Compressibility of entrained and trapped air in violent water wave impacts

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Abstract Pressures in violent water wave impacts can greatly exceed atmospheric pressure, and the compressibility of air is then important. The results of computations including such compressibility are presented and discussed in the context of experimental measurements.

1. Introduction

The most violent wave impacts on structures usually occur when the wave is at or near breaking. In such cases air is often trapped between wave and structures, and the water usually contains many entrained air bubbles. Engineers have long been aware that the effects of compressibility differ for ordinary small scale experiments, typical dimensions tens of centimetres, when compared with prototype conditions with wave heights of a number of metres. For a review see Peregrine (2003). A project, "Breaking Wave Impact on COastal STructures" (BWIMCOST) has been conducted with the aim of improving understanding of scaling for violent water wave impacts. The project included

a) field measurements on Admiralty Breakwater, Alderney, Channel Islands, exposed to waves from the Atlantic Ocean. See Bullock et al. (2003) for preliminary results.
b) large scale laboratory experiments, modelling the Alderney site at the scale of 1:4, in the large wave flume (Grosse Wellen Kanal, or, GWK) at Hannover Germany. The experimental arrangement is described in Bullock et al. (2004) and a preliminary account of the experimental measurements is in Obrhai et al. (2004).
c) recently completed small scale, 1:25, laboratory experiments at Plymouth.
d) ongoing theoretical studies at Bristol which are partly described here.

There are two special features of the field and experimental studies. In addition to measurements of waves and of pressures on walls, measurements are made of the aeration, or air-water fraction. These measurements are valuable for interpreting the impact events. Further, as well as making pressure measurements on a single vertically-oriented series of sensors, measurements are made at another horizontal position, hence giving a clear indication whether or not the events are two-dimensional.

The theoretical input to the project aimed to supplement the measurements with numerical computations, to assist in their interpretation. The experimental results from waves in the GWK incident on the 1:4 scale model of Alderney's breakwater gave the most comprehensive data. Originally it had been intended to model the ocean waves as measured on the breakwater, but the violent impacts measured at the breakwater were too sparse.

2. Experimental measurements.

The GWK experiments used 240 metres of the channel, which is 5 metres wide. We concentrate on the results corresponding to some of the most violent impacts with a water depth of 4.25 metres with waves of 8 seconds period. For structures away from large seas and oceans such waves could correspond to prototype conditions, part of the motivation for the GWK's construction. However, there is one significant difference from marine conditions. The water in the GWK is not salt water. As first demonstrated by Scott (1975) the typical size of air bubbles in water is strongly affected by the salinity. Salt water has much smaller bubbles than fresh water, thus the aeration persists longer for salt water and affects the wave impacts. The effect on wave impacts was demonstrated with quantitative laboratory experiments reported in Bullock et al. (2001).

The waves were incident on a concrete wall, which was mounted in front of a concrete caisson on top of a mound constructed from stones. Experiments with a vertical wall are considered here. The mound extended for 20 metres in front of the wall with its summit 3 metres above the bed of the flume. More detail is given in the papers referred to above.

Measurements of pressure were made on the wall with two different sets of sensors placed on two vertical lines 1 metre apart. One set, of four sensors, was accompanied by aeration sensors that measure impedance between two electrodes. These aeration measurements are reported as the volume fraction of air in the water assuming a uniform distribution of bubbles. However, a sufficiently thin sheet of water on or near the electrodes could give the same effect, so that care is needed in interpreting these measurements.

3. Computation of impacting waves.

The waves' approach to the wall is modelled by assuming inviscid, incompressible, irrotational two-dimensional flow. The free surface is parameterised by following fluid particles, so that it is free to overturn. The atmospheric pressure is taken to be constant and no surface tension effects are included. The program used is an extension of Dold & Peregrine's (1986) boundary integral program on a spatially periodic domain, for a full description see Dold (1992). The extension to a domain bounded by uniform flow conditions is described in Tanaka et al. (1987). Cooker et al. (1992) describes the further extension, via conformal mapping, for on obstacle on the bed. The mound in front of the breakwater is modelled to have the shape of a quarter of an ellipse, of the same height and volume as the experimental mound, and only a metre or so shorter. The ellipse has the advantage of simple specification.

The incident waves are specified as a short wave group with three significant crests, initiated, from a third-order representation well offshore from the mound. In the examples discussed, the still water depth is 4.25m in the body of the flume and 1.25 m on top of the mound. The initial wave amplitude is varied. As in the experiments, it is hard to define an appropriate wave height for the incident wave near the wall due to interaction with the reflection of the previous wave, even in the cases we consider where the earlier wave has not been steep enough to break. Thus when a wave height is quoted the initial maximum wave height is implied. The computation is divided into three parts so that, as the wave gets closer to the wall, a shorter length of surface can be used with increased resolution. Eventually the shortest distance between the discretisation points is less than a millimetre, with time steps of less than 0.1 ms.

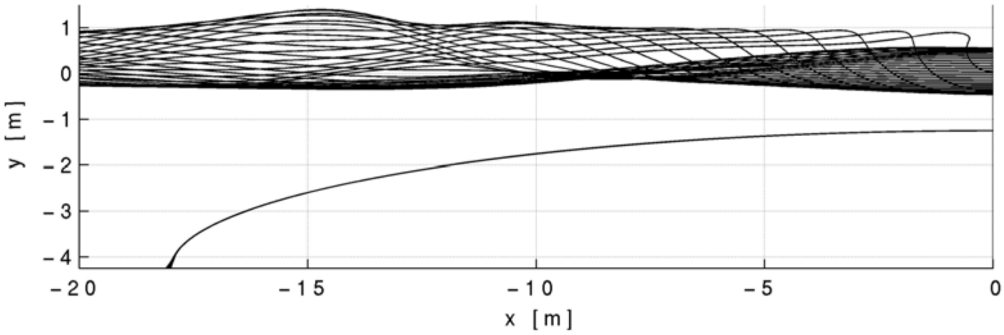

Figure 1 A set of profiles at time intervals of 0.5 sec for initial wave height 1.45m. No vertical exaggeration.

A sequence of wave profiles for waves approaching the wall is given in figure 1 for the case of wave height 1.45m. As may be seen a simple crest to trough measure of wave height over the mound would give varying results, even though in this case the reflected wave is relatively small. Another feature, that is clearly visible, is an acceleration of the front face of the wave as it

[redacted]

approaches the wall. As may be expected from the final surface profile in the figure, this wave traps an air pocket at the wall

At a time corresponding to profiles such as the last one in figure 4 the region within one metre or more, of the wall is modelled using the compressible flow Euler equations of motion. These are modified by including a variable representing the air fraction which is convected with the fluid, so there is no account of any motion of entrained air relative to the water. The equation of state is calculated on the basis that the air is an ideal gas and the water is incompressible, see Peregrine & Thais (1996). The air above the water is included in the computations at normal atmospheric pressure and density.

A finite-volume numerical scheme is used within the Clawpack package (Leveque, 2002). Initial conditions for the water are taken from the boundary integral calculation and a spatial distribution of air fraction is assigned. In the cases considered here, a uniform distribution of 5% entrained air is used. In the early stages of the compressible computation the effect of air motion is slight, so computation is started from an earlier time such that clear transients in the air flow are over, then this air flow is used for the initial condition. Boundary conditions for the water are taken from the continued irrotational flow computation for as long as is possible, with 'informed' estimates used thereafter. 'Open' boundary conditions are used for air boundaries, and impermeable boundary conditions for the wall and bed. Tests on the code showed that although generally effective, and able to follow shock waves, some spurious waves can be generated when shocks meet a diffused interface from a low density region. This does not seem to give any particular problems for this topic.

A sample output is illustrated in figure 2. The upper three panels represent density pressure and velocity at the chosen time. The traces below represent the pressure at three points on the wall. The lower panel show pressure on the wall in a space time distribution. 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. Other computations show how the peak pressure is more concentrated at larger scales as the air becomes relatively more compressed.

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, there may be minimum pressure higher up the wall at roughly the same, 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 & Thais (1996): usually around 10% to 15%. This study is continuing.

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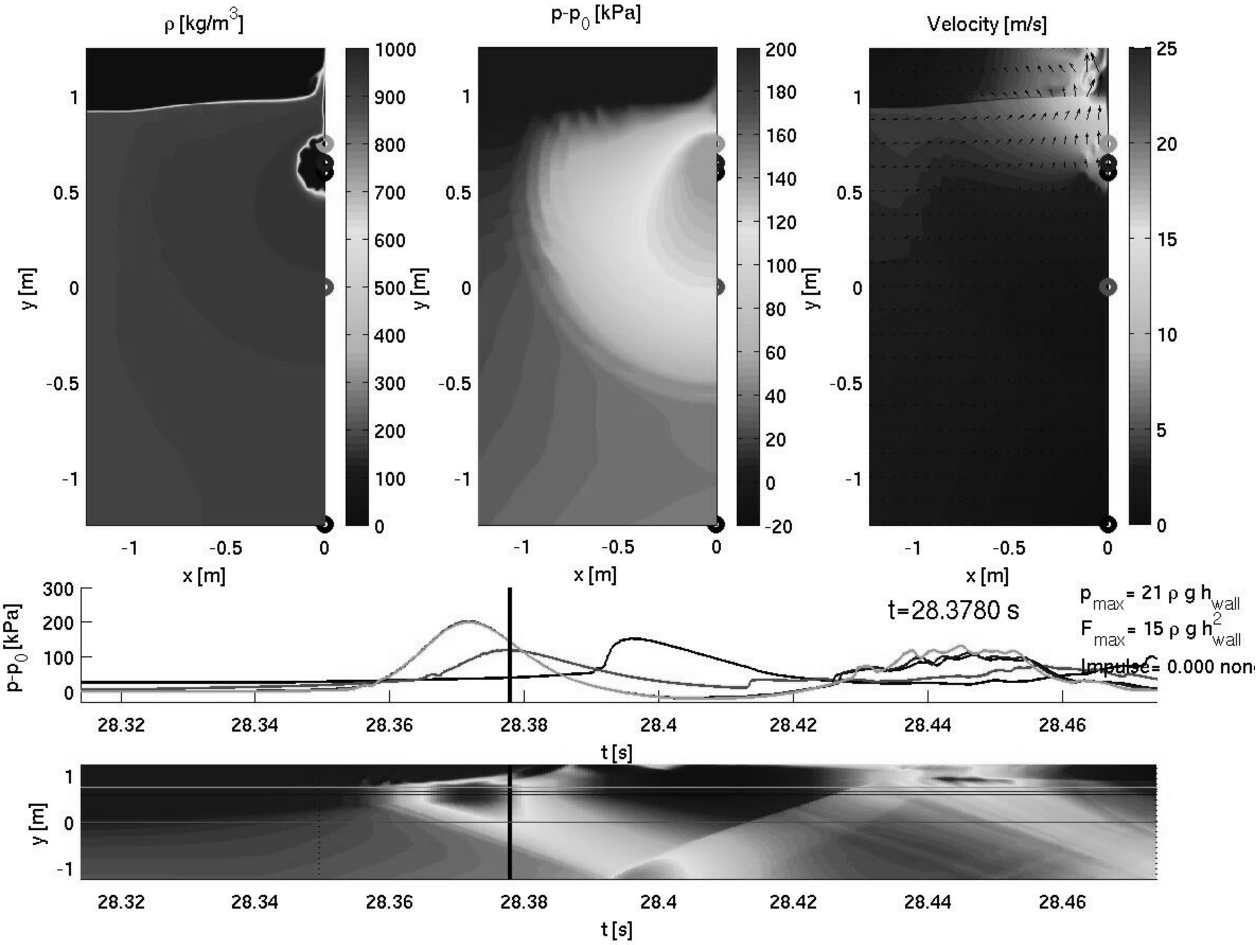

Figure 2. Sample output of wave impact from an incident wave of height 1.51m. [run 90D]

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