave impact. Its great simplification of the flow's dynamics indicates that it has value for assessment of the wider influence of wave impacts and as a design tool.

There are marine and coastal structures that do need to withstand waves of heights greater than 10 m with periods of 20 sec. The outstanding problem is how to determine the effect of entrained and trapped air in modifying water pressures at these large scales. This is the subject of ongoing research.

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Figure 1 The splash from a wave impact on a wall illustrates the acceleration of water, by high impact pressures, to velocities much higher than those directly associated with the wave motion (photograph by D.H. Peregrine).