Effect of Venting Holes to Relieve Wave Impact Pressures on Flood Gates with Overhangs

Hofland, Bas; Passos, Marlon; de Almeida Sousa, Ermano

DOI
10.18451/978-3-939230-64-9_020

Publication date
2019

Document Version
Final published version

Published in
Coastal Structures 2019

Conference Paper, Published Version

Hofland, Bas; Passos, Marlon; de Almeida, Ermano

Effect of Venting Holes to Relieve Wave Impact Pressures on Flood Gates with Overhangs

Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_020

Effect of Venting Holes to Relieve Wave Impact Pressures on Flood Gates with Overhangs

B. Hofland, M. Passos & E. de Almeida
Delft University of Technology, Delft, the Netherlands

Abstract: Flood gates in storm surge barriers or outlet sluices can be prone to violent wave impacts. When an obstruction is present at the sea side above the gate, confinement of the incoming waves can lead to impulsive wave loads, even when the waves are non-breaking. The large loads can increase the stresses in the gate and structure considerably. One of the measures that is often discussed to relieve the pressures of these impacts is to apply small openings in the gates. In this paper the potential effect of these venting holes on the wave impact loads is determined. The decrease in impact pressure impulse is determined for a range of venting hole geometries is determined by numerical 2D and 3D solutions of a schematized wave impact. In this model the pressure impulse P (integral of the local pressure over the small impact duration) is determined directly by the so-called pressure impulse theory. The potential decrease in pressure impulse due to wave impacts is presented. Moreover, some initial CFD modelling is applied, and the applicability of the pressure impulse theory is discussed.

Keywords: wave impact, flood gate, overhang, venting

1 Introduction

Flood gates in storm surge barriers or outlet sluices can be prone to violent wave impacts when an obstruction is present above the gate at the sea side of the gate. The resulting confinement of the wave can lead to impulsive wave loads, even when the waves are otherwise pulsating and non-breaking. This is a situation that occurs for instance when gates are located in a culvert. It can also occur with temporary structures used for maintenance are placed in front of flood gates. Similar situations can occur with jetties, piers (e.g. Kisacik et al. 2014), quay walls and vertical breakwaters (e.g. Castellino et al. 2018). The large impulsive loads can increase the stresses in the structure considerably. One of the measures that is often used to relieve the pressures of these impacts is to apply small openings in the gates, as can be seen in Fig. 1. Gaeta et al. (2012) and Azadbakht & Yim (2016) studied the effect of venting holes on wave loads for jetties and bridge decks, respectively, and both studied found large effects on the wave loads. The latter study showed 56% reduction of the wave loads with venting covering only 3% of the deck area. In this paper the effect of venting holes on the wave impact loads is determined. The decrease in impact pressure impulse is determined for a range of venting hole sizes.

The pressure impulse caused by impulsive wave impacts can be determined by pressure impulse theory, and has mostly be done for breaking wave impacts (Cooker & Peregrine 1990). It has also been applied (analytically for impacts by upward waves on overhangs without vents (Wood & Peregrine, 1996). In this model the pressure impulse P (integral of the local pressure over the small impact duration) is determined based on the geometry and surface velocity at impact only. In a companion paper (De Almeida et al. 2019) their pressure impulse theory prediction of the wave impact loads under overhangs is compared to measurements. From the (pressure) impulse the peak force or pressure can be estimated, but the (pressure) impulse can also be used directly to obtain the maximum stresses in a structure (Chen et al. 2019).

To determine the influence of venting holes on the wave impact loads numerical solutions of a schematized wave impact will be used to determine the total impulse that the impacting wave will exert on the flood gate. The numerical solution without vents is checked with analytical solutions of the 2D case (Wood & Peregrine, 1996), and a grid-refinement study is done.

In this paper first the pressure impulse theory for non-vented overhangs is given in Section 2. Then the numerical solution for the same setup is given in Section 3. Next the numerical solution for an adapted 2D situation with a vent is given in Section 4. In Section 5 single CFD calculation is presented of a 2D case. In Section 6, 3D solutions of pressure impulse theory are given. Lastly, Sections 7 and 8 present the discussion and conclusions. The applicability of the various models will be discussed.

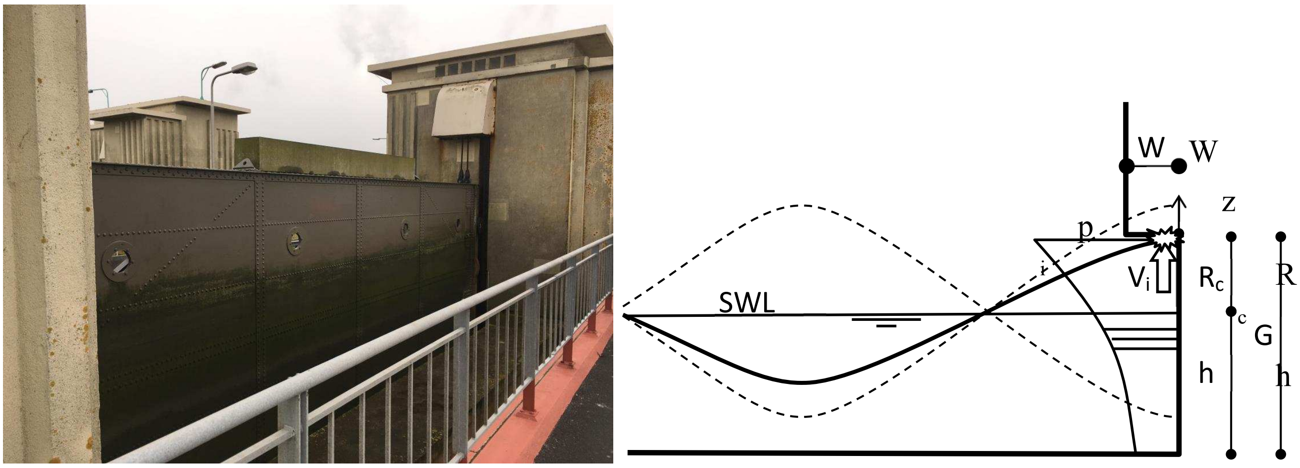

Fig. 1. Left: Afsluitdijk flood gates with venting holes (photo: Hofland). Right: situation sketch with standing wave pattern and overhang.

2 Pressure impulse theory for overhangs

The pressure impulse is the integral over time of the pressure during an impulsive impact. Here only the pressure is considered that is caused by the sudden change in direction of the fluid at a water surface that is suddenly stopped by a hard surface. The use of pressure impulse theory to directly equate the wave impact loads was introduced by Cooker & Peregrine (1995). The solution of the pressure impulse created by an upward moving water surface (of a standing wave) hitting an overhang was introduced by Wood & Peregrine (1996). The method to calculate the pressure impulse can be derived from the Navier-Stokes equation. We consider a flow with a high Reynolds number, so we can neglect the viscous term. Further we regard the non-hydrostatic pressure, and end up with the Euler equation. We regard an impact of very short duration, so the advective term can be omitted, which yields:

$$-\frac{1}{\rho}\nabla p = \frac{\partial \vec{u}}{\partial t} \tag{1}$$

where p is pressure, ρ is the water density, $\vec{u}$ the velocity vector and t time. Next we introduce the definition of pressure impulse $P = \int p dt$. This definition of P is substituted in eq. (1) and gives for the change of velocity during the impact, $\Delta\vec{u} = \vec{u}_{\text{after}} - \vec{u}_{\text{before}}$:

$$-\frac{1}{\rho}\nabla P = \Delta\vec{u} \tag{2}$$

If we then we take the divergence of this equation and assume incompressibility, $\nabla \cdot \vec{u} = 0$, this yields the Laplace equation: $\nabla^2 P = 0$. This is the so-called pressure impulse model. It shows that for a short duration impact, a sudden contact of a moving water surface with an obstacle, the pressure impulse in the fluid is entirely governed, and can be calculated by the Laplace equation. The solution of this equation only needs boundary values at the edge of the domain.

Wood & Peregrine (1996) solved this equation for the situation with an overhang. Their configuration is just as given in Fig. 1, with a zero freeboard $R_c = 0$. In their paper they integrate the Pressure impulse over the overhang width in order to obtain the total impulse on the overhang, but do not present the total impulse on the vertical gate. After implementing their solution (and correcting minor mistakes in the paper), we obtain the same solution for the overhang, and can also integrate the solution over the gate to obtain the impulse on the gate. A solution was fitted through the results of the Wood & Peregrine semi-analytical model, and it can be written as a dimensionless impulse $I / \rho V_i W^2$ for the range of overhang width W to gate height G, of W/G = 1/5 to 5:

$$\frac{I}{\rho V W^2} = 0.0053\left(\frac{G}{W}\right)^3 - 0.0713\left(\frac{G}{W}\right)^2 + 0.431\left(\frac{G}{W}\right) + 0.505 \quad (3)$$

Here V_i is the impact velocity, G the gate height, and W the overhang width. This polynomial fit is accurate, but cannot be used outside the range for which it was fitted. The solution is given in the left graph in Fig. 2. This represents the basic relation for determining the pressure impulse for a standing wave at a short overhang. In the right graph in Fig. 2 the vertical profile of the dimensionless pressure impulse on the gate is given for various overhang widths. This solution is compared to measurements in De Almeida et al. (2019).

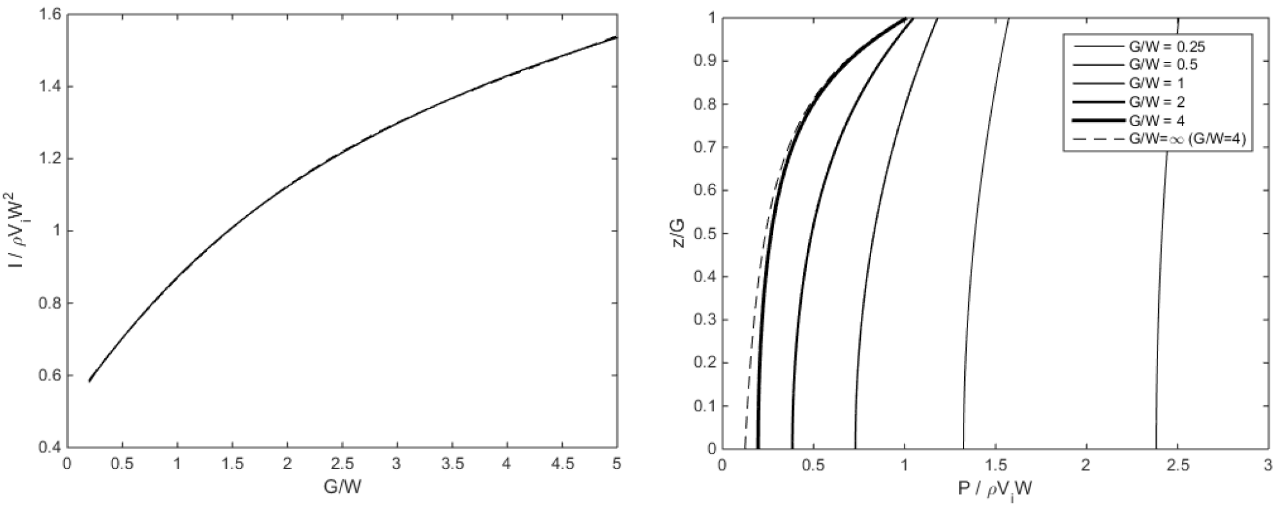

Fig. 2. Left: Total impulse on gate due to impact on an overhang calculated according to Wood & Peregrine (1996) (solid line: solution, dashed line overlapping solid line: fit in eq. (3)).

For the solution the impact velocity V_i is required. This velocity can be obtained by applying the Rayleigh distribution for the statistics of the individual wave heights to determine the (incoming) design wave height. Typically the incoming wave height is given from wave computations, so the total wave height at the wall needs to be known. For this a sensible reflection coefficient needs to be applied. For the present short overhangs near the water line a value lower than 0.9 seems applicable (e.g. 0.7). When the wave height is known, linear wave theory can be applied to determine the impact velocity that is expected at the level R_c.

3 Numerical implementation for pressure impulse theory

The solution of the Laplace equation by Wood & Peregrine (1996) does not account for an opening in the overhang. This is also not straightforward in a (semi-)empirical manner. Hence we choose to solve the Laplace equation in a numerical way, which is straightforward as the domain is simply rectangular.

The solution of the Laplace equation $\nabla^2 P = 0$ is approximated by a second order central difference relaxation scheme. For equal spacing in all three direction the second order accurate this iterative scheme is given by (see e.g. Onabid 2014):

$$P^1_{i,j,k} = \frac{\left(P^0_{i+1,j,k} + P^0_{i-1,j,k}\right) + \left(P^0_{i,j+1,k} + P^0_{i,j-1,k}\right) + \left(P^0_{i,j,k+1} + P^0_{i,j,k-1}\right)}{6} \quad (4)$$

Where i,j,k are the cell indices for the x,y,z coordinates, $P_{i,j,k}$ is the pressure impulse in grid cell (i,j,k), superscripts 0 and 1 indicate the present and next values in the iteration, respectively.
The solution for the 2D case is similar, only the third term in the numerator is dropped, and the denominator becomes 4. This relaxation solution does require many iterations to obtain a converged solution.

For the situation without vents, the accuracy of the method can be determined by comparison to the numerical solution of Wood & Peregrine (1996). The errors that were determined in that manner depend on the relative overhang width (W/G), relative grid resolution Δx/W, and the number of iterations. Some derived errors are given in Table 1. To obtain a well-converged solution with about 1% accuracy, grid sizes of in the order of W/100 and in the order of 10^5 to 10^6 iterations are needed. It is expected that for the situation with a venting hole the convergence will be slightly faster. To accelerate the convergence of the finite difference model, the simulation started with a coarse grid refinement, which provided preliminary pressure-impulse values to be used in progressively finer grids through interpolation, until the required grid resolution was reached. The upstream boundary is placed at a distance of at least 2G away from the impact/overhang. For this domain size this boundary will not influence the impulse at the wall anymore (Cooker & Peregrine, 1995).

Tab. 1. Computed errors of numerically iterated pressure impulse on gate.

$\Delta x = \Delta y$	Iteration cycles	Absolute error	Relative error (%)
$L_y = 2.0$			
0.1000	8351	0.0164	15.93%
0.0500	31463	0.0089	8.62%
0.0100	571420	0.0018	1.76%
0.0050	1909400	0.0002	0.14%
$L_y = 1.0$			
0.1000	4397	0.0907	39.29%
0.0500	16756	0.0425	18.40%
0.0100	319080	0.0078	3.39%
0.0050	1079200	0.0033	1.41%
0.0025	3516000	0.0005	0.21%
$L_y = 0.5$			
0.0500	13030	0.2834	47.43%
0.0100	248250	0.0435	7.28%
0.0050	855690	0.0186	1.86%
0.0025	2874600	0.0060	1.00%
0.0013	106750594	0.0048	0.80%

A result for the dimensionless impulse is given in Fig. 3 for a shorter overhang (dimensionless overhang width W/H equal to 6. The total dimensionless impulse $I/\rho V_i W$ for this configuration is 1.62, and the maximum pressure impulse is 1.

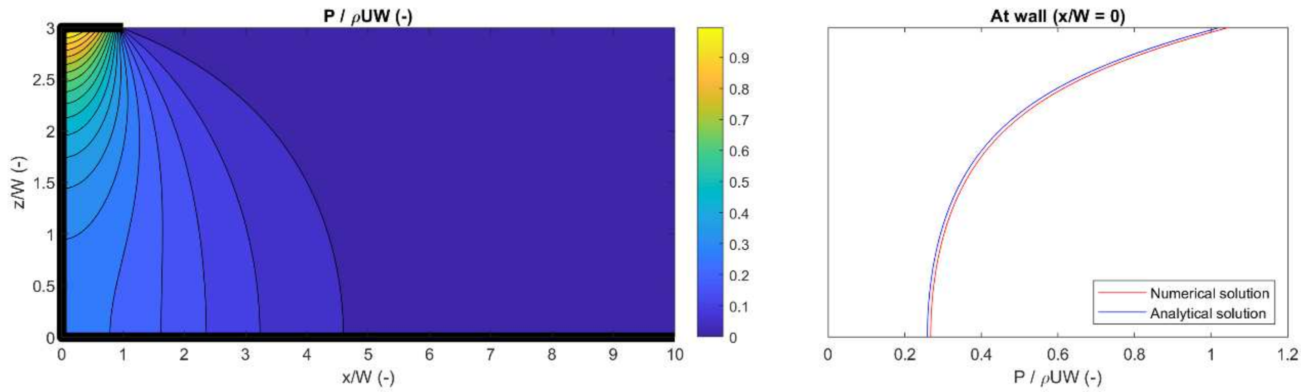

Fig. 3. Left: dimensionless pressure impulse field on overhang according to Wood & Peregrine (1996). Right: corresponding pressure-impulse on the vertical wall together with numerical solution.

4 Two-dimensional venting of impact

The numerical solution that was presented in the preceding section will now be applied to a situation where an opening is present. The opening is situated in the overhang, and near the vertical part (gate). This is a realistic situation, as typically there is space between the gate and the overhang. Moreover, as most intense pressure (impulse) is present at this location, a venting opening here would seem most effective. The resulting setup, together with the boundary conditions that have to be applied to solve the pressure impulse, are given in Fig. 4.

The solution was obtained with the numerical relaxation method explained in Section 3. In Fig. 5 the impulse on the gate with a venting opening is plotted relative to the impulse for a non-vented overhang (the solution according to Wood & Peregrine 1996). The latter is indicated by $I_{O=0}$. As the impacted area also decreases with increasing opening width O, the dashed line in Fig. 5 depicts the impulse that would be expected if the impulse on the gate would decrease proportional to the remaining overhang width W-O, this relation is given by 1-O/W. It can be seen that the decrease in impulse is much more than the effect of just the decreasing remaining overhang width.

For only a 5% gap (O/W = 0.05), the remaining impulse is only 15% to 55%, depending on the ratio of overhang length to gate height, W/G. The relative decrease of impact impulse increases with overhang width, so the 55% remaining impulse (45% decrease) occurs for the shortest calculated relative overhang width (W/G = 1/4), and the 15% remaining impulse (85% decrease) occurs for the longest considered relative overhang width (W/G = 4).

In the right panel of Fig. 5 the vertical profile of the pressure impulse is presented for various relative venting opening widths (O/W), for an overhang width of W/H = 0.25.

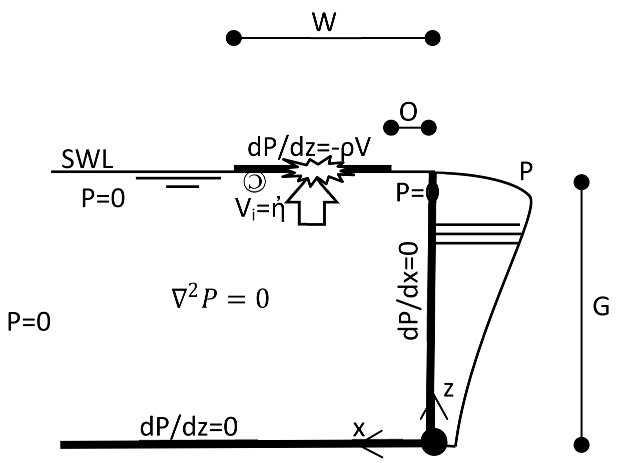

Fig. 4. Adapted schematization of impact for numerical solution for pressure impulse calculation of 2D impact with venting opening of width O, including boundary conditions applied

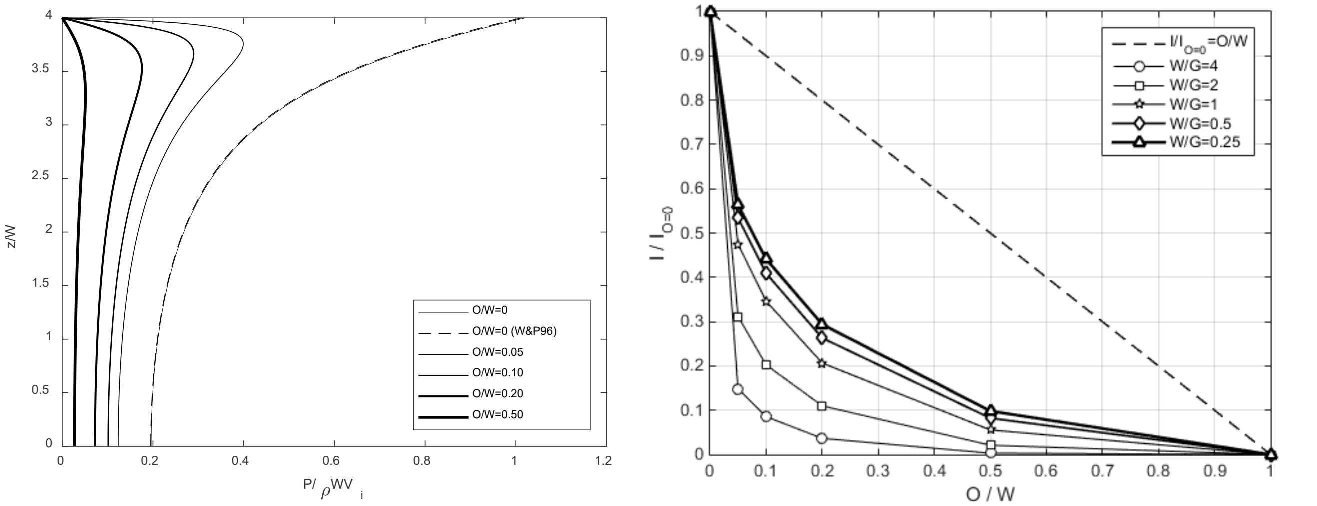

Fig. 5. Left: Impulse on gate due to two dimensional venting opening in overhang near wall. Plot gives relative impulse $I/I_{O=0}$ dimensionless opening width O/W. Right: The vertical profiles of pressure impulse for different opening widths, and W/G = 1/4.

5 CFD calculation of 2D problem

In order to investigate the validity of the pressure impulse theory for the present application, a comparison is made with a CFD calculation. Only an initial calculation is given here, so this is as of yet still far from a full validation. The full impact is calculated by OpenFoam, together with the waves2Foam toolbox (Jacobsen et al. 2011). Using the utility blockMesh, several two-dimensional meshes are created from a composition of blocks with controlled number of segments along each coordinate direction.

A series of regular waves is run. The mean water level is equal to the bottom of the overhang. The simulation is run at model scale with a water depth of h = 0.6 m, and an incoming wave height and period equal to H_i = 0.06 m and T = 1.3 s. Thus the relative overhang width is W/H = 1/6. The wave length to overhang width ratio is L/W = 24.2, and the wave steepness is H/L = 0.025.

A grid resolution study was done first using 5 different meshes. Meshes 1 to4 were had uniform mesh sizes around the overhang, width grid sizes of 6.3, 9.1, 12.5, and 20.0 times the overhang width. In Mesh 5 the grid was locally refined around the venting hole by a factor 4, as can be seen in the left panel of Fig. 6. In the right panel of that figure the calculated impact is shown, compared to the measurement by De Almeida et al. (2019). It is clear that with increasing resolution of the vent, the impulsive peak is better resolved. However the difference between meshes 4 and 5, with respectively 2 and 8 grid cells over the venting opening, do not differ very much. It can also be seen that the measured peak force and total impulse of the impact are still somewhat higher. This might be due to the fact that the wave in the model is slightly higher, as also the pulsating wave load seems to be slightly higher.

Fig. 8 depicts three snapshots of the numerical calculation. The middle panel depicts the situation during impact. It can be seen that the situation is very similar to the configuration that is considered in the Wood & Peregrine schematization.

The force on the gate is shown in Fig. 7. It can be seen that the peak force is clearly lower for the vented situation, in comparison to the non-vented situation. The impulse as calculated by the impulse theory would be the surface area under the peak. There are different methods to split the peak from the normal, pulsating (or quasi-steady) wave load. The decrease in impulse is roughly 20 to 30%. The smallest opening in Fig. 5 is O/W = 1/4, instead of 1/6, but a decrease of roughly 60% is expected. So even though the relative decrease of impulse is substantial, it is less than given by the pressure impulse theory.

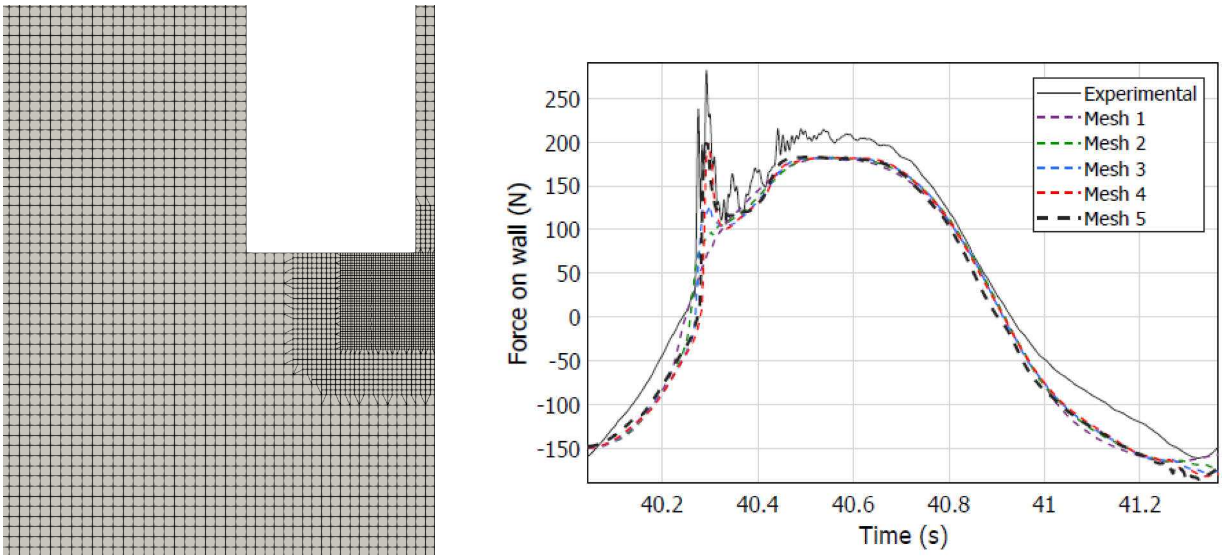

Fig. 6. Left: grid around overhang, with refinement in corner. Right: calculated force on gate with and without vent for various mesh sizes.

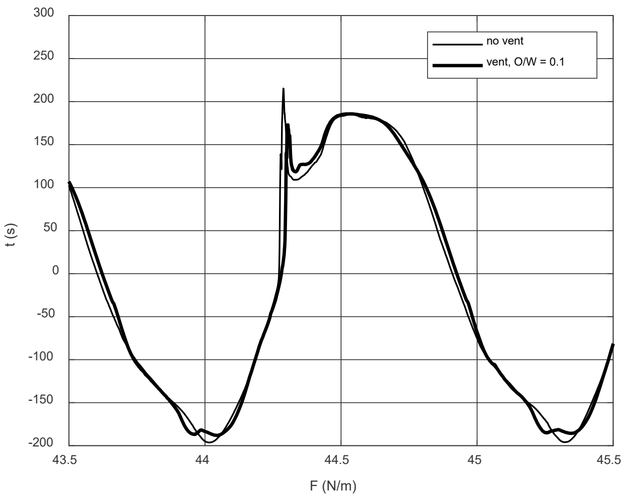

Fig. 7. Force on the gate with and without vent, calculated by OpenFOAM for the case W/G = 1/6, L/W = 24, h/L =0.25, H_i/L = 0.025.

Fig. 8. Snapshots of water body just before, during, and after impact of a regular wave on an overhang (O/W = 0.1, W/G = 1/6, L/W = 24, h/L =0.25, H_i/L = 0.025). Only a part of the domain around the overhang is shown.

6 Three-dimensional venting of impact

In this section some results are shown for the 3D implementation of the pressure impulse theory. Now local venting holes with regular spacing are studied. By using symmetry arguments only a limited domain has to be modelled to obtain a solution for an infinitely wide gate. The potential decrease in pressure impulse due to wave impacts can be calculated with the pressure impulse theory. The setup is given in the left panel of Fig. 9. Only the rectangular volume with the grey boundaries can be modelled, as due to symmetry in the infinitely wide pattern, the transversal derivative of the pressure impulse is zero (dP/dy = 0). So, when this boundary condition is applied at the 'side walls', this is actually a solution for the infinitely wide domain. The additional geometrical parameters we introduce to define this problem are the relative venting hole dimensions, width W_h and length L_h, and hole spacing S. These are indicated in the figure as well.

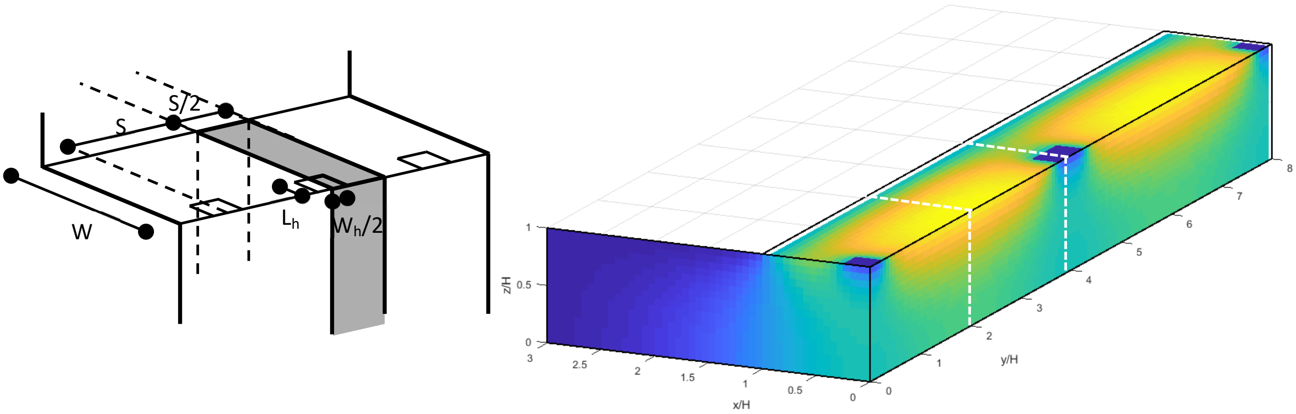

Fig. 9. Left: parameters describing the problem. The grey area is the modelled domain. Right: indication of calculated pressure impulse on flood gate (gate is located at x=0), overhang (z/G=1), and sidewall (y=0). Yellow: high pressure impulse, blue: low pressure impulse.

In the right panel of Fig. 9 the calculated pressure impulse field can be seen for a relative overhang width of W/G = 1, and $L_h = W_h = 0.25W$, and S/W = 4. The calculated domain is the part between the white dashed lined. It can be seen that if the domain is mirrored at the edges, as has been done in the figure, the pressure impulse field on an infinitely wide gate can be modelled. It can also be seen that the pressure impulse around the relatively large venting holes is reduced considerably.

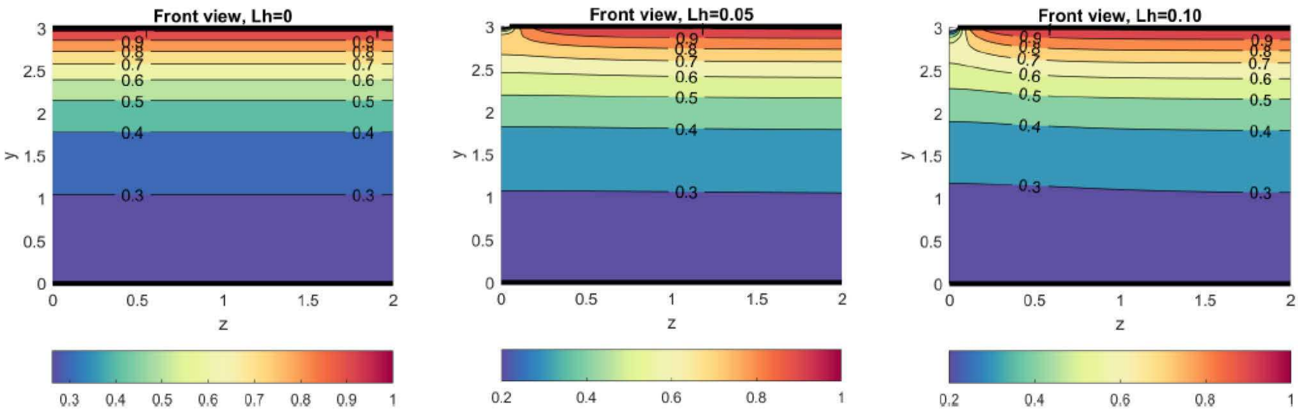

Fig. 10. Pressure impulse on gate (looking toward gate) for an overhang with regularly spaced square venting openings of size (graphs from left to right) $L_h = W_h = 0$, 0.05 and 0.1, W/G = 1/3, S/W = 8. The colourbars depict $P/\rho V_i W$

In Fig. 10 the pressure impulse field on a gate is shown with various sizes of the 3D venting holes. These square openings have side widths of 0, 0.05W and 0.1W. They are spaced very far apart, such that the pressure impulse profile between the vents is nearly equal to the 2D case without vents. The total impulse is lowered for these cases by 8% and 15%, respectively.

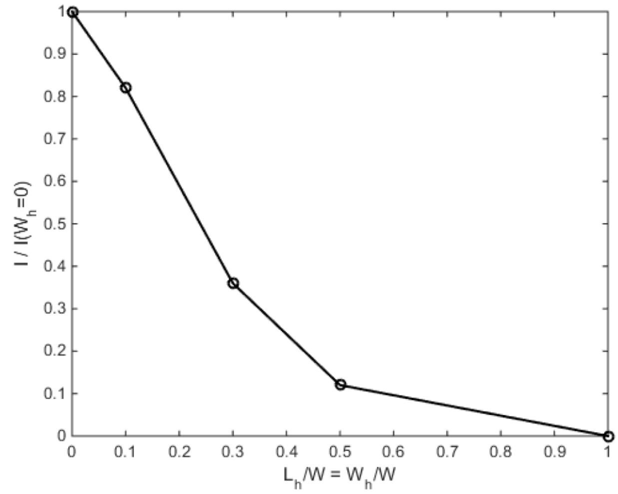

Fig. 11. Normalized impulse on the gate for various square venting hole size ($L_h = W_h$), for a configuration with W/G = 1/6 and venting holes spaced by one overhang width, or S/W = 1. The dimensionless impulse for this case without venting holes is $I(W_h=0)/\rho V_i W^2 = 1.62$.

7 Discussion

In this paper a short overhang is discussed. 'Short' is defined in two senses. In one sense the overhang is short compared to the wave length. In that case the upward velocity under the overhang is relatively uniform, as assumed in the Wood & Peregrine (1996) approach. For very long overhangs, the assumption that the impact takes place over the entire overhang will not hold. In a second sense, if the overhang is short compared to the gate height, smaller than about 1/4, the dimensionless pressure impulse will be equal to 1, and the pressure field under the overhang will be similar.

The present schematization is shown to represent a relatively realistic impact by the CFD calculation. However, this is the case where the water level is around the overhang. The upward velocity can also be calculated for other freeboards. However, then the water surface will be less horizontal during the impact, such that the resemblance with the present impulse-theory schematization will be somewhat less.

The impacts are influenced by air (see e.g. Bagnold 1939, Ramkema 1978). For the shorter overhang, it seems credible that most of the air is expelled before the impact, as seems to occur in the CFD calculation for W/G = 1/6. With a vent the air can be expelled even more efficiently. The exact role of air is not clear. According to Wood et al. (2000) due to 'bounce back' of air the total impulse can increase. However, typically air dampens the impact as it increases the duration of the impact. The force is typically related to the impulse by assuming a triangular force in time, which leads to a peak force of $F = 2I/\Delta t$, where Δt is the impact duration. In this way the paradoxical influence of the air seems to be that the impulse can increase, while the force decreases. The latter also seems to be observed in experiments (Mao 2019), but certainly warrants further study.

Another aspect is the question when pressure impulse theory is actually valid. For this the duration of the impact should be very small compared to the wave period. Then the pulsating load and the impulsive load can be split easily. However, this is not exactly the case. Hence splitting the impulsive load from the pulsation load in an experiment or CFD calculation introduces some uncertainty.

Converting the impulse to a peak force via $F = 2I/\Delta t$ introduced some uncertainty. However, the pressure impulse can also be introduced to assess the dynamic structural response directly. This is studied for instance by Chen et al. (2019). The detailed structural response also needs to be considered. This can be done by the application of efficient detailed fluid-structure-interaction models (Tieleman et al. 2019).

8 Conclusions

In this paper the use of pressure impulse theory to determine the effect of venting holes on the loads on flood gates due to wave impacts on overhangs is investigated. The pressure impulse theory is a promising technique which seems to have the potential to enable us to regard wave impacts in a less empirical manner than has been done up to now.

The pressure impulse theory was used to calculate realistic pressure impulse fields on the gates with and without venting holes in the overhang. From these calculations it becomes clear that venting holes in an overhang can decrease the impulses due to the upward motion of standing waves considerably. Graphs have been derived from pressure impulse theory that give the relative degree of decrease of the pressure impulse. Even for a relatively small 2D venting opening near the gate of 5% of the overhang width, the predicted decrease in total impulse on the gate is 45% for a short overhang to 85% for a long overhang. Also estimates of the effect of 3D venting holes were made. For larger venting gap sizes the decrease in pressure impulse becomes larger. An initial CFD calculation confirm the decrease in impulse, albeit less. More study is needed on physical and numerical modelling with attention to the exact way to split the impulse from the quasi-steady or pulsating load.

Air also influences the impact impulse, so should be considered. In the models used in this paper, the influence of air is not (exactly) taken into account. This warrants further study.

Acknowledgement

This research was partly supported by NWO grant ALWTW.2016.041.

References

Azadbakht, M. & Yim, S. C. (2016), 'Effect of trapped air on wave forces on coastal bridge superstructures', Journal of Ocean Engineering and Marine Energy 2(2), 139–158.

Bagnold, R.A., 1939. Wave-pressure research. The institution of Civil Engineers, 12, 202–226.

Castellino, M., P. Sammarco, A. Romano, L. Martinelli, P. Ruol, L. Franco, P. De Girolamo (2018). Large impulsive forces on recurved parapets under non-breaking waves. A numerical study. Coastal Engineering 136 (2018) 1–15.

Chen, X., Hofland, B., Molenaar, W., Capel, A., Van Gent, M.R.A., 2019. Use of impulses to determine the reaction force of a hydraulic structure with an overhang due to wave impact. Coastal Engineering, Elsevier, 147 75–88.

Cooker, M. J. & Peregrine, D. H. (1990), A model for breaking wave impact pressures, in 'Proc. Coastal Engineering Conference 1990', Delft, The Netherlands.

De Almeida, E. Hofland, B. Jonkman, S.N. (2019), Wave impact pressure-impulse on vertical structures with overhangs. Coastal Structures 2019. Hannover, Germany.

Gaeta, M. G., Martinelli, L. & Lamberti, A. (2012), 'Uplift forces on wave exposed jetties: Scale comparison and effect of venting', Coastal Engineering Proceedings 1(33), 34.

Kisacik, D., Troch, P., Bogaert, P.V., Caspeele, R., 2014. Investigation of uplift impact forces on a vertical wall with an overhanging horizontal cantilever slab. Coastal Engineering, Elsevier, 90, 12–22.

Mao, Y. (2019), Wave loads on vertical structure with overhang considering air influence, Master thesis, Delft University of Technology.

Ramkema, C., 1978. A model law for wave impacts on coastal structures, in: Proceedings of Coastal Engineering Conference. pp. 2308–2327, Hamburg, Germany.

Tieleman, O.C., Tsouvalas, A., Hofland, B., Jonkman, S.J., 2019. A three dimensional semi-analytical model for the prediction of gate vibrations. Marine Structures, Elsevier, 65, 134–153.

Wood, D. J. & Peregrine, D. H. (1996), Wave impact beneath a horizontal surface, in 'Proc. Coastal Engineering Conference 1996',Orlando, United States.

Wood, D.J., Peregrine, D.H., Bruce, T., 2000. Study of wave impact against a wall with pressure-impulse theory, I: Trapped air. Journal of Waterway, Port, Coastal and Ocean Engineering, 126 (4), 182-190.

Onabid, M. A. (2012), 'Solving three-dimensional (3D) Laplace equations by successive over-relaxation method', African Journal of Mathematics and Computer Science Research 5(13), 204–208.