Extreme wave impact pressures and the effect of aeration

Henrik Bredmose[1], Howell Peregrine[1], Geoffrey Bullock[2], Charlotte Obhrai[2], Gerald Müller[3], Guido Wolters[3]

[1] School of Mathematics, University of Bristol, UK, h.bredmose@bris.ac.uk, d.h.peregrine@bris.ac.uk
[2] Civil & Structural Engineering, University of Plymouth, UK, g.bullock@plymouth.ac.uk, c.obhrai@plymouth.ac.uk
[3] Civil Engineering, Queen's University, Belfast, UK, g.muller@qub.ac.uk, g.wolters@qub.ac.uk

1 Introduction

Violent pressures from wave impacts can cause severe damage on breakwaters, ships and off-shore structures. While pure still water is incompressible with good approximation, impacting water is often compressible due to air bubbles from wave breaking and entrapment of air. The salinity of sea water and the associated reduction in bubble size leads to longer rise times for bubbles in sea water and thus to increased compressibility effects. This makes the scaling from fresh water laboratory impact tests to sea water and prototype scale non-trivial. Indeed the mechanics of compressible wave impacts is not yet fully understood.

This has motivated a coordinated research effort in the BWIMCOST project (Breaking Wave IMpacts on COastal STructures), where impacts of aerated water on breakwaters are being investigated, see Bullock et al. (2003). The project includes field measurements at the Admiralty Breakwater on Alderney, Channel Islands, a comprehensive programme of laboratory tests at scale 1:4 in Grosser Wellen Kanal (GWK), Hanover, and small scale experiments (1:25) at the University of Plymouth. Additionally to the experiments and data analysis, numerical modelling of the impacts is undertaken to enhance our understanding of the impact mechanisms.

The experimental programme in the GWK finished in summer 2003 and the data analysis is now in progress. In this abstract characteristics of our measurements are shown and results of our numerical modelling of compressible flow presented.

2 Laboratory measurements

The GWK experiments were conducted for a range of water depths around 4 m shoaling to around 1 m at the wall and with incident waves up to 1.7 m height. Two sets of different pressure sensors were used. Each set was arranged in a vertical line, the lines being 0.94m apart, with some sensors placed at the same horizontal level. One of the sets (denoted PAU sensors) were of the same type used at Alderney which also include conductivity sensors allowing for estimation of the void fraction (Bird et al., 1998). Data was sampled at 10kHz.

Figure 1 gives an example of pressure time series for an impact with a maximum pressure of 3.4 MPa from a wave of 1.35 m height. This pressure is at least 3 times as large as any field measurement on the breakwater on Alderney. These extreme pressures occured over a range of wave and depth parameters. As a multiple of the pressure due to a head of water this is nearly 300 times the incident wave height, a ratio above that of any previous measurement, in the field or in the laboratory. The next closest is a pressure of 150 times the wave height (of 10mm) in Hattori et al. (1994).

An important feature of these high pressures is that they are both brief and localised. Some examples last less than 1ms and if the sensors were to be sampled at 1 kHz, some events would have been totally missed. Such severe pressures are usually recorded at one sensor only. Thus there are strong indications that the extreme pressure only acts over a very short time, O(1ms), and a small area, perhaps about 0.2 m×part of flume width.

Although the impact pressure of an event like the above is severe, its pressure impulse, i.e. integral of pressure with respect to time over the event, is no worse than a more typical impact of, say, 300 kPa acting over 20 ms. The pressure impulse is usually a better measure of the effect of impact. However, it is clear from the strong shaking that we felt as observers, from the motion of the structure, the wave flume, and the building, that the effect of the wave impact was more significant. Our most recent wave tests therefore incorporated measurements of horizontal acceleration on the structure to quantify this.

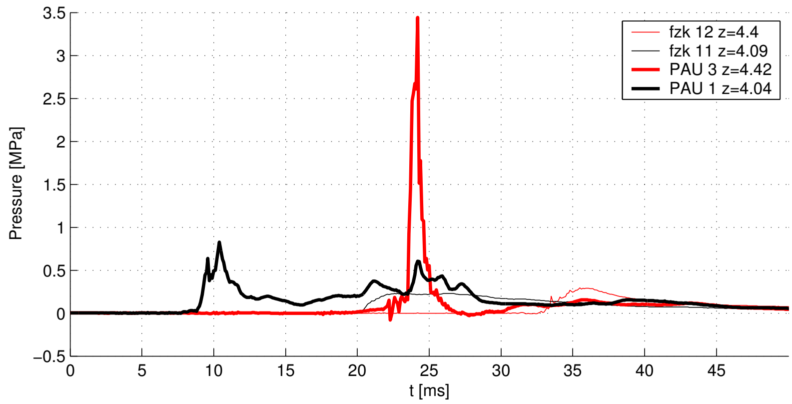

Figure 1: Pressure record for violent wave impact from the GWK experiments.

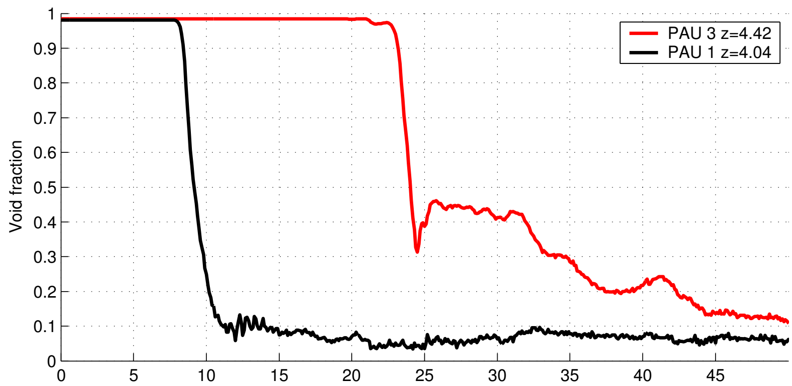

Figure 2: Void fraction estimated from measured conductivity for the same impact as in figure 1.

The large impact pressures measured are way beyond any hydrostatic pressure associated with the incoming wave. For incompressible, potential flow, Cooker & Peregrine (1990, 1992) have demonstrated that the so-called 'flip-through' effect can generate large impact pressures through 'focusing' of the free surface towards a point close to the breakwater wall. M. Cooker (private communication) have given examples which in this context correspond to more than 0.5 MPa.

Aeration and turbulence in the water occur from the breaking of previous waves and tend to be non-uniform. They both introduce three-dimensionality. Although aeration has generally been thought to soften the impact pressures, it also introduces strong gradients of sound velocity, and it seems possible that these could focus pressure waves from wave impact, as is seen with shock waves in a gas incident on 'low velocity' bubbles (e.g. Zabusky & Zeng, 1998).

For the impact shown in figure 1, the corresponding void ratios, estimated from the PAU measurements, are shown in figure 2. The highest sensor (the one measuring the largest impact pressure) shows a rather high aeration level at and after impact — estimated to be about 0.45. This corresponds to a very low sound velocity. Further, a compression of the air-water mixture is seen at the time of maximum impact pressure. An important aspect here, however, is that the water is continuously moving past the sensor due to the motion of the flow. This often complicates the interpretation of measurements, since changes in void ratio can then be due to simple advection as well as changes in pressure.

3 Modelling the compressible flow

We model the compressible flow of an air-water mixture using the model of Peregrine & Thais (1996). Conservation of mass and momentum is

$$\rho_t + (\rho u_i)_{x_i} = 0 \tag{1}$$
$$(\rho u_j)_t + (\rho u_j u_i)_{x_i} + p_{x_j} = 0 \tag{2}$$

where ρ is the density of the mixture, u_j is the velocity and p is pressure. Denoting the volume fraction of gas by β, and the microscopic density of the gas phase by $\hat{\rho}$, the overall density of gas is $\beta\hat{\rho}$, and conservation of gas mass is then

$$(\beta\hat{\rho})_t + (\beta\hat{\rho}u_i)_{x_i} = 0. \tag{3}$$

To close the system a relation between the densities and pressure is needed. Again following Peregrine & Thais (1996) we assume the liquid phase incompressible and the air phase to behave like an ideal gas under adiabatic compression. This gives for the pressure

$$p = p_0 \left(\frac{\beta\hat{\rho}\rho_\ell/\rho_0}{\rho_\ell - \rho + \beta\hat{\rho}} \right)^\gamma \tag{4}$$

where ρ_0 is the gas density at the reference pressure p_0, ρ_ℓ is the density of the liquid and $\gamma = 1.4$ is the exponent of adiabatic compression.

The above equations are written in conservation form, suitable for a treatment using the finite volume method. Eventually, we aim at modelling the wave impacts as a 2D flow with a free surface, allowing for entrained air and entrapment of air pockets at the breakwater wall. At present, however, a 1D version of the equations has been implemented using the finite volume method. The implementation builds on the software package CLAWPACK (`www.amath.washington.edu/~claw`, see also LeVeque (2002)) providing a framework for solving hyperbolic conservation laws. The solution scheme is based on solving a sequence of Riemann problems between neighbouring cells in each time step. Information on the emerging waves are then used to update the cell averages.

The compressible flow model can be used to study the behaviour of shock waves from impacts against a rigid wall. Consider the situation in figure 3, where a uniform flow with constant velocity u_B is hitting a rigid wall. Due to the impermeability of the wall, the mixture in front of it has zero velocity, and a shock wave is moving away from the wall with speed s. Conservation of mass, momentum and gas mass over the shock leads to three shock conditions

$$s(\rho_B - \rho_A) - (\rho u)_B = 0 \tag{5}$$
$$s(\rho u)_B - \left[\rho_B u_B^2 + p_B - p_A\right] = 0 \tag{6}$$
$$s((\beta\hat{\rho})_B - (\beta\hat{\rho})_A) - u_B(\beta\hat{\rho})_B = 0 \tag{7}$$

which follow from the conservation laws (1)–(3). Additionally, the equation of state (4) is valid in state A and B. Now given p_A, p_B and β_B plus the parameters p_0, ρ_0, ρ_ℓ and γ, the unknown variables can be solved for. Inspired from the measurements of figures 1–2, we pick an example of a wall pressure of 3 MPa and a voids fraction of $\beta = 0.4$ in state B. The shock is found to move with a speed of 73 m/s, with $u_B = 42$ m/s. The

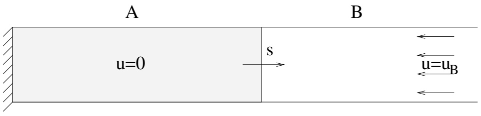

Figure 3: Sketch for uniform impact at a rigid wall.

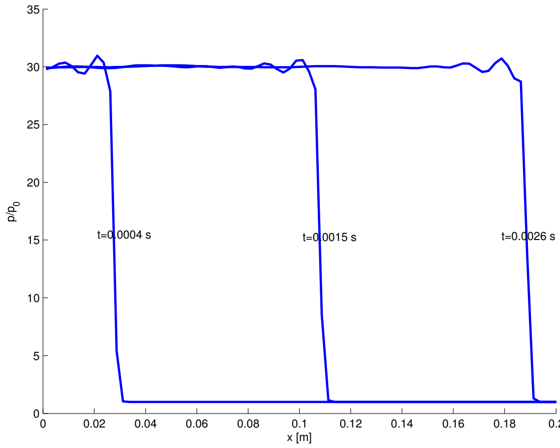

Figure 4: Pressure profiles in space for $t = 4, 15, 26$ ms after impact.

voids fraction in state A is around 0.06. Results from modelling the above flow with the 1D implementation of the unsteady equations are shown in figure 4. Pressure profiles in space are plotted at 4, 15 and 26 ms after impact, the rigid wall being placed at $x = 0$. The model is initiated with data corresponding to state B of the above calculation. A shock is certainly developed, separating two states of constant pressure. The pressure in state A is 3 MPa, agreeing closely with the above calculation. All other quantities of state A and the shock speed s are reproduced with close agreement as well.

The compressive reduction of β for such an impact does not fit with the results of figure 2. The above computation, however, gives a good idea of the space and time scales for impacts at such large pressures. We are currently investigating further unsteady flows and will shortly be implementing a 2D version of the compressible flow model. We expect to present results from this model at the workshop. Such results will provide useful guidance for the interpretation of our measurements of extreme impact pressures.

Acknowledgements The investigation was supported by the UK's Engineering and Physical Sciences Research Council and the EU's Transnational Access to Major Research Infrastructure activity. The tests in GWK were carried out in collaboration with J. Grüne of the FZK, Hannover, Germany. Inspiring discussions with professor Randall LeVeque, University of Washington are also acknowledged.

References

Bird, P. A. D., Crawford, A. R., Hewson, P. J. & Bullock, G. N. (1998), 'An instrument for field measurement of wave impact pressures and seawater aeration', *Coastal Engng.* **35**, 103–122.

Bullock, G., Obhrai, C., Müller, G., Wolters, G., Peregrine, D. H. & Bredmose, H. (2003), Field and laboratory measurements of wave impacts, *in* 'Proceedings of the 3rd Coastal Structures conference', ASCE.

Cooker, M. J. & Peregrine, D. H. (1990), Computation of violent wave motion due to waves breaking against a wall, *in* 'Proceedings of the 22nd Int. Conf. Coastal Engng.', Vol. 1, ASCE, pp. 164–167.

Cooker, M. J. & Peregrine, D. H. (1992), 'Wave impact pressure and its effect upon bodies lying on the sea bed', *Coastal Engng.* **18**(3–4), 205–229.

Hattori, M., Arami, A. & Yui, T. (1994), 'Wave impact pressure on vertical walls under breaking waves of various types', *Coastal Engng* **22**(1-2), 79–114.

LeVeque, R. J. (2002), *Finite Volume Methods for Hyperbolic Problems*, Cambridge University Press.

Peregrine, D. H. & Thais, L. (1996), 'The effect of entrained air in violent water wave impacts', *J. Fluid Mech.* **325**, 377–397.

Zabusky, N. J. & Zeng, S. M. (1998), 'Shock cavity implosion morphologies and vortical projectile generation in axisymmetric shock-spherical fast/slow bubble interactions', *J. Fluid Mech.* **362**, 327–346.