Violent water wave impact on a wall

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Abstract. The most severe impacts of waves upon a coast are considered. It is demonstrated that the violence of impact depends very sensitively on the transformation of waves approaching a wall, making the most violent impacts correspondingly rare. Pressures are high enough to cause compressibility effects to be important. Numerical solutions show the significant effects of the compressibility of both trapped air pockets and of air entrained into the water.

Introduction

Coasts that are open to ocean waves experience rogue waves. These are dangerous to people at the edge of the sea where the coast rises abruptly from the water. There are numerous cases of people being swept to their death by single unexpected waves. For example this happens sufficiently often along the coastline of Sydney, Australia, that wherever rock ledges occur near the level of the ocean, warning signs are erected. Coastal and marine structures are vulnerable to extreme waves, and the main aim of our study is to increase understanding of the most damaging and violent impacts. The results apply to both coastal and offshore impacts, although the study is directed towards coastal structures.

Violent impact of an extreme wave onto a structure can be the criterion that determines a number of design parameters. Within the BWIMCOST (Breaking Wave IMpacts on COastal STructures) project such impacts have been measured in the field and the laboratory for waves breaking onto a sea wall or breakwater, see *Bullock et al*. (2004) and *Obhrai et al.* (2004). The time and space scales of violent impact are sufficiently small that the hydrodynamics of impact is unlikely to differ for waves in deep water which hit fixed or floating structures. In practical situations when pressures exceed a few atmospheres, it has long been appreciated that compressibility of air becomes important for air that is trapped by overturning waves. Of equal importance is the compressibility of water which carries bubbles of entrained air. Such 'white water' is ubiquitous in rough conditions where waves are breaking. This compressibility is evident in the very low velocity of sound in the air-water mixtures and is a primary concern when small-scale laboratory data is being used to estimate large-scale prototype impacts, since the usual Froude scaling is unlikely to be correct. *Peregrine* (2003) gives a review of water wave impact on walls; work subsequent to that review is reported here.

The three main strands of data for the BWIMCOST project are from

1) prototype: on the Admiralty breakwater, Alderney, Channel Islands, which is exposed to waves from the Atlantic Ocean.
2) 1:4 scale: in the big wave channel (Grosser Wellenkanal, GWK) Hanover.
3) 1:25 scale: laboratory experiments in Plymouth with both fresh and sea water.

Few examples of violent impacts have been obtained from Alderney. The most severe impact that occurred can be described well as a rogue wave, as the other impacts in the record were very much smaller in magnitude. The GWK measurements, however, have yielded exceptionally violent impacts with pressures over 3 MPa. These impacts vary in character, a few details are presented here. In this context the 'rogue' character of waves relates to the violence of the impact rather than to an incident wave of unusual height.

The theoretical studies include careful analysis of the data for waves approaching the breakwater; development of simple mathematical models for the impacts, and the development and study of detailed

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numerical models. Here attention is focussed on the detailed modelling.

Measurements

The Admiralty breakwater, Alderney, stands on a mound about 12 m above the nearby sea bed. It is exposed to the full force of Atlantic Ocean waves. Incident waves are recorded by an array of pressure cells on the sea bed. A set of instruments on the face of the breakwater measure both pressure and the aeration of the water, in terms of the volume fraction of air. Severe impacts are relatively rare. As an example, the pressure record for the most extreme impact is shown in Figure 1 on a time interval which shows several associated impacts. The peak pressure of 745 kPa is the highest ever recorded on a breakwater in the field. Like other rogue waves, there were no comparable impacts in the remainder of the 20 minute record.
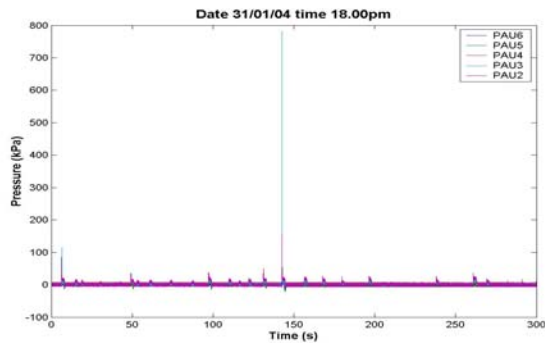

Figure 1. Pressure measurements of the extreme wave recorded from the Admiralty Breakwater, Alderney.

A much more intensive distribution of measurements of wave properties is possible in the GWK. These also included pressure and air fraction measurements with instruments similar to those used in the field. Thus it is these measurements that we have sought to understand in detail. Figure 2 gives a sample of one severe impact: two plots are shown. The upper one shows the highest pressure in detail. The duration of the pressure peak is just one millisecond. Data were usually sampled at 10 kHz - this was verified to be sufficiently frequent by taking some data at 40 kHz. The lower plot sets this peak pressure in the context of the impact as a whole, by including both a larger time interval and a nearby lower measurement together with the aeration. Other time series of impact give differing features, e.g. some have a sudden rise to a peak followed by a steady decline in pressure, and others have oscillatory pressures, sometimes leading to sub-atmospheric pressures. Our aim is to understand these in detail: e.g

the main peak in Figure 2 shows a surprisingly smooth rise and fall in pressure which is nearly symmetrical about the time of the maximum, and is also preceded by a smaller initial peak.
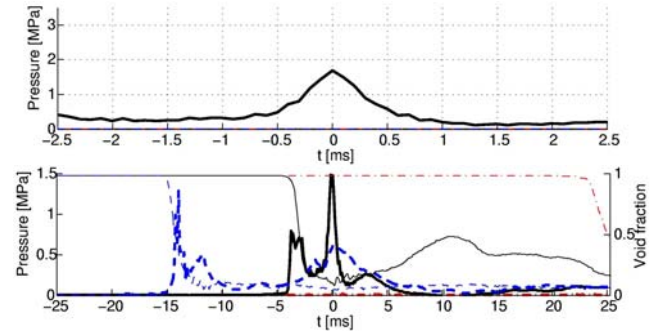

Figure 2. Pressure measurements from the GWK, on two differing time scales.

Inviscid incompressible flow modelling

Waves approaching the wall are approximated with irrotational flow for which a boundary-integral computation is used following *Tanaka et al.* (1987), *Cooker et al*. (1990) building on the method of *Dold and Peregrine* (1986), see *Dold* (1992): an example is shown in Figure 3. This computation stops when the wave hits the wall or the flow becomes too violent, or rough, or a jet becomes too slender.
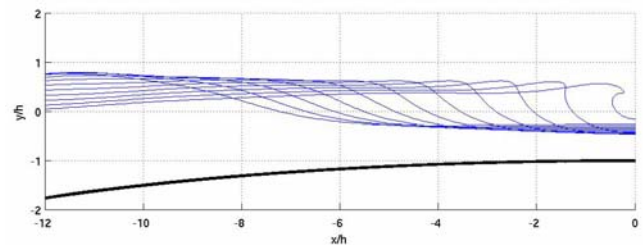

Figure 3. Example of a computed wave overturning as it approaches the wall.

Wave behaviour at the wall varies. The gentlest waves simply slosh up and down and are reflected. Overturning waves trap a pocket of air as they hit the wall. Broken waves arrive with strong turbulent motions. As far as these computations can go the most violent case is on the margin between sloshing and the trapping of an air pocket. In this case the wave surface, in its motion, seems to focus towards one point where it creates a violent upwards jet with strong pressures. This is described by *Cooker and Peregrine* (1990, 1992) as 'flip through'. This marginal case means that the pressures on a wall are remarkably sensitive to the incoming wave's shape, as is illustrated by the pressure

time series in Figure 4, which are for a small range of incident wave amplitudes.
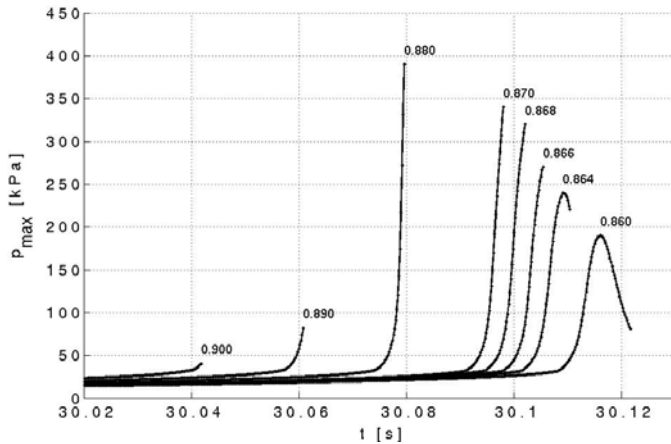

Figure 4. Maximum pressure at wall against time for numerical accumulations conditions in the GWK. The numbers on each curve give the height in metres of the offshore incident wave.

The limitations of the computational method mean that only two of the curves in Figure 4 extend as far as the maximum pressure, although estimates of maximum pressure can be made from the rate of increase of the pressure in the other cases. Our results indicate that just one per cent change in wave amplitude can give as much as 100% change in maximum pressure. It is also found that by changing the topography of the mound over which the waves approach the wall, a 1% change in shape, retaining the same mound volume, can give as much as a four fold change in maximum pressure. This strong sensitivity of the most violent impact pressures implies that such violent impact pressures occur in a very limited region of the parameter space. Further, this sensitivity to wave conditions makes it difficult to predict wave forces. In any practical case neither waves nor bed topography are known with sufficient precision. However, it is useful to note that the total impulse of a wave impact is not a sensitive quantity - in confirmation of basic principles.

Details of wave impact for deep water are similar as may be seen from the experiments of Chan & Melville (1988) with deep water waves hitting a vertical plate.

Aerated wave impacts and compressibility

The numerical implementation, for 2D unsteady flows with gravity, is formulated in conservative form using the finite volume approach. An exact Riemann solver has been developed and implemented in the

CLAWPACK framework (*LeVeque* 2002) for hyperbolic conservation laws. This numerical treatment allows for the development of discontinuous solutions such as shock waves. Results from an incompressible potential flow computation are used for both initial and boundary conditions. The model allows for a large range of surface configurations, since no explicit tracking of the free surface is needed. The air-water interface is treated implicitly, as mass moves between the computational cells. This has the disadvantages of numerical diffusion of the interface. Advection of an initially sharp interface, will typically produce a stable smeared interface, stretching over a number of grid cells. Exploratory computations have shown that reflection of pressure shock waves approaching the air-water interface from the wet side is little affected by this smearing, while the transmission of pressure shock waves propagating into the water from the air side are substantially affected, with creation of an oscillatory wave, due to the variation in sound speed over the smeared interface. So far, our wave-impact computations do not appear to be noticeably affected by this effect, but care is taken when examining the computational results.

The compressible flow computations are initialised from the incompressible computation before any large pressures occur and covers a region close to the wall, as shown in Figure 5. The flow is solved for the air-water mixture as well as for the surrounding air, thus including, for example, the escape of air prior to an air pocket closing, which is a significant aspect of the flow field. The initial phase of the compressible flow evolution shows no effects of compressibility since pressure variations are slight, compared with atmospheric pressure, and velocities are well below the velocity of sound. For this phase of the flow, we find good agreement in comparison with incompressible solution, giving a good test of the program. Once excess pressures become comparable with atmospheric pressure, compressibility is important.

Figure 5 shows several of the features we have found for such compressible impacts of waves which overturn or flip-through. This example corresponds to a large ocean wave, with an initial air fraction of 5% in the water and zero water in the air. The three upper panels, from left to right, show density, pressure and velocity magnitude with colour shading as indicated, at a time close to that of maximum pressure. The middle strip shows pressure as a function of time for four points on the wall. The black line is pressure at the base of the wall. The three coloured lines correspond to the three points marked in the upper panels by small semi-circles of the corresponding colour. The bottom panel shows

Figure 5. Results from a compressible flow computation. See text for details.

pressure on the wall as a function of time, using the same colour scheme as in the upper plot of pressure.

Features that occur include the following. An impact pressure occurring significantly before the main pressure peak, caused by the impact of the overturning jet. Pressure varies smoothly from air pocket to water. Pressure in the air pocket rises smoothly to a maximum, and then falls almost symmetrically thereafter, compare with Figure 2. Pressure of the air pocket falls below atmospheric pressure: this is hard to see on these particular plots. These plots have too short a duration to show the longer-period oscillations associated with pulsation of the air pocket. A pressure pulse propagates down to the base of the wall steepening to become a shock wave by the time it reaches the bed. The reflection of the shock wave off the bed gives rise to a remarkably high pressure at the base of the wall. Such pressures may have important

consequences for the stability of a caisson if they penetrate beneath the caisson, since in addition to maximum pressure at the bed, at roughly the same time as minimum pressure higher up the wall, leading to a strong turning moment towards the sea.

For those cases where we can compute through the time of maximum pressure with the incompressible boundary-integral program, we find that compressibility reduces the maximum pressure by amounts very similar to those found for 'filling' flows by *Peregrine and Thais* (1996): usually around 10 to 15%. This study is continuing.

Conclusions

Rogue waves are a topic of study and concern because of their potential to cause damage and

disruption. Here we present a brief account of studies that are bringing significant understanding of the detailed fluid dynamics associated with the most violent wave impacts that have been measured.

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