COMPARISON OF NUMERICAL MODELS FOR WAVE OVERTOPPING AND IMPACT ON A SEA WALL

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The paper discusses three different numerical models in a study of wave overtopping and impact on a sea wall. The models used are SWASH (based on the nonlinear shallow water equations), DualSPHysics and FLOW-3D (both based on the full Navier-Stokes equations). The models are validated against experimental measurements in a setup with a quay wall and berm in front of the sea wall. The two models based on the full Navier-Stokes equations provide good estimates of the wave impact on the sea wall. Moreover, reasonable agreement with experimental values of averaged overtopping discharges was found for the full test time series simulated with FLOW-3D. Notwithstanding the SWASH model provides reasonable estimates for the wave overtopping on a simple quay wall, at a significantly lower computational cost than the other two models, it clearly underrates the overtopping discharge in the case of a combination of a quay wall, berm and sea wall. Further investigation is needed to draw conclusions on the model accuracy of SWASH in such a case.

Keywords: numerical model , sea wall, wave overtopping, wave impact, validation, wave flume experiment

INTRODUCTION

In the framework of the “Masterplan Coastal Safety, Horizon 2050” developed by the Coastal Division (Department of Public Works and Mobility, Flemish Government), several weak links in the Belgian coastal defense line have been identified. One of these weak spots is the part of quay wall on the west side of lock “Vandammesluis” in the inner port of Zeebrugge, indicated in Figure 1. In extreme N-NW storm conditions, a considerable wave disturbance is expected in front of the quay wall, which, in combination with a storm surge, leads to large overtopping and possible erosion of the landward slope behind the quay wall. As a countermeasure, the construction of a sea wall at a certain distance behind the quay wall edge is proposed, in combination with a revetment on the landward slope.

The design study of the sea wall is supported by physical and numerical modeling conducted at Flanders Hydraulic Research and Ghent University. The main research question is to find an optimal combination of (minimal) wall height and distance from the quay wall edge, so the overtopping criteria in the particular design storm conditions can be met. Another question is to estimate the maximum impact forces during storm conditions, needed for the structural design of the sea wall.

In the numerical part of the design study, three different models have been employed to assess the average overtopping discharge and wave force acting on the wall. The paper treats the validation study of the numerical models against measurement data from a physical scale model (1:25) in a wave flume.

Figure 1. Location of planned sea walls in the inner port of Zeebrugge. Studied area west of Vandammesluis indicated in the circle.

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NUMERICAL MODELS

The three models used in the numerical study are SWASH, DualSPHysics and FLOW-3D®. They are considerably different in modeling approach and implementation. SWASH is based on a simplified version of the Navier-Stokes equations (i.e. the nonlinear shallow-water equations) whereas DualSPHysics and FLOW-3D are based on the full Navier-Stokes equations, however with a different approach to the numerical implementation (Eulerian versus Lagrangian method, respectively). A brief introduction of each model is given hereafter.

1. SWASH

SWASH is a non-hydrostatic wave-flow model and is intended to be used for predicting transformation of dispersive surface waves from offshore to the beach. It is commonly used to study the surf zone and swash zone dynamics, wave propagation and agitation in ports and harbours, rapidly varied shallow water flows typically found in coastal flooding.

SWASH is a time-domain model based on the nonlinear shallow-water equations including a non-hydrostatic pressure term. The computational domain can be divided in the vertical into a fixed number of terrain-following layers. More details about the model can be found on *swash.sourceforge.net*, including a full description of the numerical model, boundary conditions, numerical scheme and applications (Zijlema et al. , 2011).

2. DualSPHysics

DualSPHysics is based on the Smoothed Particle Hydrodynamics method (SPH), a fully Lagrangian method with a discretization of the fluid into a set of particles. Each computational unit, referred to as a particle, is a nodal point where physical quantities are computed as an interpolation of the values of the nearest particles. Mathematically, the contribution of the neighboring particles is weighted according to the mutual distance using a kernel function and a smoothing length. The smoothing length is a characteristic length used to define the area of influence of the kernel beyond which the contribution with the other particles can be neglected, that is, the kernel has compact support. In the classical SPH formulation, the Navier-Stokes equations are solved and the fluid is treated as weakly compressible. The conservation laws of continuum fluid dynamics, in the form of differential equations, are transformed into their particle forms by the use of the kernel functions. For further details see Gómez-Gesteira et al. (2010).

DualSPHysics has been designed from the outset to use SPH for real engineering problems with software that can be run on either Central Processing Units (CPU) or Graphical Processing Units (GPU). DualSPHysics is open source and can be freely downloaded from *dual.sphysics.org*. The GPU code proved to achieve speedups of up to two orders of magnitude compared to a single core CPU code.

3. FLOW-3D

FLOW-3D® is a multiphysics CFD code developed by Flow Science Inc. (USA). Conservation of mass and momentum, in the form of the full 3D Navier-Stokes (NS) equations are the basis of the model. Options for turbulence modeling include Reynolds-averaging of the NS equations (RANS) and Large-Eddy Simulation (LES). The governing model equations are discretized in space with a finite difference/finite volume technique, using Eulerian structured grids with staggered mesh topology. A cut-cell method is used for obstacle representation, defining cell-based area and volume fractions which are directly incorporated in the conservation equations of mass and momentum. This method is very efficient in terms of computational cost and the amount of interaction needed from the user (compared to e.g. body-fitted meshing), but also limited in accuracy by the mesh resolution. The Volume-of-Fluid (VOF) technique is used for free surface tracking, which can be used in both single- and two-phase modeling. A full description of the model and its numerical implementation is given by Flow Science (2014).

To use FLOW-3D as a numerical wave flume, it is crucial to maintain the stability and accuracy of the incident wave field with long test durations. To that purpose, the model has been equipped with a piston wavemaker with active absorption The operation of the wavemaker, under linear wave theory, is similar as in the laboratory. The performance of FLOW-3D as a numerical wave flume, including wave interaction with a rubble mound breakwater has been extensively validated (Vanneste, 2012).

SETUP OF THE VALIDATION EXPERIMENT

Short-crested waves hit the quay wall near ‘Vandammesluis’ under varying angles. This, together with the fact that the quay wall features a corner, as shown in Figure 1 lead to a problem of clear 3D nature. In the design study, the actual situation has been simplified to 2D, i.e. perpendicular wave incidence of long-crested waves. A sketch of the experimental setup is given in Figure 2. To find the optimal distance and height of the sea wall for the given wave conditions, tests have been performed in the wave flume of Ghent University (Van Doorslaer et al, 2012) on a scale 1:25. From this test program, two tests have been selected for the validation study, which only differ in the length of the berm with slope 1:100 between the quay and the sea wall: 15 and 37.5 m respectively (in prototype). The Still Water Level (SWL) corresponds with the top quay level at +8.0 m TAW. The incident waves (Jonswap spectrum) have a significant wave height H_{m0}= 2.5 m and peak period T_p=12 s. Force transducers are installed on the 3.5 m high sea wall to measure the impact forces.

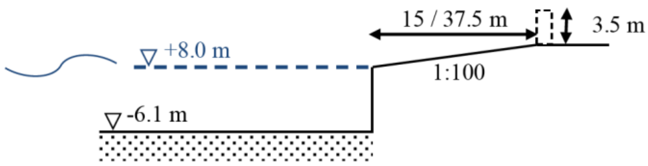


Figure 2. Cross section of the experimental setup (prototype dimensions, levels in m TAW).

The design condition restricts the average overtopping rate to maximum 1 l/s/m, which implies that the overtopping (and maximum impact on the sea wall) will be determined by few events. Therefore, the wave test series need to contain a sufficient number (min. 1000) of waves. Due to the long test duration and high reflection at the quay wall, it is necessary to apply a well-controlled wave generation in the numerical models, where active absorption of reflected waves is crucial. At the moment the study was performed, it was possible to execute the full tests series with SWASH and FLOW-3D. Since the wave generation in DualSPHysics did not dispose of active absorption, a comparison of a limited number of wave impacts was performed with this model.

To achieve a good simulation performance, the numerical model should correctly capture the flow over the quay wall, rushing over the berm where it finally impacts on the sea wall. In that respect, it can be expected that SWASH will be the most efficient in computational terms but that the spatial discretization might limit the predictive accuracy. The two other models, DualSPHysics and FLOW-3D have more capability to represent the flow characteristics in detail, but at a higher computational cost. In the following, the performance of each model is investigated in detail using the validation case.

VALIDATION : SWASH

The performance of SWASH is first tested for a vertical wall case as depicted in Figure 3 (a). Simulations were run with two different levels of SWL each with two different wave heights (between 1.63 and 2.05 m) and three different crest levels, which yields 12 different test conditions.

Numerical simulations were run with SWASH (version 1.10AB) using a grid size of 2.0 m in the horizontal direction with an initial time step of 0.02 s. One layer was used in the vertical direction which is enough to resolve the frequency dispersion since kd < 1.0 at the wave boundary. The calculation time step is automatically adjusted depending on the CFL condition.

The JONSWAP (γ=3.3) spectrum was prescribed as the wave boundary condition of the numerical simulation. A weakly-reflecting wave boundary was applied in order to minimize the effect of the re-reflection from the wave generator. The distance from the wave generator to the quay wall is 400 m, which is enough to accommodate two wave lengths of the incident waves. A Manning’s friction coefficient of 0.019 was used to represent bottom friction in numerical model runs. The time duration of the numerical simulation was 1 hour 40 minutes, for about 500 waves.

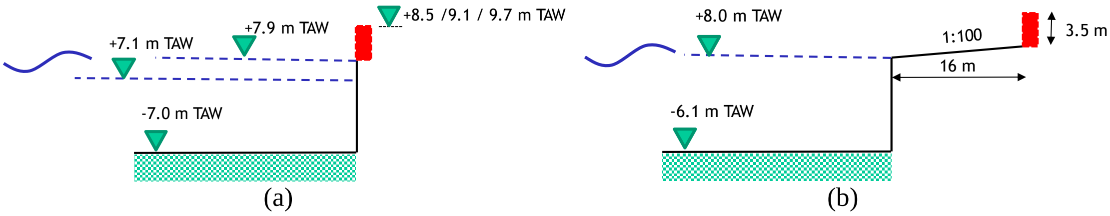


Figure 3. Configuration of SWASH model tests : (a) vertical wall case and (b) quay wall – berm –sea wall case. Dimensions in prototype values.

Numerical values of wave overtopping discharge are compared with values predicted by Eq.(1) EurOtop (2007) where dimensionless freeboard Rc* and overtopping rate q* are defined in Eqs. (2) and (3).

$$q^* = 0.04\exp\left(-2.6.R_c^*\right) \quad (1)$$

$$q^* = \frac{q}{\sqrt{g \cdot H_{m0}^{\;3}}} \quad (2)$$

$$R_c^* = \left(\frac{R_c}{H_{m0}}\right) \quad (3)$$

Numerical values of average wave overtopping discharge in Figure 4 generally compare well with EurOtop predictions, except for a few cases outside the 5 % exceedance limits. These cases correspond with the highest crest-freeboards and high wave reflection.

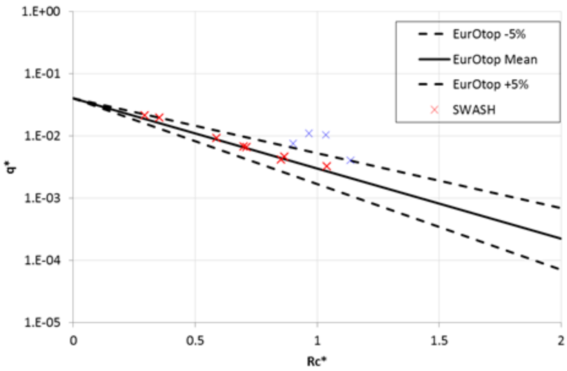


Figure 4. Non-dimensional computed mean wave overtopping discharge (crosses) plotted against EurOtop (2007) equation (thick line) for vertical wall with 5% upper and lower exceedence limits (dashed lines)

Next, SWASH is validated for the case with the berm (15 m) and sea wall, presented in Figure 2. As can be seen in Figure 3 (b), the length of the berm in SWASH is 16 m instead of 15 m in the physical model, since the grid cells need to be fitted to the geometry. The bathymetry created in SWASH (in prototype values) is shown in Figure 5. Simulations are performed in 2D. A grid size of dx=2 m is used in the entire study to keep a reasonable accuracy (dx<L/50) and calculation time. No bottom friction is used. The numerical domain is in total 600 m in x direction. The wave boundary position is the same location of the wave paddle in the flume.

- start of the 1/20 slope: 190 m (-12.85 m TAW)
- end of the 1/20 slope: 324 m (-6.1 m TAW)
- quay wall: 486 m (+8.0 m TAW, berm length is 16 m and 1% slope)
- sea wall: 502 m (+11.65 m TAW : 3.5 m wall)

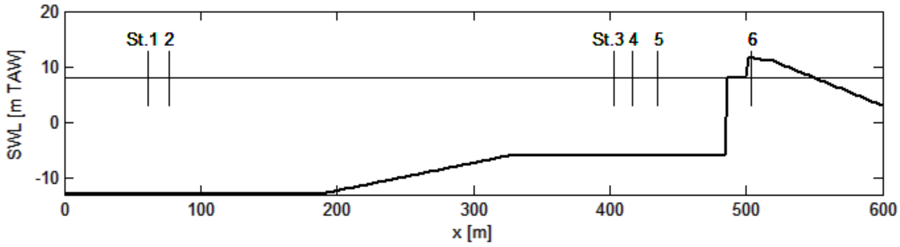


Figure 5. The bathymetry for the SWASH calculation.

Waves are generated with a weakly reflecting wave boundary at x=0 m using the following wave parameters (prototype values): H_{m0}=2.53 m and T_p=11.6 s. with typical wave spectrum shape (JONSWAP, γ=3.3). Note that the time series generated in the SWASH model is different from the one used in the physical model. Therefore, wave by wave comparison is not conducted in this validation.

Table 1. Comparison of incident wave field and overtopping discharge between physical model and SWASH.

	Physical model	SWASH
$H_{m0,inc}$ [m]	2.50	2.58
CR [-]	0.78	0.86
q_{avg} [l/s/m]	2.58	0.15

Table 1 contains the measured and simulated incident wave field and overtopping discharge. From this comparison, the incident wave height in the SWASH model seems well reproduced (within 5%), however a slightly higher value of the reflection coefficient is obtained compared to the physical model. A much bigger discrepancy is noticed between the experimental and numerical value of the average overtopping rate. Compared to the physical model result, the wave overtopping obtained from SWASH is underestimated more than 10 times even though the incident wave height is almost the same. Time series produced by SWASH also show a number of overtopping events which is much lower than in the physical model.

It seems that SWASH is not able to reproduce the wave overtopping discharge for the berm and sea wall case, even though for the quay wall case, the model shows values of mean wave overtopping discharge values which are comparable to EurOtop (2007) calculation results. The reason can be probably related to the number of the vertical layers in the computation. In this case, one layer is used so the horizontal (and also vertical) velocity value is uniform in one column, as shown in Figure 6. In the present case, the velocity profile in front of the quay wall differs between the water surface and the bottom due to the deep water condition also as shown in Figure 6. A single-layer calculation cannot deal with this velocity difference, possibly leading to an underestimation of the velocity of the overtopped water mass. The high velocity water mass at the surface in front of the quay wall is not conserved and transmitted directly on the quay wall, but somehow the energy is averaged at the grid cell at the edge of the quay wall and a smaller velocity can be allotted at the grid cell on the quay wall. The high reflection coefficient shown in Table 1 can be also explained by this hypothesis. In the physical model test, a water mass with high velocity mass flows on the quay wall, so that the reflection remains relatively small.

However, the question remains why the wave overtopping discharges computed by SWASH appear reasonable for the vertical wall case, even though the same consideration regarding the overflow on the quay wall applies as with the quay–berm–sea wall case. It is however possible that SWASH overestimates the water level in front of the quay wall and underestimates the velocity. The discharge is determined as the product of water level and horizontal velocity, so the overtopping rate can be accidentally the same in the quay wall case while the wave overtopping discharge at the sea wall can be different. As a solution, it might be possible to improve the accuracy by using more layers in the vertical direction. Preliminary simulations however proved to suffer from instabilities, and more research should be done to obtain further insight in the cause of the mismatch in predicted overtopping discharge for the quay–berm–sea wall case.

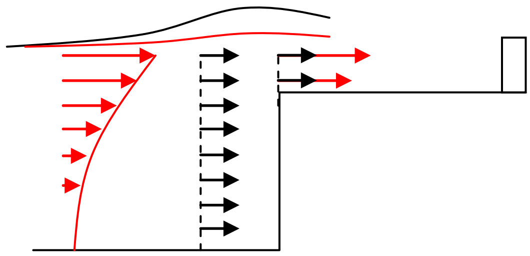


Figure 6. A sketch of velocity profile in front of the quay wall and on the berm, as represented in the physical model and in SWASH.

VALIDATION : DualSPHysics

Model setup

A validation test is performed for the test with berm length 0.6 m (model scale, 15 m in prototype). Figure 7 shows the numerical domain, which is an exact reproduction of the physical test setup at model scale 1:25, conceived within x [0; 21.2] and z [0;1.6] (dimensions in m), with the following characteristic points:

- initial position of the right piston face in the numerical model : x=0.56 m
- foreshore (1:20) starting at x=8.2 m, level of horizontal part : z=0.27 m
- position of quay wall front : x=20.058 m
- position of front of sea wall : x=20.658 m

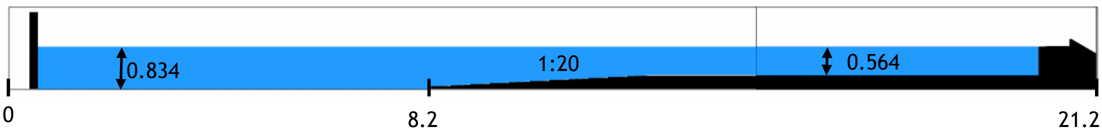


Figure 7. Wave flume setup in DualSPHysics, test with 0.6 m berm length (dimensions in m).

Wave generation is achieved using a piston-type wavemaker. No active wave absorption is implemented in DualSPHysics, so a re-reflection is expected after a while. Therefore, only the first 120s of the experimental wave time series have been simulated.

Free-surface elevations are measured at exactly the same positions as in the physical model, indicated in Table 2. The two wave gauges for the active wave absorption in the physical model are located at x_1 and x_2 in front of the piston. Another 3 wave gauges, located at x_3, x_4 and x_5, are used for the determination of wave reflection according to the 3-gauge-method of Mansard and Funke (1980).

The force on the sea wall is measured in DualSPHysics as summation of the pressures exerted on the particles that form the wall. Hence, the number of the points where the pressures are measured depends on the particle size.

Table 2. Wave gauge positions in the numerical model

Test	x_1 [m]	x_2 [m]	x_3 [m]	x_4 [m]	x_5 [m]
berm length 15 m	3.00	3.62	16.68	17.21	17.95
berm length 37.5 m	3.00	3.62	15.78	16.31	17.05

The solid obstacles within the numerical domain (i.e. the quay wall, slope and sea wall) are modelled using the dynamic boundary conditions (DBCs). Those conditions satisfy the same equations of continuity and state as the fluid particles in SPH, but their positions remain unchanged or are externally imposed (Crespo et al., 2007). This boundary condition is easy to implement due to its computational simplicity where the fluid-boundary interactions can be calculated inside the same loops as fluid particles. The most important numerical parameter settings are listed in Table 3. Parameters not included in this list have default settings.

Table 3. Main numerical parameters used in DualSPHysics

Option	Set up	Parameter
Fluid	Weakly compressible	coefsound=[10÷20]
Kernel function	Wendland	Kernel=2
Improved formulations	δ-SPH	DeltaSPH=0.1
Viscosity	Artificial	Visco=0.01
Density filter	NO	ShepardSteps=0
Time integration scheme	Sympletic scheme	StepAlgorithm=2

Simulation results: incident wave field

Time series of free-surface elevation are initially unaffected by wave reflection on the quay wall. Good agreement is observed between experiment and numerical model during the first 45 s at a location close to the piston (x_1), see Figure 8. After this time, the reflection pattern establishes and clearly differences between experimental and numerical model. The same considerations can be made for the time series measured closer to the quay wall.

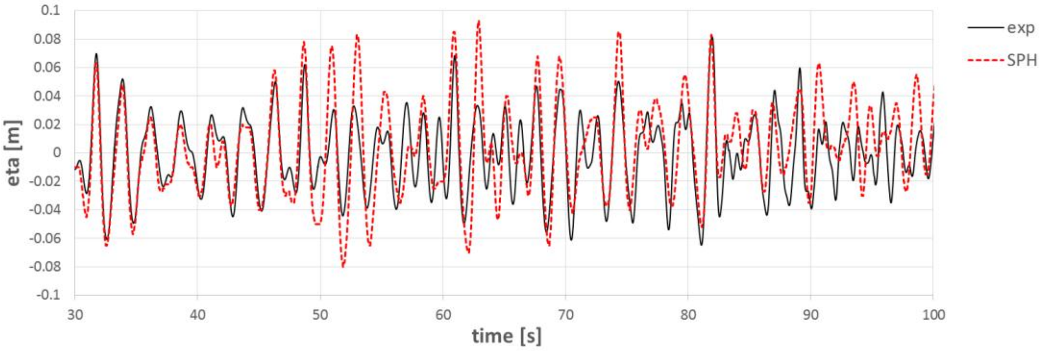


Figure 8. Comparison between experimental and numerical time series of free surface elevation in x=x_1.

The sensitivity of the incident wave field (in terms of reflection coefficient *CR*, spectral wave height H_{m0} and peak period T_p) to the particle size (i.e. spatial resolution) and fluid compressibility has been verified, with results shown in Table 4. Notwithstanding the loss of correspondence in the instantaneous free-surface elevation in front of the quay wall, good agreement is obtained between experimental and numerical spectral incident wave parameters. It is noticed that higher resolutions (smaller particle size) give better results.

As an indication of simulation duration it can be mentioned that a simulation with *dp*=0.01 m (136 k particles) took a total of 3.1 h computational time for 120 s simulation time, on a workstation with a Tesla K20 GPU (13 multiprocessors, 2496 cores, 0.71 GHz)

Simulation results: impact forces on sea wall

Impact forces on the sea wall, measured in the physical model and simulated by DualSPHysics are compared in Figure 9. The numerical signal exhibits some noise, which can be related to the Dynamic Boundary Conditions used in DualSPHysics. Therefore, the numerical force time series have been filtered. Physical and numerical wave impacts generally compare well, see Figure 9. In particular the first few wave impacts, unaffected by the presence of re-reflection in the numerical wave flume (due to the absence of active wave absorption) show a good correspondence.

Table 4. Sensitivity of wave reflection to numerical parameter settings in DualSPHysics.

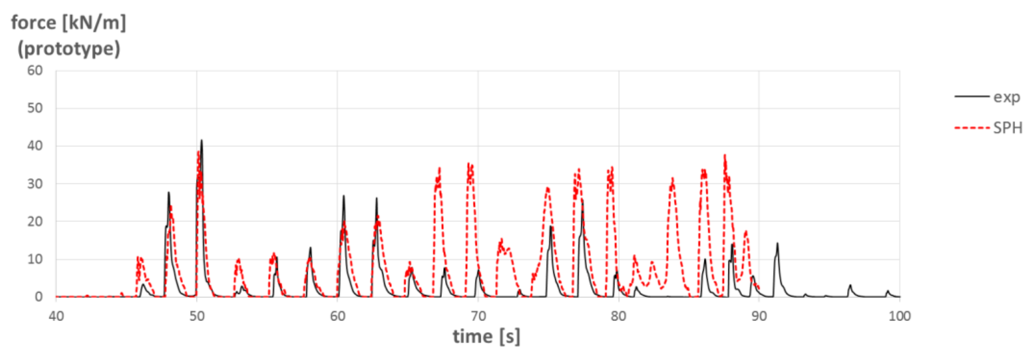
TEST ID	dp [m]	H [m]	coefsound [-]	visco (α) [-]	CR [-]	H_{m0} [m]	T_p [s]
Physical model (berm 0.6m)					0.72	0.108	2.13
VDMS_kh190_sos16_0.5cm	0.005	0.0134	16	0.01	0.72	0.112	2.13
VDMS_kh190_sos10_0.5cm	0.005	0.0134	10	0.01	0.70	0.112	2.13
VDMS_kh190_sos16_0.8cm	0.008	0.0215	16	0.01	0.72	0.110	2.13
VDMS_kh190_sos10_0.8cm	0.008	0.0215	10	0.01	0.65	0.107	2.13
VDMS_kh190_sos20_1.0cm	0.01	0.0268	20	0.01	0.62	0.103	2.13
VDMS_kh190_sos16_1.0cm	0.01	0.0268	16	0.01	0.71	0.108	2.13
VDMS_kh190_sos10_1.0cm	0.01	0.0268	10	0.01	0.75	0.107	2.13
VDMS_kh190_sos10_2.0cm	0.02	0.0537	16	0.01	0.58	0.091	2.13

dp **is the initial particle interspace**

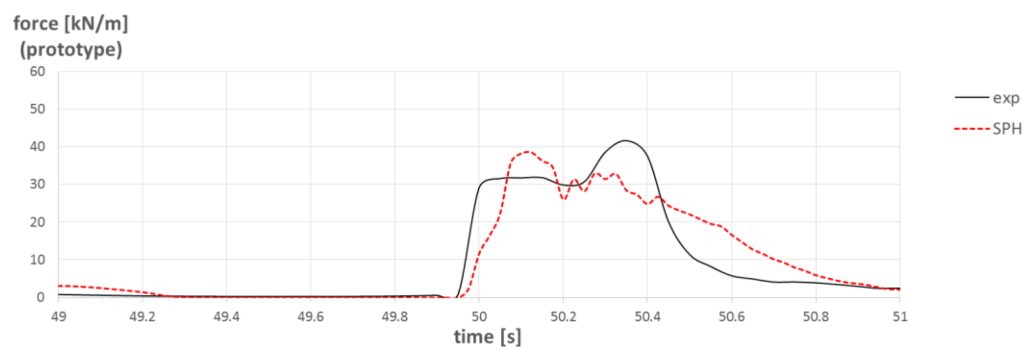
h **is the kernel length defined for a 2D case as h=k•dp•sqrt(2), where k has been assumed equal to 1.9 in this case. The kernel length defines the "interaction domain" around each particle, hence it is a realistic indication of the spatial resolution (modeling errors can be related more to the order of magnitude of h than dp).**

coefsound **is a coefficient that is used to calculate the speed of sound in the fluid, assuming a weakly-compressible fluid and Tait's equation of state relating the density to the pressure.**

α **is the coefficient of the artificial viscosity term in the equation of momentum conservation.**



(a)



(b)

Figure 9. Comparison between experimental and numerical impact force time series: (a) overview of full time series and (b) detailed view of single impact.

VALIDATION : FLOW-3D

Model setup

The validation is carried out for the two tests with berm length 0.6 m and 1.5 m. For both tests, the setup of the numerical domain is identical as for DualSPHysics, see Figure 7. The only difference is the position of the quay wall front due to the different berm length (the position of the sea wall is fixed): the quay wall front is located at x=20.058 m (berm length 0.6 m) and x=19.158 m (berm length 1.5m).

The piston wavemaker is operated using the moving object model in FLOW-3D. Thereto, piston control velocities are derived from the exact time series of piston displacements, as operated in the physical model test. Piston velocities are prescribed with a sample frequency f_s. The wave generation is operated in active wave absorption mode, which is based on the same AWASYS system as in the UGent wave flume (Frigaard and Christensen, 1994). However, the system uses a single-point velocity measurement as the input for the corrected piston movement, whereas the system in the physical wave flume is based on free surface measurements at two locations closely spaced in between (Vanneste, 2012).

Simulations are performed in 2D (1 cell in transverse direction). Uniform cell dimensions are used in the entire study, yielding the highest possible accuracy. Mesh boundaries are ‘free slip’, except at the right domain boundary, where an outflow condition is applied. The solid obstacles within the numerical domain (i.e. the quay wall, slope and sea wall) are modelled as ‘no slip’. The model is run in laminar flow mode, i.e. without a (RANS) turbulence model. The numerical time step dt is controlled automatically, based on stability limits. A maximum value $dt = f_s^{-1}$ is applied, due to the fact that the calculation of the filter convolution in the active absorption method is required at regular times instants f_s^{-1}, which is not fulfilled when dt exceeds this value. The most important numerical parameter settings are listed in Table 5. Parameters not included in this list have default settings. A simulation with the finest mesh (dx=0.01 m, 339k grid cells) took a total of 78 h computational time for 2287 s simulation time, on a 12 core Xeon 2.8 GHz workstation running FLOW-3D v10.1.

Table 5. Main numerical parameters used in FLOW-3D

Option	Set up	Parameter
Fluid	Incompressible	ICMPRS=0
Viscosity	Newtonian fluid	IFVISC=1
Viscous stress	Laminar	IFVIS=0
Turbulence	Laminar calculation	
Pressure solver	General Minimal Residual (GMRES)	IGMRES=1
Momentum advection	First-order, upwind explicit scheme	IMPADV=0, IORDER=1, ALPHA=1
VOF advection	Split Lagrangian method	IFVOF=6
Time step control	automatic	AUTOT=1
Maximum time step size	f_s^{-1}	DTMAX

Free-surface elevations are measured in the exact same positions as in the physical model, see Table 2. The location of the sea wall and overtopping measurement system is the same in both tests. The front edge of the sea wall is located at x = 20.658 m. Pressure gauges are positioned with a small distance in front of this location (at x = 20.65 m), in order to prevent issues which might be caused be a reduced effective representation accuracy of the sea wall in the model, which is related to the grid size. In order to measure the pressure distribution on the front wall, 10 measurement locations are distributed at equidistant locations along the height of the wall. In order to measure wave overtopping, a flux plane is created at x = 20.69 m, just behind the crest of the sea wall, in the declining part.

Simulation results: incident wave field

Time series of free-surface elevation are initially unaffected by wave reflection on the quay wall. Good agreement is observed between experiment and numerical model (dx=0.01 m) in Figure 10 (a), showing results for the test with 0.6 m berm length at a location close to the piston ($x = x_1$). After a while, the reflection pattern establishes and clearly differences between experimental and numerical model, see Figure 10 (b). Most probably, the loss of correspondence is caused by a difference in simulated wave reflection and differences in the operation of the active wave absorption method.

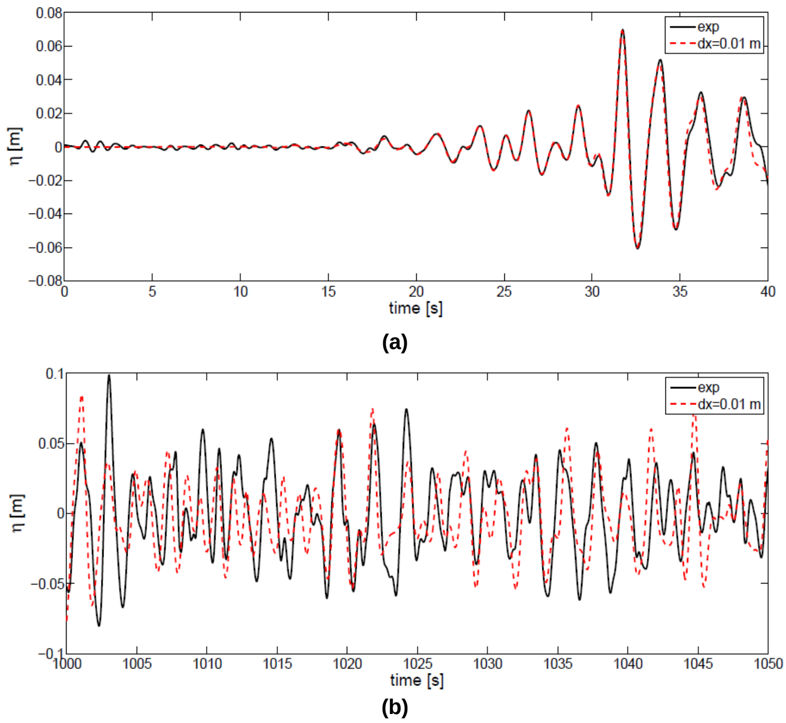


Figure 10. Comparison between experimental and numerical time series of free surface elevation: (a) good correspondence for pure wave propagation at $x=x_1$ and (b) loss of correspondence in disturbed wave field at $x=x_6$.

Notwithstanding the loss of correspondence in the instantaneous free-surface elevation in front of the quay wall, good agreement is obtained between experimental and numerical spectral incident wave parameters, shown in Table 6. The convergence in the numerical results of the reflection analysis moreover shows that the mesh resolution is sufficient.

Table 6. Reflection analysis of FLOW-3D results

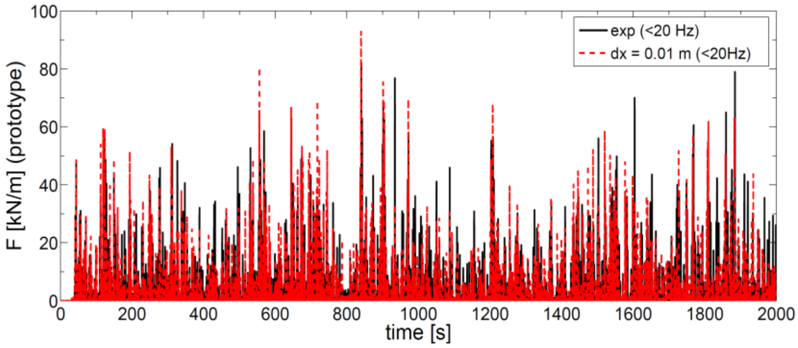
Test ID	dx [m]	f_s [Hz]	CR(f) [-]	H_{m0} [m]	T_p [s]
Physical model test 0.6 m berm length	**-**		***0.78***	***0.100***	***2.33***
SM_004_40Hz	0.04	40	0.78	0.098	2.33
SM_002_100Hz	0.02	100	0.79	0.099	2.36
SM_001_200Hz	0.01	200	0.80	0.101	2.36
Physical model test 1.5 m berm length	**-**		***0.79***	***0.103***	***2.44***
SM_001_200Hz	0.01	200	0.82	0.102	2.36

Simulation results: impact forces

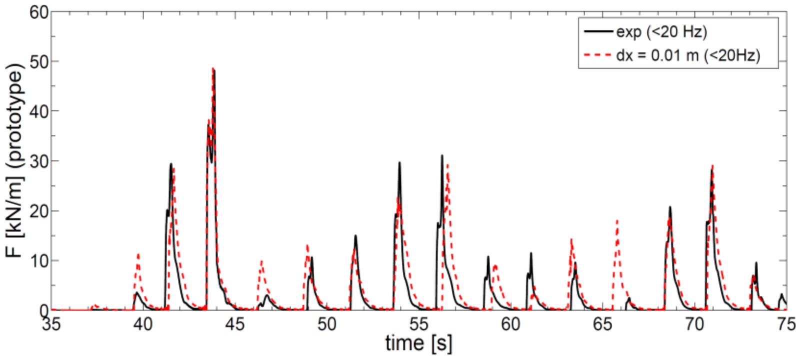
Impact forces are computed from discrete integration of pressure measurements in front of the sea wall. An import remark concerns the spikes observed in the pressure time series and consequently the time series of impact forces. These spikes are not physical but an artefact of the numerical model, since it runs under the assumption of an incompressible fluid and single-phase flow and thus cannot represent possible pressure oscillations caused by entrapped air. However, it is difficult to ascertain the exact cause of this numerical scatter. A known source for numerical pressure oscillations is the so-called 'checkerboard problem', associated with collocated grids. However, FLOW-3D uses a staggered grid arrangement in which pressure (at the cell center) and velocity (at the cell face) are intimately coupled.

Applying a low-pass filter to the force time series can have an significant effect on the retained level of the force peak. In the physical model, a cut-off of 20 Hz was applied, based on considerations related to the natural frequency of the measurement system including the force transducers. Here, two different cut-off levels are considered: 20 and 70 Hz .

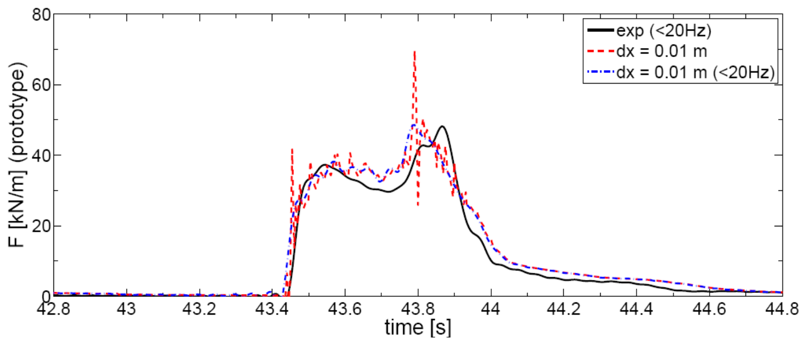
Figure 11 shows the impact force time series for the test with 0.6 m berm length. Figure 11 (a) and (b) show the correspondence between experimental and numerical time series (filtered at 20 Hz) of the full and a selected part of the total simulation, respectively. Figure 11 (c) shows a close up on one single impact with filtered and raw numerical data. The results of measured and simulated impact peak forces are shown in Table 7. It is noticed that in general, the specific value of the low-pass filter has a limited impact on the retained peak forces. Good agreement is observed, with numerical peak forces being slightly higher than measured values. The comparison between both tests shows that the length of the slope (1:100) in front of the sea wall has a limited effect on the maximum impact force.



(a)



(b)



(c)

Figure 11. Comparison between experimental and numerical impact force time series, test with 0.6 m berm length.

Table 7. Impact forces in the physical and numerical model (prototype values).

Test ID	dx [m]	f_s [Hz]	sampled/filtered [Hz]	F_{max} [kN/m]	$F_{1/250}$ [kN/m]
Physical model test 0.6 m berm length	**-**	**-**	***1000/-***	***91.4***	***78.3***
			1000/70	***91.1***	***80.1***
			1000/20	***82.3***	***77.1***
SM_001_200Hz	0.01	200	200/-	126.6	112.8
			200/70	116.2	106.1
			200/20	92.9	79.7
Physical model test 1.5 m berm length	**-**	**-**	***1000/-***	***86.8***	***79.9***
			1000/70	***79.9***	***75.6***
			1000/20	***80.3***	***73.6***
SM_001_200Hz	0.01	200	200/-	92.6	82.6
			200/70	88.7	80.6
			200/20	87.9	75.0

Simulation results: wave overtopping

The overtopping in the numerical model is deduced directly from the code, using a flux plane defined at x = 20.69 m. Instantaneous overtopping rates cannot be accurately compared, due to the relatively small rate (5Hz) at which samples of the balance signal were recorded in the physical experiments. Instead, time series of the cumulative water mass flowing over the sea wall are verified.

The average overtopping rate q_{avg} is derived from the total simulation duration, encompassing approximately 1000 waves. Results are shown in Table 8. For the test with 0.6 m berm length, the average numerical overtopping rate is higher than what is measured experimentally, although the agreement can be considered as fairly good. In the test with 1.5 m berm length, the longer slope in front of the sea wall clearly reduces the overtopping. Very good agreement is observed in this case between the experimental and numerical average overtopping rate.

Figure 12 shows the comparison between the time series of cumulative overtopping mass. In Figure Figure 12 (a), corresponding with the shorter berm in front of the sea wall, the cumulative mass curve shows a roughly uniformly increasing trend, both numerically and experimentally.

Table 8. Comparison of average overtopping discharge (prototype values).

Test ID	dx [m]	q_{avg} [l/s/m]
Physical model test 0.6 m berm length	**-**	**2.58**
SM_001_200Hz	0.01	3.58
Physical model test 1.5 m berm length	**-**	**0.96**
SM_001_200Hz	0.01	1.01

It is noticed that experimental and numerical overtopping events in Figure 12 (a) are synchronized fairly well. The cumulative mass curve for the longer berm case in Figure 12 (b) is different from the shorter berm case in Figure 12 (a). Both the numerical and experimental results show a large overtopping event at the start of the simulation (which is slightly underestimated by the numerical model), followed by a gradient in the cumulative mass curve which is significantly smaller compared to the test with the shorter berm. In the numerical simulation, a second large overtopping event is registered at the end of the simulation, which is absent in the experimental tests. The image of the cumulative overtopping mass, showing scarce events (~1/1000) with larger overtopping, suggests that one should use the statistics of the wave overtopping in the design process with precaution. A particular point of attention to the experiments backing the design is to employ wave time series with a sufficient number of waves and to use multiple time series with sufficient variation of the wave-by-wave incidence.

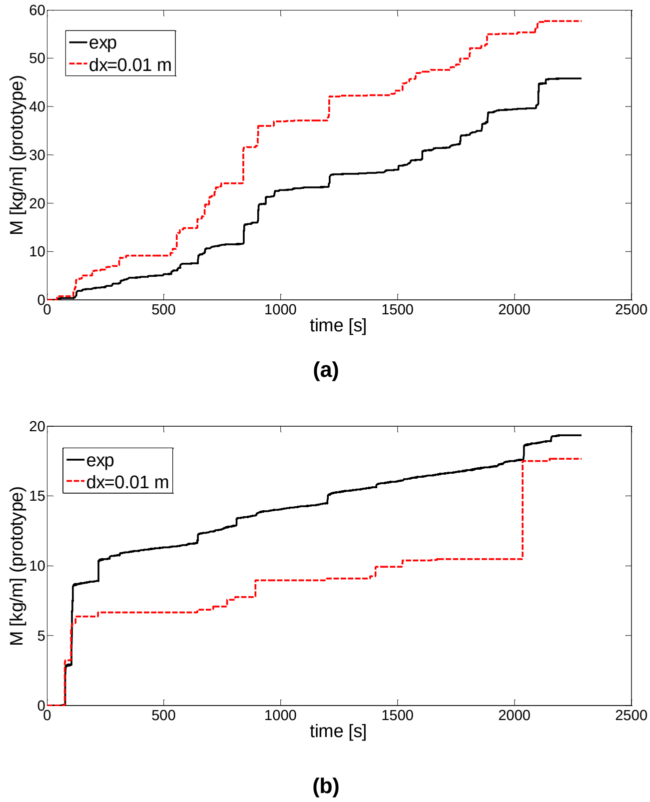


Figure 12. Comparison between experimental and numerical time series of cumulated overtopping mass (prototype values) for tests with (a) 0.6 m berm length and (b) 1.5 m berm length. Both numerical results are computed with dx=0.01 m , f_s= 200 Hz.

CONCLUSIONS

Numerical modelling is used to support the design of a sea wall, in a configuration with a quay wall and mildly sloping berm in front of it. The paper presents the results of a validation study for three different models: SWASH, DualSPHysics and FLOW-3D. Experiments in the wave flume of Ghent University were used to validate the modelling accuracy and compare the efficiency between the different models.

For the first model SWASH, average overtopping discharges over a simple quay wall case agree reasonably well with predicted values by Eurotop. In the quay-berm-sea wall configuration, the average overtopping discharge predicted by SWASH is found to be significantly lower than the experimental value. In this respect, it is mentioned that the simulations have been performed only with one layer. Further investigation is needed to draw conclusions regarding the modelling performance of SWASH in such case.

Both DualSPHyscis and FLOW-3D, based on the full Navier-Stokes equations provide good estimates of the wave impact on the sea wall. Simulation of the full time series has only been performed with FLOW-3D. In this case, reasonable agreement with experimental values of averaged overtopping discharges was found.

Since the hardware configuration on which the FLOW3D and DualSPHysics models were run is not comparable, it's not possible to rigorously compare the computational efficiency of both models. Nevertheless, the calculation times obtained with both models have the same order of magnitude and prove to within reach of common computational infrastructure nowadays available. The simplicity of the SWASH model enables a significant reduction in computational effort compared to the other two models, but needs further investigation to ascertain its limitations in more complex cases of wave interaction with hard structures.

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