An Investigation of Water on Deck Phenomena

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Shipping of water on deck represents a danger both for moored (as FPSO) and for advancing ships. When a compact mass of water ('green water') is shipped onto the deck, the fluid moves with high speed, being able to damage superstructures and equipments and to be a risk for human lives. Also, the shipped water can significantly alter the dynamics of smaller vessels. Such events make the green water loads an important parameter to take into account even at design stage and call for predictive tools. However, knowledge about the physics involved is still limited and motivates increasing research effort.

At present, we are not able to deal with the problem as a whole and, moreover, the physical and numerical complexity can easily obscure the underlying fundamental aspects. Therefore we deviced a set of basic prototype phenomena and, although in reality they are strongly coupled, we analyzed them separately. In this framework, the main stages to be considered are wave–body interaction, shipping of water, flow onto the deck, impact of water with superstructures.

Though the problem is three–dimensional, we learned from the water entry problem that physical insight can be gained through a two–dimensional analysis and provide a guidance on how to approximate numerically the more complex three–dimensional one. We assume in addition inviscid fluid, which is known to be a proper approximation, but we fully retain nonlinearities due to the motion of the free surface and solid body. A potential flow model results and a mixed Eulerian-Lagrangian approach is adopted to solve the unsteady interaction between the body and the free surface. Briefly, the fluid velocity $\boldsymbol{u}$ is evaluated in terms of the potential $\varphi(\boldsymbol{P}, t)$, which in turn satisfies the Laplace equation with mixed Dirichlet-Neumann boundary conditions. This kinetic problem is solved by a direct boundary integral formulation. The numerical solution is achieved by a collocation method with piecewise linear shape functions and collocation points at the edges of each element. At the contact point body–free surface, a weak regularity of the solution is assumed by enforcing the continuity of the potential. Though no rigorous justification is available, this procedure guarantees convergence of the numerical results under grid refinement (cfr. [4]). However when the angle between the free surface and the body surface is very small numerical problems may always occur. The time dependence enters through the evolution of boundary data, ruled by kinematic conditions on free and moving boundaries, and a dynamic condition for the free surface. A Lagrangian description is adopted and the problem is stepped forward in time by using a Runge-Kutta fourth order algorithm.

The first step to predict the deck wetness at the bow region (the most severe in head sea conditions) is an adequate estimate of the wave elevation near the bow. Here, due to nonlinear interactions, wave forms are strongly deformed relative to the incident waves. As a very preliminary study, we have considered the run–up of solitary waves on plane walls with different slopes. In particular, figure 1 shows the numerical maximum run–up, defined as the maximum vertical distance R between the still–water level and the intersection between wall and free surface, in the case of a vertical wall. Results are compared with experiments [3] and analytical values [1]. For (initial) wave height-to-depth ratio H/h sufficiently small all the results are in a reasonable agreement, while for larger amplitudes only the numerical results follow the experiments.

When the wave elevation exceeds the freeboard, the water can flow over the deck. According to experimental observations [2], the considered flow field resembles the one after a dam breaking. Therefore we have assumed the latter suitable to check our model of the evolution of the water on deck. Figure 2 gives numerical and analytical [6] pressure distributions on the 'deck' just after the dam breaking. The initial height of the water is h and $\tau = \mathrm{t}\sqrt{\mathrm{g/h}}$ is the non-dimensional time. As we can observe, the two solutions fit well and show a sudden departure of the pressure from the initial hydrostatic value. Free surface profiles as time increases are examined in figure 3. In this case we compared the numerical solution with experiments from [5], with satisfactory agreement during the whole considered time interval. Though in the initial stages dispersive wave effects matter, for large times the evolution can be adequately described by the shallow water solution, also presented in figure.

While flowing over the deck, the fluid can violently impact against obstacles and cause damage of superstructures. In general, the flow field will depend on the motion of the deck but the characteristics of the original incoming waves are expected to be weak because of the small time and space scales involved. On this ground, it is reasonable to focus only on the impact problem and we adopted the dam breaking flow as initial condition. The initial stage of the phenomenon is shown in figure 4, where a vertical obstacle is placed 3.366h far from a dam which initially limits a region of water with height h and length 2h (see top plot in figure 5). The flow field is not modified except in a small region close to the structure, where the flow behaves like a half–wedge of fluid hitting the wall. Further gravity effects are modest since the vertical acceleration of the contact point is $\mathcal{O}(5\mathrm{g})$

for small times after initial impact. Both these aspects are confirmed by the satisfactory comparison with a gravity-less similarity solution from [7]. At the latest time considered the numerical contact point moves with a higher vertical velocity than the analytical one (see right plot). However, as in the two previous instants, the numerical mass flux related to the jet flow is in quite good agreement with the analytical one. Qualitatively, just after the impact the water deviates by 90° and evolves in the form of a tiny jet. At this stage, spray formation is expected which can not be handled by the present method. Anyway we believe that this detail is not relevant for structural loads. To avoid numerical problems associated with the intersection between the free surface and the wall, the jet was partly cut.

Later evolution is presented in figure 5 where, due to the gravity, the vertical velocity of the water decreases, eventually becomes negative and the free surface overturns. In the same figure, for $h = 0.6\,m$, the two bottom plots show the time history of the water level h_W at the two locations $(x/h)_A = 3.721$ and $(x/h)_B = 4.542$. Good agreement between numerical results and experiments [8] is observed until the breaking occurs. Because of the lack of a detailed description of the experiments in [8], we have shifted the time axis of the experimental curves so that numerical and experimental h_W become different than zero at the same instant. When using the predicted pressure distribution on the wall, this has to be analyzed from a structural point of view and possible hydroelastic effects have to be considered.

Clearly, 'water on deck' arises by the coupling of all the problems mentioned above. As a last item, we focus on a simple problem in which incoming waves in deep water can interact with straight walls with different slopes and possibly wetting the deck. The vertical extension of the obstacle is large with respect to the wavelength λ. Different values of the height-to-wavelength ratio (H/λ) have been considered. When the water reaches the freeboard (f) of the wall it is forced to leave it tangentially upwards. In figure 6, the case of a vertical wall and an incident wave with $H/\lambda = 0.06$ is shown. Horizontal and vertical scales are nondimensionalized in terms of the maximum exceedance (h) of the freeboard by the free surface. At first, the water near the wall gets mainly a vertical velocity and the exceedance of the freeboard increases quicker than the horizontal displacement of the water. Later on, horizontal velocity of the fluid already on the deck increases while the vertical velocity of the water approaching the structure reduces because of gravity. This causes two wave flows. One is a reflected system and the other propagates along the deck. The latter phenomenon is qualitatively like the flow caused by dam breaking. This is also confirmed by a reasonable agreement of the numerical free surface profiles with the corresponding experimental data [5] for the dam breaking. The final sequence 7 analyzes the water on deck for a wall at 45° with $f/H = 0.36$ and $f/H = 0.55$, respectively. Still incoming waves with $H/\lambda = 0.06$ are considered. For the larger value of f/H just a little amount of the water wets the deck. The maximum exceedance of the freeboard is smaller than in the other case and the gravity matters before the water on the deck reaches a sufficient horizontal velocity. In this case most of the water returns back leaving the deck.

In the latest figures both the stem overhang and the freeboard are involved, however many other parameters enter the problem as well as three–dimensional effects making it much more complicated. As an example, if the body moves when water reaches the freeboard, the relative vertical velocities involved can be large enough to cause a jet flow leaving the bow without occurrence of water on deck. The analysis presented gives a certain confidence about future possibilities to attack more realistic conditions.

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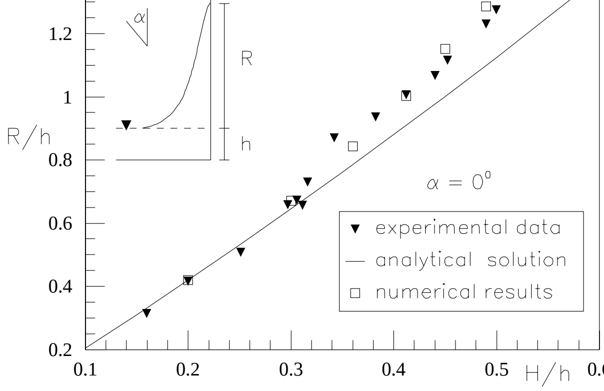

Figure 1: Maximum run–up R on a vertical wall of a solitary wave with amplitude H.

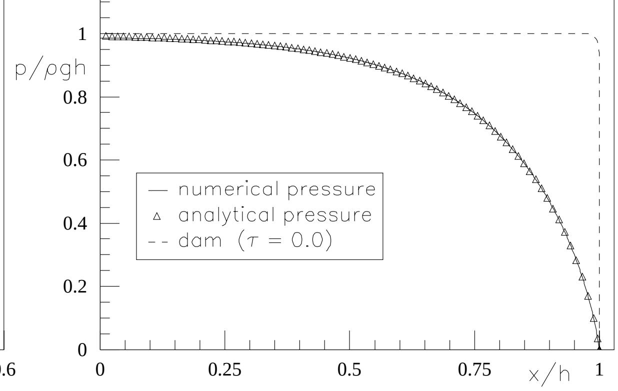

Figure 2: Comparison of analytical [6] and numerical pressure distributions at the beginning of dam breaking.

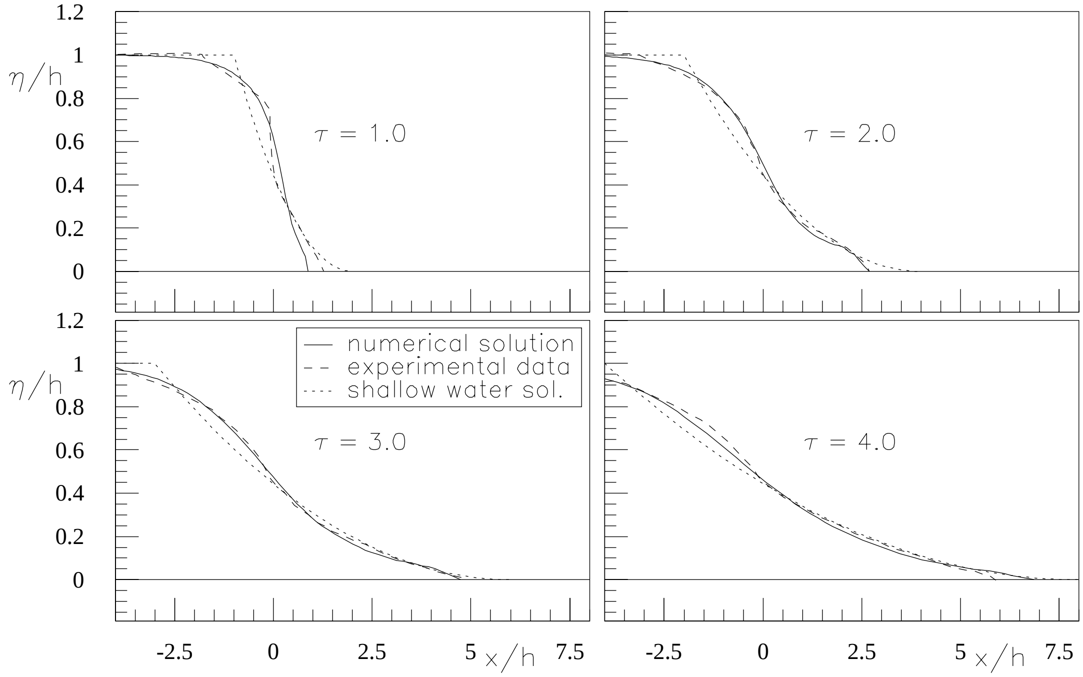

Figure 3: Free surface profiles after the dam breaking. Experimental data [5] and fully nonlinear and shallow water solutions ($\tau = \mathrm{t}\sqrt{\frac{\mathrm{g}}{\mathrm{h}}}$).

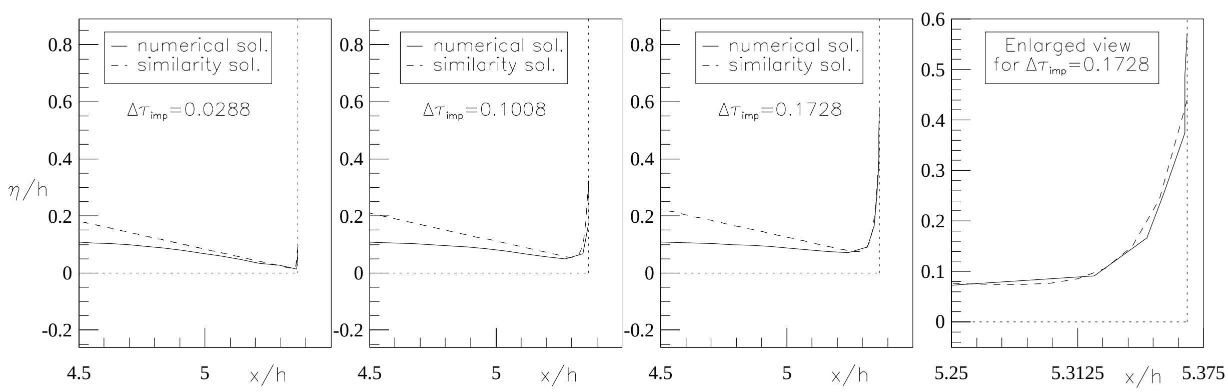

Figure 4: Initial stages of the impact problem after the dam breaking. Numerical results are compared with similarity solution of [7]. $\Delta\tau_{\mathrm{imp}}$ is the dimensionless temporal distance from the impact. In the right plot the horizontal scale is magnified by a factor 4.18 with respect to the vertical one.

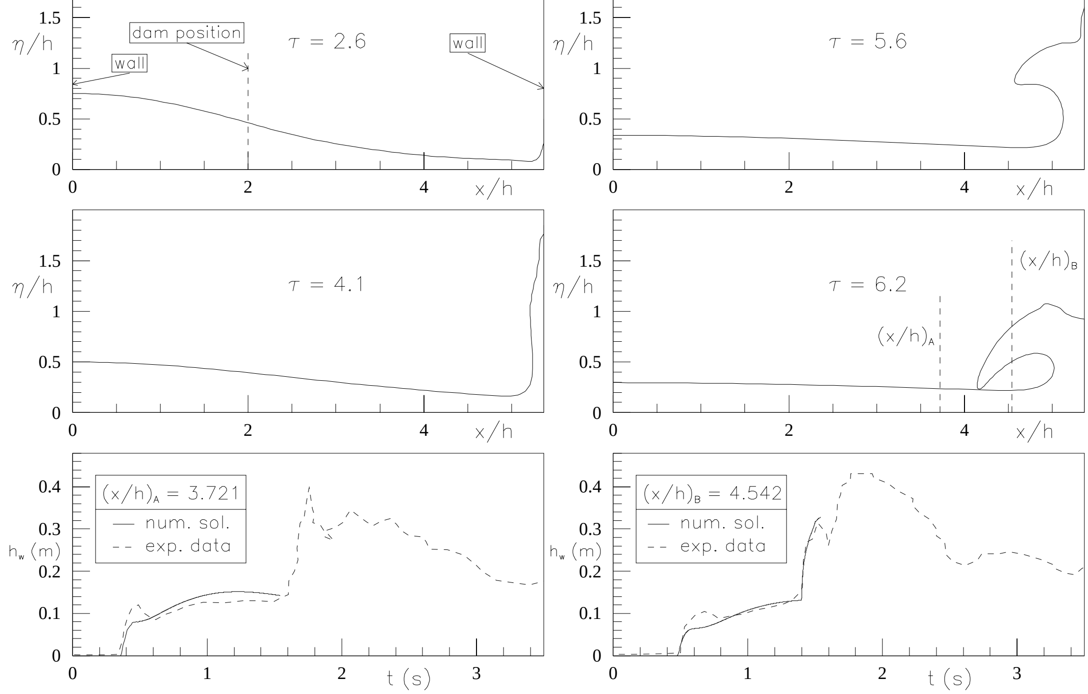

Figure 5: Simulation of dam breaking and impact with a vertical structure (top and central plots). Experimental [8] and numerical level of water at $(x/h)_A = 3.721$ and $(x/h)_B = 4.542$ as a function of time (bottom plots).

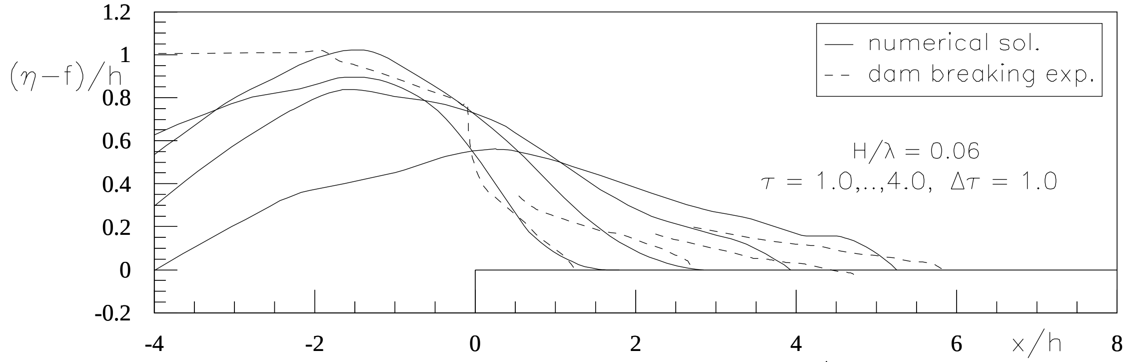

Figure 6: Simulation of water on deck due to incoming waves with $H/\lambda = 0.06$ for a 'deep' vertical wall. f is the 'freeboard' and $h = (\eta - f)_{max}$. Numerical free surface profiles are compared with experimental data [5] for the dam breaking.

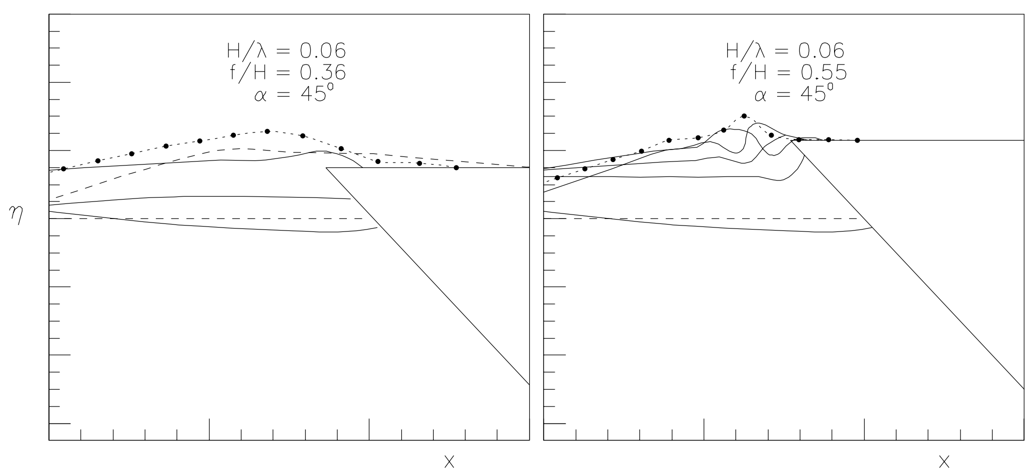

Figure 7: Simulation of water on deck due to incoming waves with $H/\lambda = 0.06$ for a 'deep' wall at 45° with f/H= 0.36 (left plot) and f/H= 0.55 (right plot).