Impact of breaking waves over emerged and submerged coastal structures

Stéphan T. Grilli [1], and M.A. Losada[2] and F. Martin [2]

Introduction

Recent advances in the modeling of fully nonlinear water waves (e.g., Vinje & Brevig 1981, Dold & Peregrine 1986 (DP), Grilli *et al.* 1989 (GSS)), have made it possible to address increasingly complex problems of breaking wave interaction with ocean structures of arbitrary shape. Predictions of wave impact pressure on coastal structures have recently been obtained, mostly based : (i) either on solving two-dimensional (2D) fully nonlinear potential flow equations by a Boundary Integral Equation method (BIE) (e.g., Cooker and Peregrine 1991 (CP), Grilli *et al.* 1992 (GLM)); (ii) or on solving 2D Euler equations by a Volume Of Fluid method (VOF) (e.g., Wang and Su 1992, Van der Meer *et al.* 1992). In general, the first approach has proved more efficient and accurate, but it cannot model post-breaking behavior, or be extended to include fluid viscosity. The second approach seems somewhat less accurate, but it is more general and more efficient in dealing with wave breaking and fluid discontinuities (e.g., air, jets,...).

In parallel to this modeling effort, more and more accurate field and experimental measurements have been obtained, for the peak impact pressures on structures. For coastal structures, wave pressure on seawalls and mixed breakwaters has particularly been measured in the three following cases (e.g., GLM, Schmidt *et al.* 1992) : (i) non-breaking waves; (ii) waves with flat impact on the wall (i.e., with an almost vertical front face); (iii) waves with falling breaking jets, and imprisoned air under the wave (e.g., plunging breaker). Models based on satisfying continuity equation in the fluid, like the BIE method used in GLM, can deal with cases (i) and (ii), in which very little or no air entrainment occurs, but they cannot deal with case (iii) without modification, further than the time the breaking jet impinges on the wall.

Kirkgöz 1991 (KIR), in his review of the experimental work to date, shows that the average maximum pressure on vertical walls, p_{max}, varies between 20 and 75 times $p_H H/d$ (where $p_H = \rho g d$, with ρ the water density, g the acceleration of gravity, H the incident wave height, and d the local depth), and that the highest maximum pressure can reach up to 220 times this value. A somewhat unexpected result obtained by GLM in case (ii), for both numerical and laboratory experiments, is, when peak pressures occur on a vertical wall, large impact pressures also occur on the bottom, up to twice the local depth from the wall. When significant air is imprisoned at the impact (case (iii)), experiments show, large high frequency pressure oscillations occur at the wall, after the impact (Hattori & Arami 1992 (HA)). A simple air cushion model has been developed by HA for studying these cases, and an idealized mathematical analysis has been proposed by Topliss *et al.* 1992, based on the same experiments..

Present studies

In the present studies, laboratory experiments are performed to measure wave kinematics above (surface elevation, internal velocity), and impact pressure on the vertical wall of, a mixed breakwa-

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[1] Dept. of Ocean Engng., University of Rhode Island, Kingston, RI 02881, USA, Ph.Nb.: (401) 792-6636

[2] Dept. de Ciencias y Tecnicas del Agua, University of Cantabria, Santander 39005, Spain

ter, for case (ii) defined above (Fig. 1). Experiments were conducted in the 70x2x2m wave flume of the University of Cantabria. Details of experimental procedures can be found in GLM. Large solitary waves have been mostly used as incident waves, both for simplicity, and because they are believed to have the largest impulse, impact force and runup on structures. Incident cnoidal waves have also been used for comparison.

Experimental results are compared with computational results obtained using the 2D fully nonlinear potential model by GSS. Largest impact pressures on the wall are obtained for incident waves with large height to depth ratios. This was achieved, e.g., in earlier computations by CP, by introducing very high but quite arbitrary long waves into their model, and assuming a symmetry at the wall. The present numerical model works and is used for arbitrary geometry and incident wave conditions. Hence, this enables us to closely reproduce the experimental set-up in the numerical model (Fig. 1), while dealing with a more realistic coastal structure. Laplace's equation is solved in the model in the physical space, using a higher-order Boundary Element Method (BEM). Time integration is based on a second-order Taylor expansion similar to that introduced by DP, expressed in a mixed Eulerian-Lagrangian representation. New integration methods have been implemented in GSS's model, to improve the accuracy of integrations for cases with a very narrow geometry leading to quasi-singular integrals (like in the up-rushing jet along the wall, after wave impact). The accuracy of computations is checked by verifying that wave mass above SWL, and total energy are conserved within 0.01-0.05%.

Results and discussion

Experimental and numerical results are presented in Fig. 1,2 and 3, for a solitary wave with incident height $H/h = 0.322$. Fig. 1 shows, the agreement between both of these is quite good for the wave elevation, up to the step ($x = 0$). Downstream of the step ($x > 0$), the agreement is less good, and the model overpredicts maximum surface elevation by 5-15%. This is due to energy loss by flow separation at the step, not included in the model. Fig. 2a shows a blow-up of computed free surface elevations near the wall, up to maximum impact pressure on the vertical wall. One sees, a small jet forms close to the wall in the last surface profile. Maximum water velocity and acceleration in the jet reach about $20\sqrt{gd}$ and $9800g$ (with $d = h - h_1$), respectively, at this stage. These large values are similar to those obtained by CP, and provide a physical justification for the occurrence of large impact pressure on the wall (Fig. 2b). The internal velocity field (not reported here) shows, the wave flow strongly converges towards the upper part of the wall, while its horizontal momentum gradually transforms into vertical acceleration. This acceleration, in turn, is balanced by a large pressure gradient close to the wall (as can be obtained from Euler equations).

Pressure along the wall reaches a peak almost simultaneously for all elevations. Hence, the envelope of maximum pressure on the wall, given in Fig. 2b, also corresponds to maximum impact force on the wall. This was also observed by KIR. Maximum measured peak pressure is $12p_H$ at $z = 0.37$ above SWL, and decreases both for larger and smaller values of z, but stays quite constant under SWL, down to the bottom. All peak pressures are followed by small high frequency oscillations. Structural vibrations of the vertical wall model have been eliminated by using a stiff thick plate, and stiffeners. Thus, high frequency oscillations can be a sign, a small quantity of air is imprisoned between the wave and the wall during the impact. This can also be seen in Fig. 3, that shows the total force on the wall as a function of dimensionless time ($F_H = \frac{1}{2} p_H d$). Agreement between experiments and computations is quite good in Fig. 3, up to maximum impact. Peak pressures, however, are overestimated in the model (Fig. 2b). Apart from a slightly smaller incident wave in the experiments, due to dissipation at the berm, this is likely to be due to irregularities in the experimental incident wave, and to the wall roughness, that may limit the jet formation and the build up of pressure gradient and acceleration.

Pressure on the berm bottom also exhibits a peak of decreasing magnitude when x decreases, i.e., when moving away from the wall (not reported here). Although it had been suggested earlier that peak pressures might be large on the bottom, it is, to our knowledge, the first time, comprehensive measurements of wave impact pressure on the berm of a breakwater have been made. The large impact pressures on the bottom, as far away as $2.4d$, require that they be considered when analyzing the berm stability, particularly for porous berms with large permeability (coarse granular media).

Present experimental and numerical results are bringing new light into the creation of large impact pressures on coastal structures. Effects of changes in the incident wave (height, type), and in the geometry of the structure (berm), not reported here, will be presented during the workshop.

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Figures

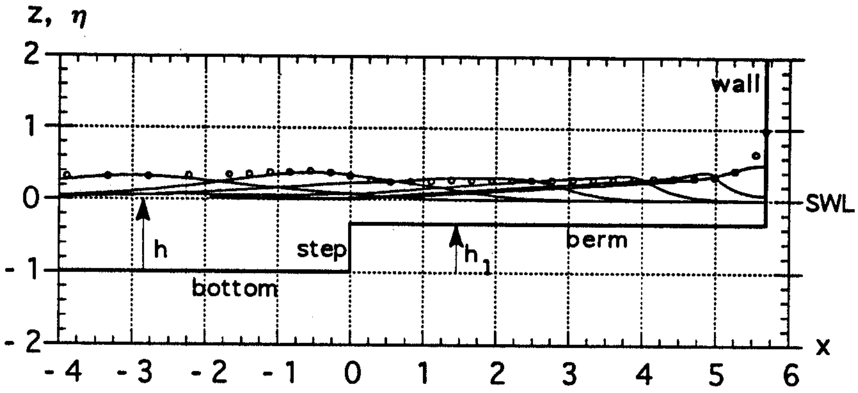

Figure 1: Sketch of a mixed breakwater, and main geometrical parameters, for $H/h = 0.32$ and $h_1/h = 0.67$: (—–) Comp. surface elevation up to maximum impact. (○) Meas. surface envelope.

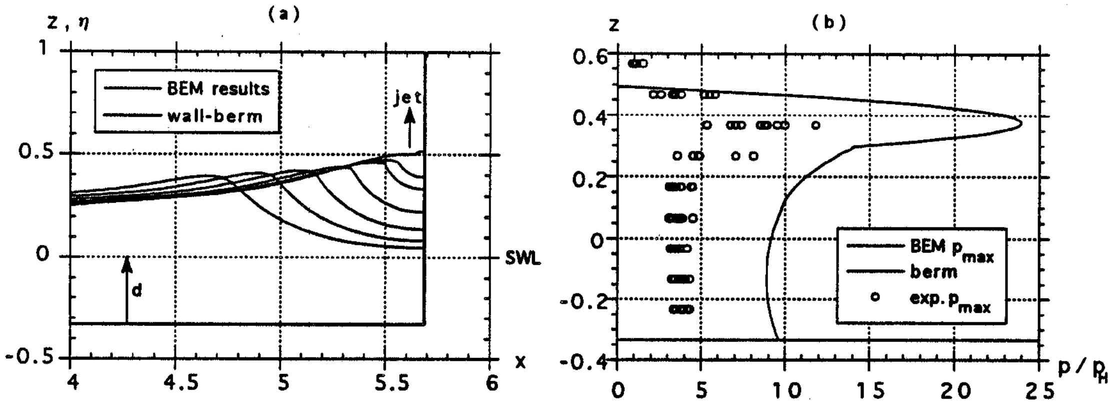

Figure 2: (a) Blow-up of surface elevations as in Fig. 1. (b) Maximum pressure on the wall.

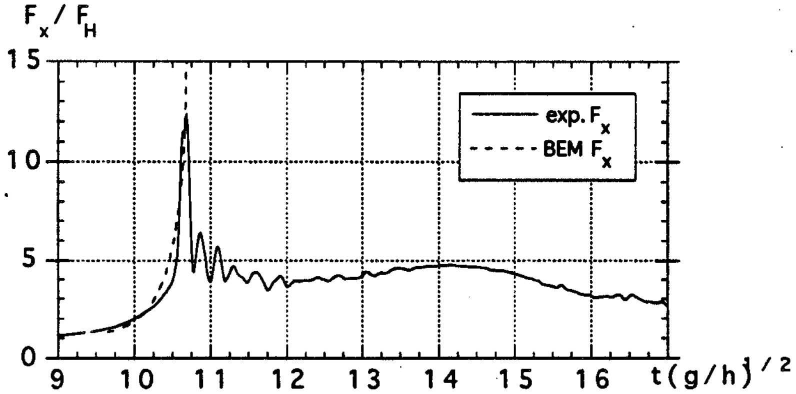

Figure 3: Horizontal impact force F_x on the wall, as a function of time t