Numerical Simulation of the Impact of a Plunging Breaker on a Vertical Structure and Subsequent Overtopping Event Using a Navier-Stokes VOF model

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ABSTRACT
We study processes that occur during impact of a breaking wave on a vertical wall, and the resulting overtopping event, based on numerical simulations using a multiple-fluid Navier-Stokes VOF model (air-water). The latter allows to track high interface deformations during the breaking and impact. Both impact process and overtopping event are studied as a function of the relative distance of the vertical wall from the breaking point (defined as the location where a vertical tangent appears on the free surface). We study hydrodynamic forces and pressure peaks on the vertical wall, with the temporal and spatial discretizations. Expectedly, a finer discretization leads to a better description of the pressure peak on the wall, which can increase the total force applied to the wall by up to a factor 6. Similarly, we study, overtopping rates as a function of the distance of the breaking point in front of the wall. Some studies indicated that the critical case, yielding maximum volumetric rate, is for a wall placed at the breaking point. In the application studied here, the maximum overtopped volume of water occurs for a distance to breaking equal to 1.69 times the breaking wave height.

KEY WORDS: breaking waves, impact, maximum forces, peak pressure, overtopping.

INTRODUCTION
Improving the design of coastal defenses requires in-depth understanding of wave impact and overtopping phenomena. Various time scales are involved in these phenomena, which must be considered in work aimed at achieving such understanding. Many studies, more related to engineering applications, have focused on the larger time scales, by considering the cumulative effects of many waves, for instance on the total overtopping volume. However, individual wave and smaller time scales, must be considered in order to better understand the detailed flow that occurs during individual impact events. In this respect, the experiments of Schmidt et al. (1992) illustrated the effect of breaking point location has on the impact intensity on a vertical wall. Specifically, these identified four impact regimes, depending on the distance between the breaking point and the wall. Kirkgoz (1995) proposed a similar classification but identified three cases according to wave shape at the impact duration. In early numerical simulations, Grilli et al. (1992,1993) and Zhang et al. (1995) studied the impact of a two-dimensional plunging breaker on a vertical wall using a Boundary Element Method (BEM). The former study showed the possible occurrence of very large impact pressures (and related vertical accelerations and total force). Zhang et al's work showed that the maximum impact pressures can be scaled by the local breaker parameters at impact. Although there were many other studies in the interim, based on inviscid flow theory, it is not our purpose here.
to give an exhaustive review of the literature, and we just mention in closing the recent work by Duan et al. (2009), who studied the impact with a BEM of a plunging breaking wave on a vertical wall, by simulating an oblique collision of an asymmetric solid wedge. Pressure distribution near the wave tip were computed for many cases. BEM methods, however, cannot deal with post-breaking flows and cases of highly turbulent impacts. Models with more complete physics, such as based on the solution of Navier-Stokes (NS) equations, are required.

In this paper, we use Abadie et al’s (1998) et al and Lubin et al.’s (2006) NS-VOF model to investigate the impact force and overtopping flow generated by a large plunging breakers on a vertical wall. The effects of the distance between the breaking point and the wall, on the impact flow, are analyzed through numerical simulations. The paper is organized in five parts. We first briefly present the numerical model. The second part presents numerical experiments. Wave breaking stage is validated in the section 3 by comparing interfaces profiles computed by NS-VOF and BEM models during the breaking stage. The fourth and fives parts are devoted to the detailed analysis of wave impact forces and overtopping flows. Specifically, in the fourth section, we analyse breaking wave impacts obtained with two different meshes, and compare numerical results to experiments. Section four brings into light differences induced by different meshes on the numerical simulation of the impact proper. Pressure time history and forces induced by impact are reported and analyzed in order to validate simulation of the impact process and determine the grid resolution required to model such impact process. Section five identifies the consequences of impact on fluids kinematics. Overtopping flow rates are reported and compared in different cases. Critical situations are highlighted and discussed in the final part.

THE MODEL

In our breaking wave simulations, we consider incompressible, non miscible two-phase flows of water and air, described by two-dimensional NS equations. As in Lubin et al. (2006), turbulence is resolved using a Large Eddy Simulation (LES) approach, with a Mixed Scale subgrid model. The interface between water and air is tracked using the Volume Of Fluid (VOF) method of Hirt and Nichols (1981). The water volume fraction evolution is calculated by solving a pure advection equation, assuming that the interface is moving at the fluid velocity.

The resulting linear algebraic system of equations, obtained for each time step, is solved using the direct solver MUMPS (Multifrontal Massively Parallel sparse direct Solver (Amestoy et al., 2000)). At the end of each time step, the average water volume fraction in each cell is used to recalculate local values of density and viscosity used in NS equations. For cells containing a fraction of water and air, equivalent density and viscosity are calculated by linearly interpolation based on the water fraction $F$.

DESCRIPTION OF NUMERICAL EXPERIMENTS

The physical problem considered is sketched in Fig.1. All computations have been done in a square domain, 10 meter high and 10 meter long, with an initial constant depth of 1.3 meter. As we concentrate here on modeling the impact processes, we simply initialize computations with a first-order Stokes wave of non-physical height, which rapidly evolves to breaking, as a large scale plunging breaker, close to the wall. Parameter $d$ represents the distance of the wall to the breaking point, which is made to vary by adjusting the position of the wall, given a breaking wave. The breaking point is defined as the location where the inflection point of the free surface profile has a vertical tangent. All computations have been performed using the same wave characteristics, detailed latter. Two different model grids (coarse and finer) were tested, in order to assess the required mesh size to correctly model impact and interface deformations. Mesh sizes are identical in horizontal and vertical directions. The coarser mesh has spatial steps of 0.05 m while the finer mesh has steps of 0.0125 m. The total corresponding number of nodes in the discretization are 40,401 and 641,601 respectively. Time step is computed by specifying a mesh Courant number less than 0.3.

Computations of impact have been done in two stages. A first-order Stokes wave is generated and propagates in the domain, assuming periodic boundary conditions at the left and right domain sides.

Figure 1: Sketch of physical problem

The NS-VOF equations are discretized on a fixed Cartesian grid, using

![Figure 2: NS-VOF simulations of breaking wave impact on a vertical wall](image-url)

An open boundary condition is imposed at the domain top to allow air
to escape without influencing water flows. At the bottom, a free-slip condition is imposed. The initial wave period is $T_o = 3.024$ s and the wave height is specified equal to the still water level: $a_o = SWL = 1.3$ m. Parameters $l_o$ and $H_o$ represents respectively the wavelength ($l_o = 10m$) and the wave height at the breaking point. The large value of wave steepness ($\epsilon = 0.13$) leads the computed wave to rapidly become unstable and develop a large plunging breaker jet. Those characteristics correspond to the case studied by Vinje et al.(1981) using a BEM. A comparison of free surface profiles and kinematics, between NS-VOF and BEM model results, is provided in Section 3.

After the breaking point is reached, computed waves characteristics and shapes are recorded and used to directly initialize impact computations on a vertical wall. Impact computations are performed in a domain of similar dimensions. Boundary conditions on the left and right sides are changed from periodic to symmetrical. The vertical wall is placed on the right side (Fig. 1). It is designed as a crown wall, followed by a reservoir in which overtopping water will collect. This will allow assessing overtopping rates occurring during the impact process. In successive numerical experiments, the wall distance ahead of the breaking point is varied from $d = 0$ to $3$ m, with a constant space step $\Delta d = 0.25$ m. In the following we refer to non-dimensional distance $d^* = d/H_o$ ($d^* = 0$ to $2.536$ with $d^* = 0.21$). In addition, all non-dimensional parameters are noted with the exponent *. The wall height is $H_w = 2.5$ m for all computations, which proved low enough to yield significant overtopping events.

In the multiple-fluid numerical model, the structure to the right is simulated as a porous media with infinite porosity, using a penalty method. This imposes a velocity equal to zero on the obstacle (no flow), and forces fluids particles to abruptly change direction (essentially from horizontal to vertical) when collision occurs. Fig. 2 shows the effect of such a porous media on both velocity magnitude in water and interface (black line). Such change in velocity direction are quantified by measuring the flow rates across vertical and horizontal lines. In Fig. 1, $D_3$ is horizontal level placed at height $H_{water}$, while $D_1$ is a vertical line localized at the wall absissa. In all cases, flow rates $q_1$ and $q_2$ are calculated during the impact process for further analysis.

Figure 3: Plunging breakers simulated in NS-VOF and BEM models. 
(a) $t = 0.17T_o$ (b) $t = 0.37T_o$ (c) $t = 0.38T_o$ (d) $t = 0.46T_o$
300 kPa, for 1.5 meter high tested waves. The Fig. 4, reproduced from Schmidt et al. (1992), shows the time evolution of the applied horizontal force on a vertical wall during the impact process, in two time scales. The first one at larger time scale (little frame at the right) shows one pronounced peak force, reaching about 200 kN/m, then a second moderate increase in force, with a longer duration and a local maximum of about 50 kN/m. This second maximum value in the force is reported to be reached at the run-up time, that is to say, when the water interface reaches its maximum height on the wall during impact. The main frame in Fig. 4, at finer time scale, allows to see that in fact the first peak consists in two separate peaks, of which the first is smaller than the second one. Experimental measurements identified the expected impact force duration, defined here as the duration between those two successives force peaks, at about 20 ms. Moreover, falling time assessed from the second peak is about 30 ms. Those peaks are followed by relatively lower frequency oscillations which are reported to be caused by expansions and compression of the air pocket entrapped between the plunging breaker and the wall, under the highly transient pressure field. Since our numerical model does not take compressibility into account, this phenomena will not be discussed here.

In the following, we model the impact process for the same incident breaking wave (discussed before), for 13 different $d^*$ values ranging from 0 to 2.53 (which is equivalent to $d$ ranging from 0 to 3 m) with a constant step $\Delta d^* = 0.21$ ($\Delta d = 0.25$ m). For clarity, only cases $d^* = 0$, 0.422, 0.845, 1.268, 1.690, 2.113, and 2.536 are discussed in the following.

Figure 5 shows the time evolution of the simulated horizontal impact force applied to the wall (Fig.1), using a coarse grid, for various cases of $d^*$ parameter. In these simulations, horizontal and vertical non-dimensional space steps are $\Delta x / H_o = \Delta x / H_o = 0.0422$ ($\Delta x = 0.05$ m). The total node number is 40,401. The total force applied on the vertical wall is calculated by integrating the fluid pressure on the obstacle. Non-dimensional results are shown, based on a characteristic force : $F_0 = P_o H_o = \rho_o c^2 H_o$ with $\rho_o = 1000$ kg/m$^3$, $c_o$ and $P_o$, representing respectively the characteristic pressure, and the mean particles velocity calculated on the vertical line locates at the breaking point. The latter has been assessed to $c_o = 3.30$ m/s, also equal to the linear wave celerity given by $c_o / T_o$ (with $T_o$ the wave period). Time values have been made non-dimensional by using $t_o = h_o / c_o = 0.35$ s. During computations, time steps range around $10^{-3}$ s. As the impact duration is expected to be about $10^1$ to $10^2$ s (Zhang et al., 1996), we also expect this parameter low enough to correctly describe the impact processes.

Globally, forces histories in Fig.5 have identical behaviors, that is, a rapidly increasing force until a maximum value, and then a more gradual decrease and stabilization around a constant value ($\approx 1.5$). Critical cases are identified for $d^* = 1.268$ ($d = 1.5$ m), for which the maximum values reach 3.75, that is almost 50 kN/m. The width of the force peak seems to decrease, the larger $d^*$, until the critical case is attained, and then to become wider until the last value of $d^*$.

Figure 6 details the force time history for the particular case of $d^* = 1.268$. In this figure, axes are dimensional values of forces and time, in order to facilitate the comparison with Schmidt and al.'s (1992) results. Comparing numerical results in Fig. 6 with experimental measurements in Fig. 4, we see that the maximum computed force in the coarse grid is significantly smaller, with 200 kN/m ($=15.47$ in our non-dimensional conventions) for Schmidt and al. (1992) experimental results versus 50 kN/m for NS-VOF simulations ($= 3.7$ in our non-dimensional conventions). In addition, falling time is assessed to 0.5 s, which is much low than in Schmidt and al.'s study (30 ms). However, it should be stressed that experimental results are subject to wide scatter, as pointed out, e.g., by Kirkgoz (1982) where experimental impact loads varied drastically for apparently identical wave impacts. In fact, the high sensitivity of impact forces on a vertical wall to small variation in incident wave in both experiments and simulations, has already been identified in many works (e.g., Grilli et al., 1993). Further to this, in Zhang et al.'s (1996) experimental results, initial wave amplitudes were higher than ours and maximum forces only reached about 30 kN/m, in experimental conditions closer to ours.

As the total force applied to the wall is obtained by spatially integrating the pressure distribution, if the latter is underestimated then dynamic pressure applied to the wall must be too small on the wall. Hence, in order to better validate our simulations of impact processes, we have to study the sensitivity of maximum pressure on the wall to numerical and other parameters and establish sufficient result convergence.

Figure 4: Force history - Schmidt et al. (1992)

![Figure 4: Force history - Schmidt et al. (1992)](image4)

Figure 6: Time evolution of impact force in NS-VOF simulations - Coarser mesh grid

![Figure 6: Time evolution of impact force in NS-VOF simulations - Coarser mesh grid](image6)
Figure 6: Force history - Case $d^* = 1.27$ - Coarse mesh grid (same as curve in Fig. 5 using dimensional parameters)

Figure 7 shows the time evolution of the maximum pressure reached on the wall during the impact process, for various values of parameter $d^*$, similar to Fig.5. We see these pressure variations are qualitatively similar to those in Fig.5, with the difference that critical maximum pressure is reached for the case $d^* = 1.69$. Maximum impact pressure is $3.66$ (40 kPa), which is of the same order of magnitude as measured in Zhang et al. (1996) ($P_{max} = 58.8$ kPa, $P^{*}_{max} = 5.38$), but far less than results of Schmidt et al. (1992) ($P_{max} = 300$ kPa, $P^{*}_{max} = 27.45$). It is noted that impact pressures have faster variations in time the larger $d^*$, except for $d^* = 2.536$ ($d = 3m$). However, observed rising times range from 70 ms ($d^* = 0$) to 170 ms ($d^* = 1.69$), which is much more than in Zhang et al.’s (1996) results ($t_{max} = 3$ ms). Thus, the simulated evolution of impact pressure seems not fast enough in the case of the coarse grid.

To improve on this, we model the impact process in a finer numerical grid, in order to better track the pressure peak. The second finer mesh used here contains 15 times more grid points than the coarse one. Non-dimensional space steps are divided by a factor of 4 ($dx/H_0 = 0.0105$), and the CFL condition constrains the time step to be around $\approx 10^4$ s. The total node number is then 16 times more important. Figure 8 shows the force time history for the same range of $d^*$ parameters, in the case of a fine mesh. Note, as compared to Fig. 5, that the initial instants of impact are not the same, because the initializations of computations have not been made at the same instant. Thus, impact times are slightly delayed as compared to previous figures. However, since important characteristics are the impact duration and the maximum forces involved during the impact process, this delay does not influence the following analyses.

In Fig. 8, we observe different force evolutions, as compared to the previous coarser grid case. Maximum forces values range from 3.79 for $d^* = 0$ to 20.9 for $d^* = 1.69$, that is $F_{max} = 273$ kN/m. Note that this value is almost 6 times larger than the maximum value found in the coarse grid. Time variations of forces near the peak are wider than for the first tested cases ($d^* = 0, 0.422$ and $0.843$) but rapidly become narrower, the higher $d^*$.

Figure 8: Force history for cases similar to Fig. 5- Fine mesh grid computations

Hence, falling times (defined as the duration between the initial stage of impact and the instant when the first peak is reached) are larger for smaller values of $d^*$. The impact force rate of increase prior to the peak is also larger in Fig. 8, as compared to the previous case. Rising times involved are smaller than those computed in the coarse grid case. In these finer grid simulations, maximum forces agree better with Schmidt et al.’s (1992) or Plumertall’s (2009) experimental results, as they both found that the total force for a periodic wave impacting a vertical wall could reach more than 100 kN/m, for similar wave characteristics. Note also that the case $d^* = 1.268$, which corresponded to the critical force for the coarse mesh, no longer yields maximum impact force values but rather it now occurs for $d^* = 1.69$. 

Figure 7: Maximum pressure history - Coarse mesh grid (same cases as in Fig. 5)
OVERTOPPING FLOW RATE

We now investigate overtopping rates, which are direct consequences of the impact process. Overtopping event have been investigated experimentally and numerically, but with very limited success. Experimental difficulties to obtain significant values are often due to large parameters involved in such a process (wave shape, wall roughness, porosity, geometric wall shape, wall position, wind magnitudes, salted rate in water, presence of air entrapped, entrained ...), or to difficulties in establishing permanent regime during green water events. Such a problem is also hard to tackle with numerical models, as this involves complex simulations of fast moving, multiphase, and highly turbulent flows after a collision with a vertical wall. Few experimental studies successfully measured velocity of breaking waves impinging on structures.

Among those, several applied the dam break theory to green water modeling, as mentioned in Buchner (1995a,b), even though the similarity between dam break and green water has not been quantitatively verified. Ryu et al. (2007) performed an experimental study, based on a PIV method, to measure the kinematics of plunging breaking waves impinging on and overtopping a model structure with a deck. Breaking waves were generated in front of a model, using a frequency focusing method, and conditions were fixed to be as close as possible to maximum waves that can occur during severe storm events. For such conditions, wave period, wavelength, wave height near the structure, phase speed of the breaking wave, and water depth were respectively 1.29 s, 2.54 m, 0.17 m, 1.95 m/s, and 0.80 m at model scale. The tested structure contained no tank, in order to analyze velocity profiles on the deck. In such conditions, wave heights were more important than wall height (equal to 91 cm), which was almost 3 times H_b (defined in section 2, H_b = 2.5 m). Based on Froude scaling, the equivalent full scale wave had a height of 28 meters. Thus, the represented impact corresponds to a far more critical case of impact and resulting over topping event than in our configuration. However, Ryu et al.’s study provided interesting result regarding velocity profiles near the structure and flow behavior after impact. For instance, before the wave impinged on the structure, the maximum water velocity near the structure reached 1.5 times the wave celerity. After impact, the flow tended to follow the boundary of the obstacle, with dominant vertical velocities reaching 2.9 times the wave celerity. In the following, we compare our velocity magnitudes with those values.

Fig. 12 shows three snapshots of free surface elevation and velocity magnitude at the time of maximum upward jet motion, for d*= 0, 0.845, and 1.69. In the first case, at t*= 2.71 the air pocket is negligible, as the wave just begins to break when it impacts the wall.
Velocity is maximum at the tip of the jet. The computed value is about 3.3 times the breaking wave celerity. The second case is for \( \text{d}^* = 0.84 \) at \( t^* = 3.23 \). Here, we see a more developed air pocket. This instant corresponds to the generation of the upward ejected jet. Maximum velocity reaches about 3.77 times the wave celerity. In the third snapshot, for \( d^* = 1.69 \), at \( t^* = 3.84 \), the wave breaking is well advanced and the impact occurs at the apex of the breaking jet. In this case, there is a large size air pocket captured, since the reconnection between the breaking jet and the free surface has occurred. Maximum velocity reaches about 6.75 times the wave celerity at the top contact point between jet and wall. Note that this value is larger than in Ryu et al./s (2007) experiments, and than the order of magnitude of the two previous cases. Since the wave is lower than the wall, and the numerical wall cannot absorb any mechanical force, a large part of the kinetic energy of the fluid can be devoted to the generation of an upward jet. This justifies why upward velocities in this case should be important, leading to larger values of overtopping flow rates.

Volumetric flow rates across \( D_1 \) and \( D_2 \) have been calculated from impact computations on a coarse mesh grid, and reported on Figs. 13 and 14. Flow rates have been made non-dimensional by \( Q_0 = (g H_0)^{3/4} \), representing the characteristic rate across a vertical line whose elevation is \( H_0 \).

Figure 12 shows time series of volumetric flow rates across the horizontal line \( D_1 \), for different values of parameter \( d^* \). Flow rate evolutions have globally similar behaviors. Flow rate values increase until a maximum value is reached, then decrease until they reach negative values. These correspond to the beginning of the jet down-rush. In all cases, flow rate variations are rapid near the maxima. Then, flow rates oscillate around zero. We also observe a second local minimum of flow rate, which corresponds to the reflected wave off the wall. This second local minimum occurs in all cases but it is the most pronounced for \( d^* = 0 \), for which the nearly non-breaking wave mostly reflects off the wall. Maximum values of horizontal flow rates increase with \( d^* \) except for the last case \( d^* = 2.53 \) (\( d = 3 \) m), for which the maximum value is similar to the case \( d^* = 0 \). The critical case (for which flow rate is maximum) is for \( d^* = 2.11 \) (\( d = 2.5 \) m). In this configuration, maximum flow rate is about 0.25, that is \( \sim 1 \text{ m}^3/(\text{m.s}) \).

The total volume corresponding to the vertical and horizontal flow rates was calculated by integrating the flow rate in time until the time it becomes negative. The fact that flow rate increases up to \( d^* = 1.69 \) (\( d = 2 \) m) is in good agreement with analyses based on velocity magnitudes presented above.

The same experiment was performed on the vertical line \( D_2 \) placed between the top of the tank and the top of the domain (Fig. 1). Results of flow rates across \( D_2 \) are represented in the Fig. 14, as a function of \( d^* \), to assess the final amount of water in the tank. Flow rates have similar overall behaviors, that is, an increasing flow rate until a maximum is reached, followed by a decrease to zero. Negatives values correspond to the presence of negative horizontal velocities, of particle sinking along the wall when the downward phase is over. These however are negligible for all cases tested, compared to flow values computed during the whole overtopping event. Flow rate evolutions become slower with increasing \( d^* \). Actually, flow rates across \( D_2 \) are seen to vary as rapidly as overtopping flow rates (see previous

![Figure 12: Velocity magnitude at the time of maximum upward jet velocity.](image1)

![Figure 13: Volumetric flow rate across \( D_1 \) (Fig. 1)](image2)

![Figure 14: Volumetric flow rate across \( D_2 \) (Fig. 1)](image3)
A second local maximum value appears for the case $d^* = 1.69$. The case $d^*=1.268$ has various maximum values and a more specific behaviour. This is due to the presence of a secondary jet at the moment of impact which ejects water particles behind the wall.

However, we did not take this case into account before validate it on a finer mesh grid. The overall maximum value is obtained for the first case $d^* = 0$, with a flow rate of about 0.11 that is 0.43 m³/(m.s). The accumulated volumes for flow rates across $D_1$ and $D_2$ are given in Figure 15 as a function of the distance $d^*$ of the vertical wall to the breaking point. Values of volume have been made non-dimensional using $V_0 = (H_0)^3$. The figure shows that the total volume accumulated across $D_1$ ($Y_1$) has a maximum. This maximum ($Y^* = 0.11$) appears for the critical point, for which $d^* = 1.69$ (d=2m). Maximal volume is reached for this value as well, and two local minimum values occur for extreme values of $d^*$.

CONCLUSIONS - DISCUSSION

A NS-VOF model was used to investigate the impact force on a vertical wall, and the related overtopping rate, generated by a large plunging breaker. First, the wave breaking stage was validated by modeling the time evolution of a first-order breaking Stokes wave and comparing interface profiles with earlier BEM model results. A coupling approach, between a BEM solution and the NS-VOF model is in progress, to refine interface tracking during the breaking stage, until the time of impact, and it is expected that initial results will be presented at the conference.

The impact processes modelisation has been considerably improved by refining mesh grids. The comparison between numerical results and existing laboratory experiments and other studies present in literature have been used as references in numerical solutions. We showed that computations using a fine resolution mesh have good accuracy to describe the time history of the impact forces on the wall as described in Schmidt et al. (1992) and Zhang et al. (1996), particularly around its short duration peak. Using two different meshes grid showed that multiplying the total number of grid cells by a factor of 15 leads to a better description of the pressure peak on the wall, and to a total force applied on the wall larger by a factor of 6. Convergence of maximum pressure and force applied on the wall is still to be proved.

Overtopping events generated after the impact were studied. The magnitude of flow velocities was computed and compared with Ryu et al.’s (2007) experiments. The larger overtopping rates and flow velocities occur for a particular distance of the wall to breaking, which in the present case corresponds to $d^* = 1.69$ (d=2m). The influence of the parameter $d^*$ on overtopping flow rates was specifically studied. Velocity magnitudes near the wall reached extreme values for $d^*=1.69$. The resulting flow rates were maximum for the same case.

REFERENCES


