COMPARISON OF VALIDATION STUDIES OF WAVE-PENETRATION MODELS USING OPEN BENCHMARK DATASETS OF DELTARES

by

***P. (Pepijn) P.D. van der Ven*[1]*, S. (Bas) P. Reijmerink*[1]*, A. (Arne) J. van der Hout*[1]**
***and M. (Martijn) P.C. de Jong*[1,2]**

ABSTRACT

This paper presents a collection of open benchmark datasets. These datasets are made available by Deltares for numerical model validation studies, including port applications such as wave penetration models and tools for computing wave forces exerted on moored ships. The paper summarises the contents and characteristics of each available dataset. Furthermore, the paper makes a comparison of different validation studies that have used specific parts of these datasets to this date. This comparison is made to illustrate the possibilities of using these datasets, but it also highlights remaining questions and challenges related to numerical model validation. Researchers, engineers and advisors working on related topics are encouraged to contact Deltares to explore cooperation possibilities using these benchmark datasets.

1. INTRODUCTION

Downtime in ports is often dominated by the local nearshore wave climates and the resulting wave penetration into port basins. Geometry complexities and specific bathymetric influences, such as the effect of entrance channels, will complicate the description of wave penetration into ports and may make verifying wave conditions in relation to expected port downtime far from trivial (De Jong *et al.*, 2016, PIANC COPEDEC).

Wave conditions inside ports can be determined during the port design process with physical scale model tests or with numerical tools. Scale model tests can be considered the most complete way of design verification prior to construction. However, particularly in early stages of design numerical methods are generally preferred. Several types of numerical wave models are available, including spectral models, mild-slope models, Boussinesq-type models and (multi-layer) flow models adapted to represent also short waves. These different types of numerical wave models all have their own specific advantages and drawbacks. And although the fundamentals of such wave models have generally been validated in detail, validation of the performance of these numerical models for representing wave penetration into ports has often been rather limited. One of the main reasons for this is that datasets for validation are quite scarce. As a result, downtime estimates based on the outcomes of insufficiently validated numerical models may be inaccurate and unreliable.

Field measurement datasets for model validation are often limited in duration, cannot describe future situations, will typically not cover extreme conditions and may include only a few observation locations. To complement and extend such data, over the past decades Deltares has performed several elaborate physical scale model tests on wave penetration in different port layouts, under a wide range of controlled wave conditions and always including several measurement locations. These test series ranged from specific existing (or planned) port layouts to more schematic situations. The former were aimed at verifying the performance of specific port extension plans, whereas the latter were intended to highlight and record specific aspects of the wave penetration process. Some of the test series from the latter collection have been especially designed to serve as (schematised) validation material for numerical wave penetration models. Having these different datasets available has allowed Deltares to validate its numerical wave penetration tools in detail and it has given us detailed insights into the capabilities and limitations of different types of numerical wave penetration models (see e.g. De Jong *et al.*, 2016).

Deltares wants to make a part of its archived wave penetration datasets available to interested parties, so that they can use them in their research initiatives on numerical model validation in consultation with Deltares. It is our intention to maximize the usefulness of these datasets by sharing them with

[1] Deltares, PO Box 177, 2600 MH Delft, The Netherlands
[2] Communicating author, tel. +31 88 335 8596, martijn.dejong@deltares.nl

others and by jointly working on the validation and development of numerical wave models and on related computational tools for ports, such as calculating wave forces exerted on moored ships.

Even though already quite some studies by others and by Deltares have used the datasets presented in this paper, these data still form a valuable collection for future work. This is because parts of the presented datasets have not yet been exploited in model validation studies, and because so far only a limited set of specific models (model types) has been considered. Furthermore, parts of the validation outcomes obtained so far have been inconclusive and still require further analyses, as will be illustrated in sections further below.

The present paper summarises the contents and characteristics of the three available datasets by Deltares (Section 2). The largest part of this paper (Sections 3 to 5) consists of a comparison of a selection of the different validation studies that have used specific parts of the datasets to this date. Those earlier studies typically focussed on validating a specific numerical model, using a selection of data from the available test series. This paper presents for the first time an inter-comparison and an overarching analysis of those different results obtained based on these measurements by Deltares. This comparison is made to illustrate the potential use of these datasets, but it also highlights remaining questions and challenges related to validating numerical methods. The comparison focusses on two of the three presented datasets, since only a few studies have used the third dataset to this date and because a separate publication is foreseen on those tests. The paper ends with conclusions on the presented datasets and on the comparison of earlier studies using those data (Section 6).

Both the description of the available datasets and the comparison of earlier validation studies are meant to serve as a starting point for further cooperation with interested parties.

2. AVAILABLE OPEN DATASETS BY DELTARES

2.1 Overview of available open datasets

Table 1 gives a summary of the datasets that Deltares intends to make available to parties interested in a joint research effort on the validation of numerical methods. The available datasets include one full port layout, a schematic port layout with a captive ship (to enable the measurement of wave forces acting on the ship) and a series of schematic port layouts of increasing complexity. In the following sections the contents of each of these datasets is described in more detail. In the future we plan to extend the collection of datasets with other port situations.

Table 1: overview of available datasets

Number	Short name/reference	Compact description
1	schematic rectangular port layout with a captive ship	A large dataset of different wave conditions with a captive ship in open water and inside a schematic port layout. Conditions considered involve high waves as well, to allow the assessment of non-linear wave phenomena.
2	full port layout	This is a dataset that includes only wave parameters (H_s, T_p). However, it is useful dataset since it describes an existing port layout, a wide range of wave conditions and different construction phases of the port layout.
3	series of different schematic port layouts	This is a dataset generated specifically for wave model validation purposes and includes a systematic variation of geometry and wave conditions (regular, irregular, long/short-crested). The starting point was deliberately very simple, i.e. a rectangular basin, and complexity was added in the course of the measurement campaign (side basin, breakwater).

2.2 Dataset 1 – Captive ship in rectangular basin

An extensive measurement campaign was undertaken in 2003 in the large directional wave basin at Deltares (back then Deltares was named WL | Delft Hydraulics). The main situation measured consisted of a vessel moored in a schematic harbour basin (Figure 1 and Figure 2).

A scale of 1:100 was used for the measurements, leaving ample space in the basin (40x40 m)[3] for rubble mound slopes along all the outer vertical walls of the basin (Figure 1) to ensure sufficient damping of wave energy and avoiding as much as possible any spurious waves in the scale model.

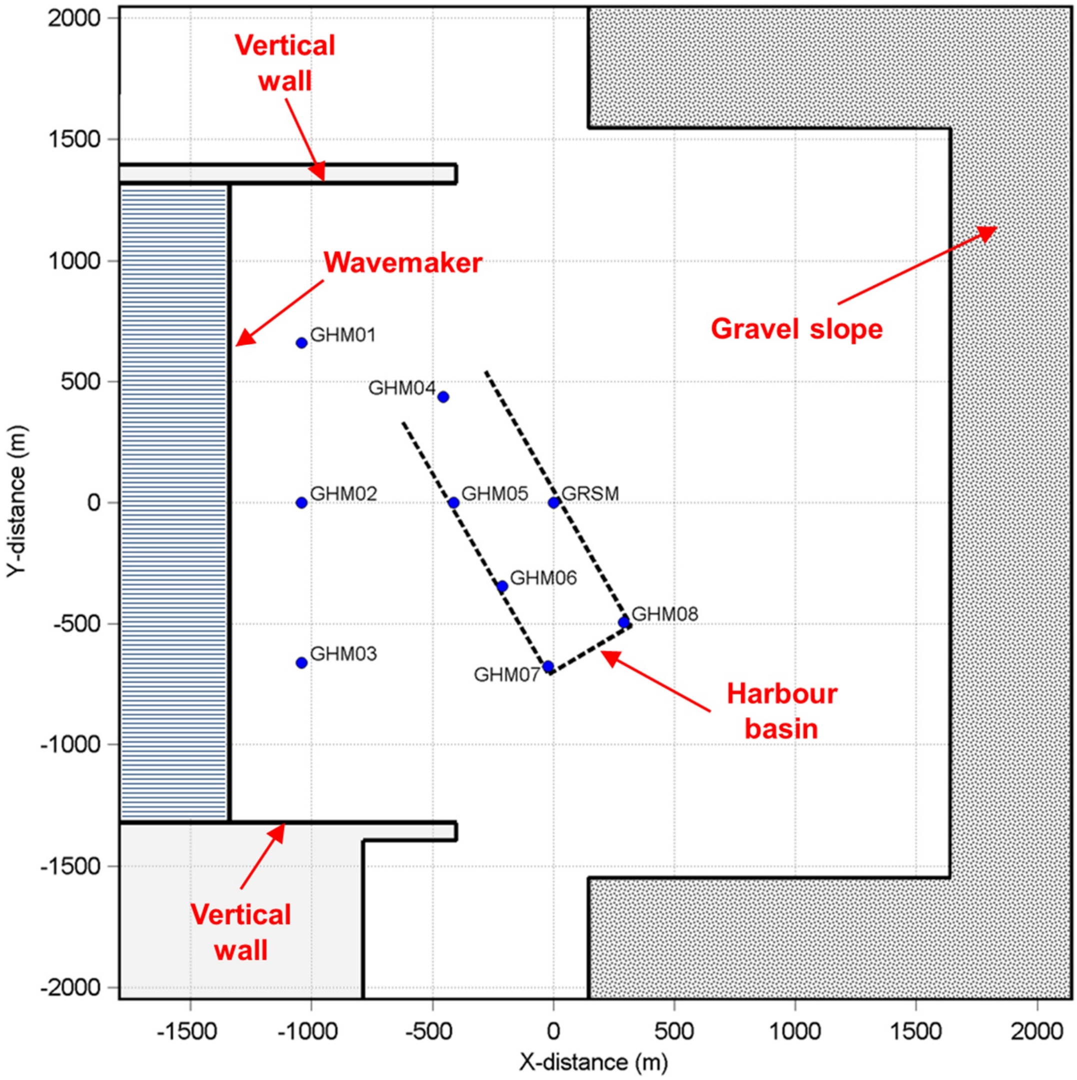


Figure 1: schematic plan view of the measurement setup of Dataset 1.

The following series of tests were performed for Dataset 1:

- Wave measurements in open water
- Measurements of wave-induced forces and moments on a vessel in open water
    - Regular and irregular wave conditions
    - Passing-ship events (focussing on secondary waves generated by the wave maker)
- Wave measurements including a schematic port basin
- Measurements of wave-induced forces and moments on a vessel in a schematic basin

A part of the test series included a 1:100 scale model of a containership (length: 255 m, width: 32 m, further details available). The ship was held captive in a rigid force measurement frame (Figure 3), allowing measurement of wave forces exerted on the ship. Situations without the vessel present were considered to measure the undisturbed incoming wave conditions. These were compared to measurements of the same wave conditions with the vessel present to assess the influence of diffraction of waves around the vessel.

---

[3] Since then this directional wave basin has been upgraded to outer dimensions of 50x50m and a new directional wave maker has been inserted of 40m length with state-of-the-art active reflection compensation.

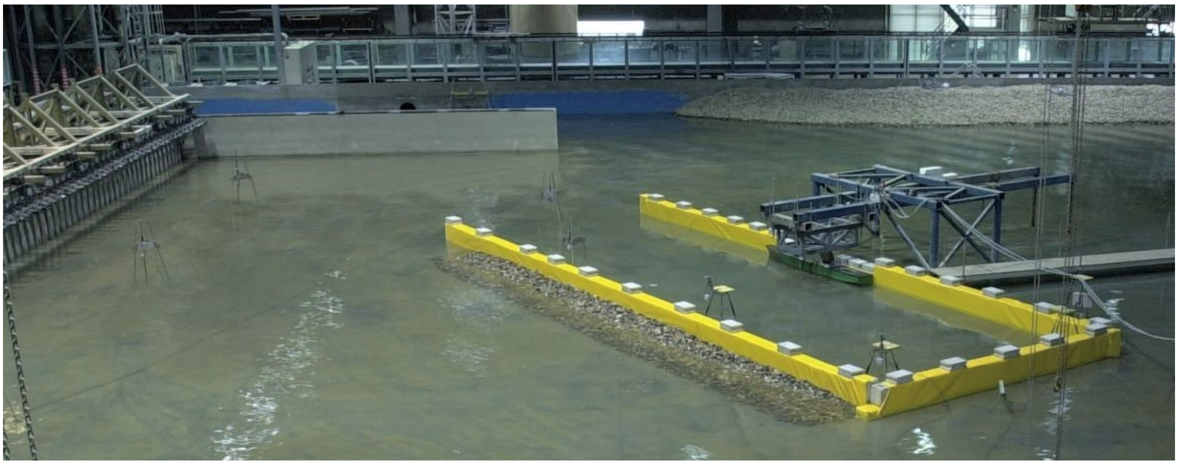


Figure 2: overview photo of a moored ship in a schematic representation of a harbour basin in the large directional wave basin of Deltares (the photo shows only a part of the basin).

The measurement campaign also included test series in open water that were intended for developing and verifying wave directionality analysis methods. The measurement locations used for this purpose included five wave probes distributed evenly on a circle, resulting in a pentagon shape. The applied radius of the circle was 75 m (prototype scale). A wave height probe was placed at the centre of the pentagon to obtain the wave signal at that location for comparison.

JONSWAP wave spectra from multiple main directions were generated, with different wave parameters. The generated waves included second-order wave forcing. The following wave parameters (prototype scale) have been used:

- T_p: 7, 10 and 15 s;
- H_s: 0.5 and 1.5 m;
- direction relative to wave board (α): 60, 90 and 120º;
- unidirectional waves;
- directional spreading (ψ): $\cos^2$ and $\cos^4$.

Figure 3: detail of moored ship held captive in the scale model (open water reference tests).

Additional test series were performed of schematic passing-ship events (wakes/secondary waves). These test series included the vessel measurement setup in open water (Figure 3). The passing-ship effects were mimicked by serial movements of the individual panels of the wave maker (vessel speeds of 12 m/s and 21 m/s, i.e. a subcritical and a supercritical vessel speed, respectively). Even though the wave maker can only make a rather crude approximation of a passing-vessel event (e.g. the panels in the shallow-water wave basin move the entire water column, whereas in reality the vessel would only occupy the upper part), these situations do provide interesting validation material.

All conditions included a water depth of 20 m and each measured irregular wave condition lasted 1800 s (prototype scale) or longer to obtain statistically representative results.

2.3 Dataset 2 – Complete port layout

The second dataset consists of scale model tests for the Port of Limassol. The city of Limassol is located along the south coast of the Mediterranean island of Cyprus, see Figure 4 for a situation sketch. Around 1990, Deltares (back then called WL | Delft Hydraulics) carried out these physical model experiments[4] to advise on the best approach for a planned port extension.

Figure 4: location and present layout of the port of Limassol, Cyprus.

Physical model experiments were carried out on a scale of 1:100 for three main directions of wave incidence, i.e. 80°, 100° and 130°N. Breakwaters were constructed in the physical scale model using rubble mound. The considered wave conditions (Table 2) included long-crested and short-crested conditions (m = 2, σ = 31.5°). In total 46 scenarios were measured. Wave heights were measured at up to 28 positions, including a number of locations outside the port for wave calibration purposes. Recorded wave data were filtered for the high-frequency part of the spectrum (0.05-0.5 Hz) and the low-frequency part (<0.05 Hz). Significant wave heights were recorded for both frequency ranges separately. Due to data storage limitations at that time, full time series were not archived and only processed wave parameter values were stored.

Table 2: wave conditions considered in Dataset 2.

Wave direction	Type of wave field	Operational		Extreme (once per year)	
		H_s (m)	T_p (s)	H_s (m)	T_p (s)
80°N	Short and long-crested	1.75	6.0	2.50	7.00
100°N	Short and long-crested	1.75	6.0	2.50	7.00
130°N	Short-crested	1.75	6.0	4.00	9.00

In total four layouts were considered (Figure 5), including the – back then – existing situation ('Hm0') for reference. Layouts were tested with and without vessels at the berths. The former were aimed at measuring the influence of local wave conditions on the moored ships, whereas the latter focussed only on wave penetration in the overall port layout.

Following the work by Deltares (WL | Delft Hydraulics) the port selected the western basin and the elongated breakwater to be constructed, which remains the existing situation to date.

2.4 Dataset 3 – Series of schematic port layouts

Dataset 3 consists of a dedicated measurement campaign that was performed to generate validation cases for different wave penetration software (Van der Ven, 2016). Three schematic port layouts (Table 3) were considered in the extended directional wave basin of Deltares (Delta Basin), which presently has outer dimensions of 50x50 m. This basin includes a 40 m wide wave maker. These tests were performed at scale 1:45. The port layouts considered were deliberately quite schematic, partly because that would provide the most straightforward validation situations and results, but also partly because of research budget restrictions. A total of 86 wave conditions were measured, including monochromatic waves, bi-chromatic waves and full wave spectra (JONSWAP). The test programme

[4] The tests for Dataset 2 were performed in a predecessor of the basin used for Dataset 1 (Figure 1). The tests facility used for Dataset 2 included a wave maker of 25.6 m length.

included a wide range of incoming wave heights (0.5 m to 9.5 m) and wave periods (4.5 s to 17 s), aimed at generating a dataset that would have a wide applicability (mild and severe wave conditions). Measurements included 22 wave height probes (estimated accuracy 0.5%) and five directional wave height probes (estimate accuracy 1%). These probes were positioned in front of and inside the schematic port basin geometry. The coordinates of the measurement locations are described in Van der Ven (2016).

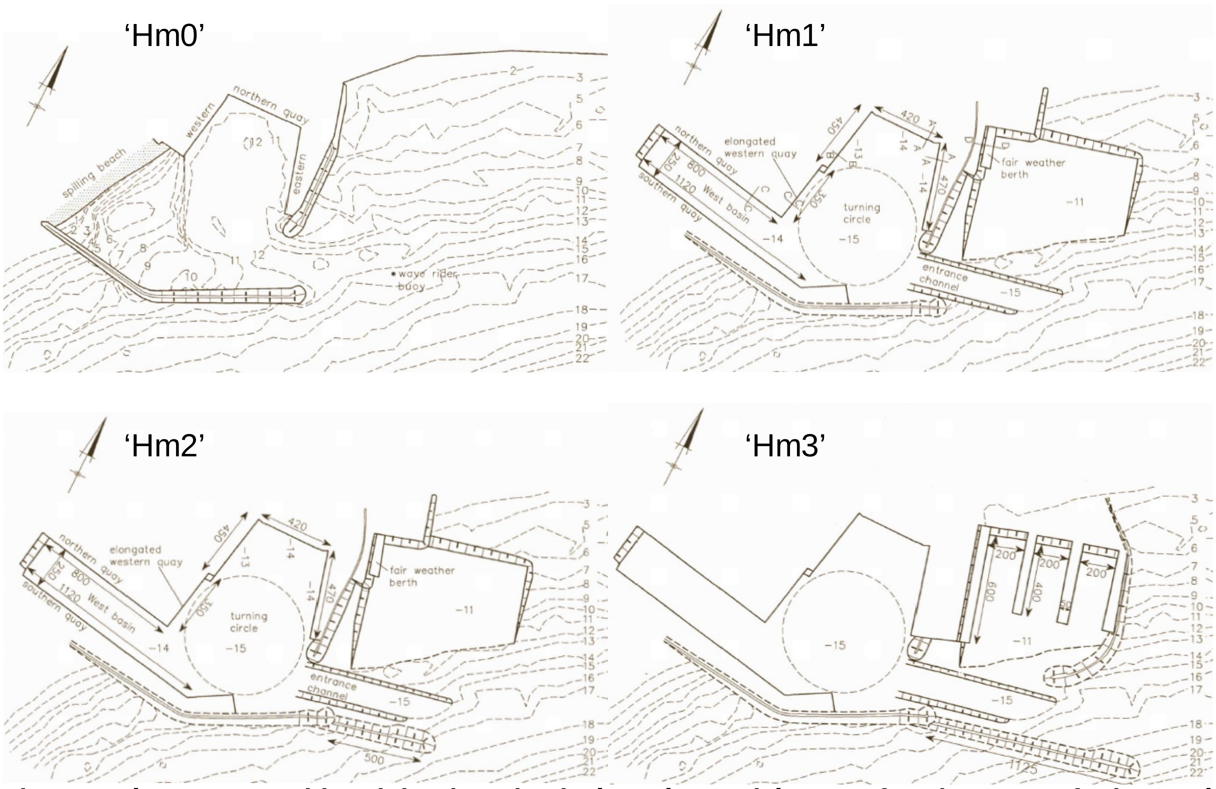
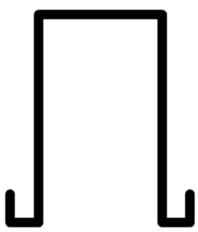
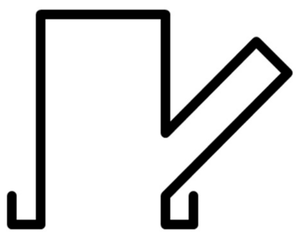
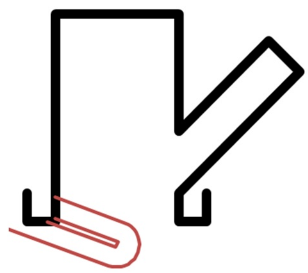


Figure 5: layouts considered in the physical scale model tests for the port of Limassol (Dataset 2).

Table 3: the three layouts considered for Dataset 3

Harbour contour Breakwater	**Layout 1** 	**Layout 2** 	**Layout 3** 
Governing wave processes	Reflection Harbour oscillations	Reflection Diffraction Harbour oscillations	Reflection Diffraction Refraction over the breakwater slope Transmission Harbour oscillations
Eigenmodes	Trivial	Less trivial	Several, increased complexity

The measurements started with a plain basin layout and additional complexity – a side basin and a breakwater – was added in two steps (Table 3). As an example, Figure 6 shows the most complex layout that was included in the final part of the test series.

Figure 6: photograph of the most complex model setup considered in Dataset 3 (Layout 3).

3. COMPARISON OF VALIDATION STUDIES USING DATASET 1

Dataset 1 has been used by De Jong *et al.* (2005), Van der Molen (2006), Dobrochinski (2014), Rijnsdorp (2016) and Wong (2016). Below we describe a selection of these studies as examples of how the information included in this dataset has been used to this date.

De Jong *et al.* (2005) used Dataset 1 to extend and illustrate the application of a phase resolving wave splitting method (Directional Phase Resolving Analysis, DPRA, originally introduced in Janssen *et al.*, 2001). Methods that allow to split a number of local surface-elevation time series (measured or computed) in separate wave components are very useful for (moored) vessel applications in and around ports, since the motion response of a vessel in complex wave conditions depends not only on the local wave height and wave frequency, but also on the wave phases and directions of the multiple wave components typically present at such locations. De Jong *et al.* (2005) considered a selection of wave height measurements from a circular array (a pentagon, hence 5 different time series). In the considered method, the full directionally spread wave system in the basin is mimicked using a small set of discrete directions. The splitting method determines a representative wave spectrum in each of these pre-selected discrete wave directions. The outcomes of the method showed that the wave signal at the centre of the pentagon could be forecasted with rather high accuracy using only three main wave directions to mimic the full directionally spread wave field (e.g. for T_p = 15 s, α = 90º, H_s = 1.5 m and $\psi = \cos^4$, correlation coefficient 0.91, time series not reproduced here).

The wave signals in the three main directions were converted to wave forces exerted on a moored vessel in open water by applying linear response amplitude operators (RAOs). The force contributions from each of the main directions were then summed to represent the influence of the full directionally spread wave system. Even though only three main directions were used to mimic the effect of directional spreading in the wave field, the accuracy of the calculated forces improved significantly compared to assuming only one main wave direction (Table 4). In the latter case the measured signal is assumed to correspond to unidirectional waves propagating in the main direction of the generated wave field, thereby neglecting the influence of directional spreading. Although relatively crude, similar methods are still frequently used in nautical / vessel motion applications.

The time series of wave forces and moments determined with the phase resolving splitting method (Figure 7) show a good correspondence with the measured forces on the ship. The accuracy found may well be within practically acceptable limits. An exception is found for roll (see also Table 4). Already during first interpretations of the measurements this was attributed to a side effect of the method that was used to derive this parameter from the signals of the force probes included in the scale model set-up: the value for roll needed to be calculated by determining the difference between two signals with relatively high values; a relatively small measurement error in one of the probes therefore could have easily resulted in a relatively large error in the value for roll.

Table 4: correlation coefficient between calculated and measured forces and moments (from De Jong *et al.*, 2005).

parameter / method	Fx surge	Fy sway	Fz heave	Mx roll	My pitch	Mz yaw
Measured wave signal, no directional spreading included	0.77	0.71	0.73	0.36	0.74	0.73
Directional spreading approximated by 3 wave directions	0.94	0.96	0.96	0.64	0.93	0.90

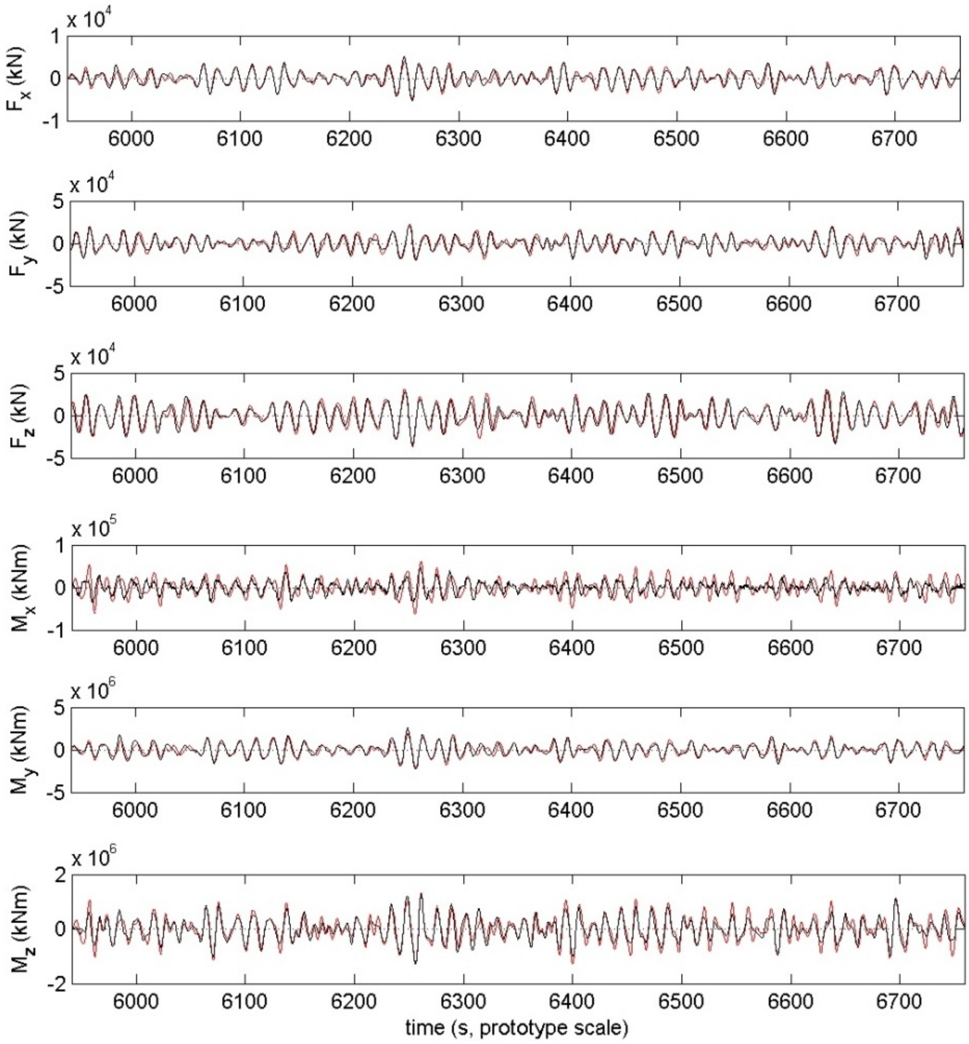


Figure 7: measured (black) and computed (red) forces and moments on the studied ship (top to bottom: surge, sway, heave, roll, pitch and yaw) (from De Jong *et al.*, 2005)

Van der Molen (2006), amongst other analyses not considered here for brevity, used parts of Dataset 1 to validate an approach for calculating the wave-induced forces on the captive vessel. He describes a similar comparison as shown in Figure 7, but now based on measured wave conditions close to the wave maker translated to the location of the ship in open water using linear wave theory.

He combined the outcome of that method with a strip theory approach to compute the corresponding wave forces on the captive vessel. The results that he presents for H_s = 6 m, T_p = 15 s (Figure 8) show quite a good agreement with the measured time series, albeit with the same issues for the roll component, as explained above.

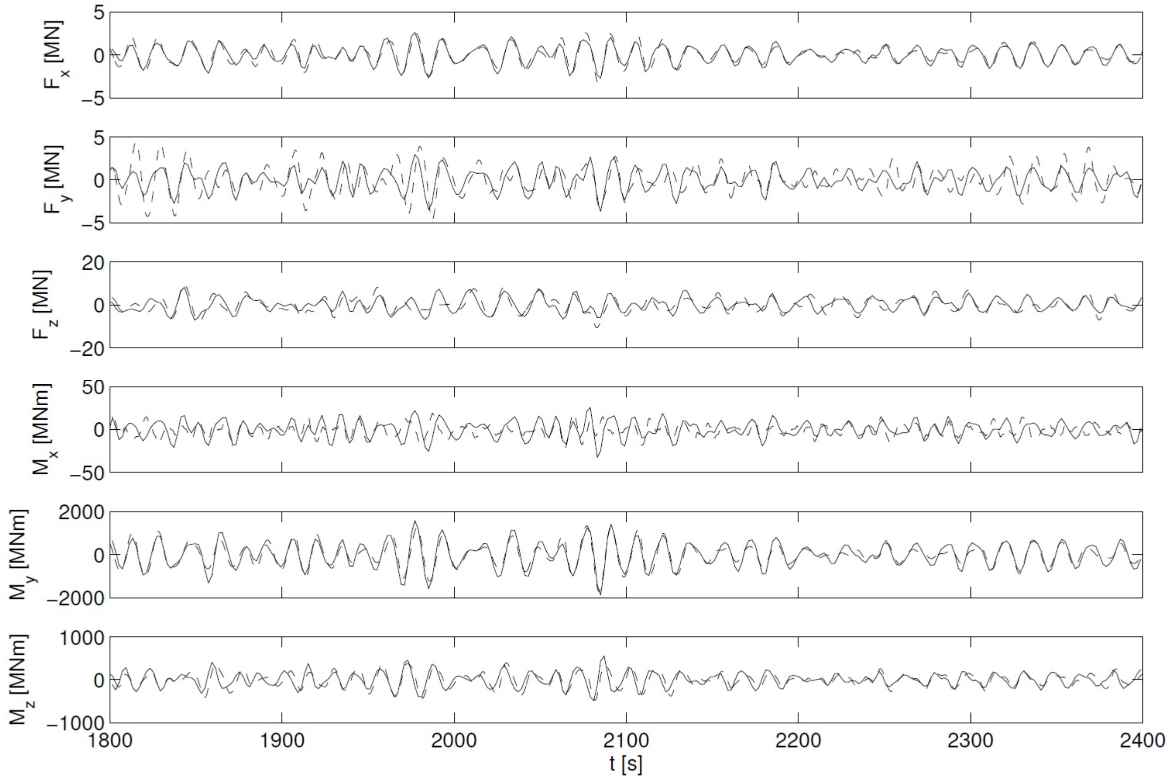


Figure 8: comparison of wave forces in open water; H_s = 1.5 m, T_p = 15 s, 210º relative to ship; – – measurements, ── strip theory (from Van der Molen, 2006).

More recently, Dobrochinski (2014) used the numerical model SWASH to reproduce a selection of the measurements included in Database 1. SWASH (an acronym of Simulating WAves till SHore) is a non-hydrostatic wave-flow model that is used in multiple vertical layers (Zijlema *et al.*, 2011). For computing forces and moments on the captive vessel the SWASH wave model was coupled by Dobrochinski to a boundary-integral diffraction model, originally developed and applied by Van der Molen (2006). Dobrochinski (2014) analysed primary waves (sea and swell) and infragravity waves from the SWASH model using two or three vertical computational layers. After calibration of the numerical wave model, the spectral results for a selection of tests in open water (not reproduced here) showed that the numerical wave model was capable of simulating the correct spectral shape of the primary waves at the considered measurement locations. Also the measured and computed spectra of forces and moments on the ship in open water showed a rather good agreement.

Condition C3 from Dobrochinski (2014), i.e. H_s = 6 m, T_p = 15 s, $\cos^4$ directional spreading, main direction 30º and including the schematic port basin, is used here to illustrate the main findings from that work. Figure 9, from Dobrochinski (2014), depicts the computed results for this condition. The dashed line in the right panel of Figure 9 indicates the extent of a damping slope that was placed in the scale model alongside the outer wall of the schematic port basin to reduce wave reflections of this part of the port layout directly facing the wave maker (see also Figure 2).

Dobrochinski (2014) describes comparisons of measured and computed total wave heights and low-frequency wave heights (T>33 s). The average difference found is around 6% for the total significant wave height and around 12% for the low-frequency wave heights, with only a few marked outliers at specific locations. The wave spectra for this condition (Figure 10) show quite a good agreement between the computation and the measurements, including the peaks measured in the low-frequency spectrum. These results indicate that the numerical model is capable of capturing (parts of) the complex processes governing high-frequency and low-frequency wave generation and propagation. A fair agreement was also found by Dobrochinski for the resulting computed forces and moments acting on the vessel moored inside the schematic port basin (not reproduced here).

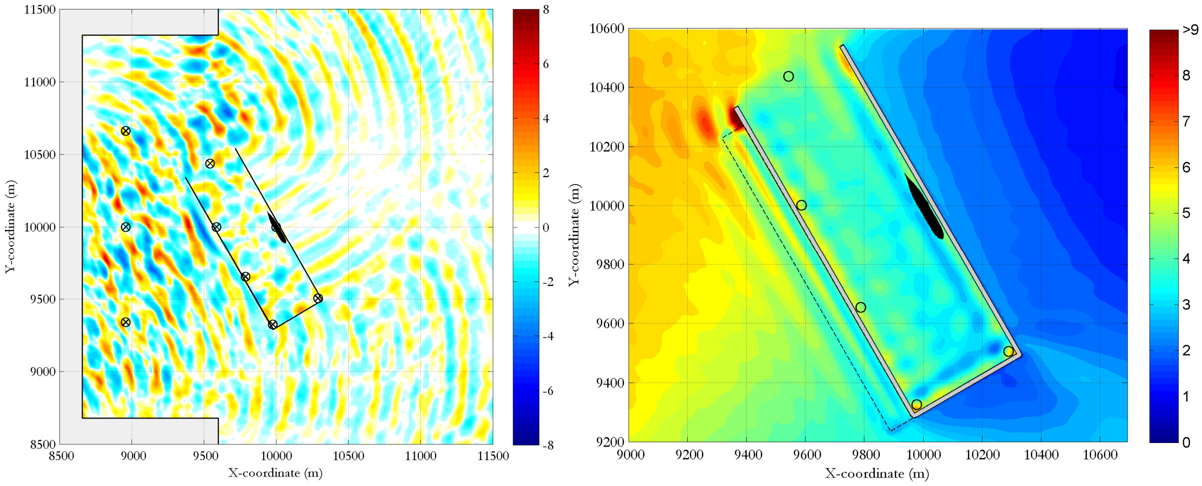


Figure 9: left panel: snap shot of the computed surface elevation inside the scale model basin; right panel: significant wave height inside and around the schematic harbour basin. H_s = 6 m, T_p = 15 s, cos^4 directional spreading, main direction 30º (from Dobrochinski, 2014).

Dobrochinski (2014) finds that quite a high bottom friction had to be applied in the SWASH model for the situations including the schematic port basin (the 'C' series in his report, including cases with H_s = 3 m and H_s = 6 m) to match the primary and low-frequency wave heights. He ascribes this to scale effects in the laboratory measurements. This is striking, since other studies using the same data or datasets from the same or a similar basin at the same model scale (some examples are discussed further below) did not report this effect at all. Therefore, bottom friction may not be the ultimate explanation of the discrepancies found. Other possible causes for the apparent overestimation of the wave heights in the (uncalibrated) numerical model could be specific choices in numerical model settings and schematisations.

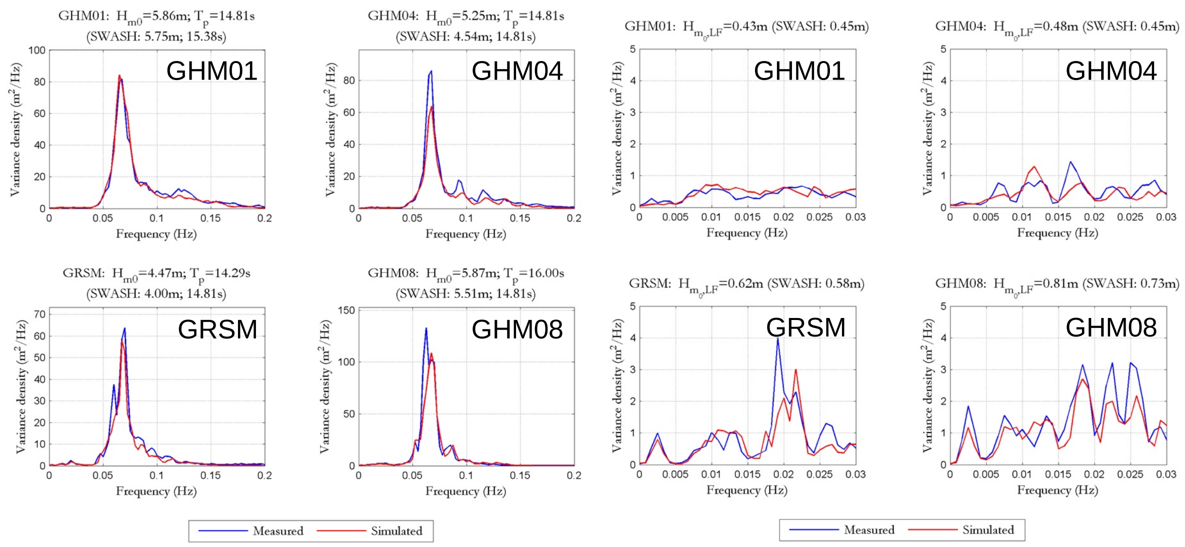


Figure 10: wave spectra of measured and computed wave conditions for Case C3. Left set of four panels: total frequency range; right set of four panels: low-frequency range (from Dobrochinski, 2014). See Figure 1 for the numbered locations.

Also Rijnsdorp (2016)[5] considered a selection of conditions from Database 1 in the model SWASH, including situations with and without the schematic port basin (up to and including H_s = 3 m). He applied the default (low) bottom friction value and does not report a systematic overestimation of wave heights in the SWASH computations compared to the measured conditions. We hypothesise that a possible explanation for this may be the use of a different computational scheme in the numerical model than was used by Dobrochinski (2014). Regardless, even though Rijnsdorp only considered the schematic port basin layout for the lower of the wave heights considered by Dobrochinski (i.e. a smaller importance of non-linear influences), this could very well indicate that scale effects related to bottom friction were not the main reason for the wave height discrepancies found in Dobrochinski (2014). As discussed above, the detailed causes of those discrepancies still need to be identified.

Before describing his validation results, Rijnsdorp (2016) first states that relatively large measurement errors are to be expected with the approach taken in tests of Dataset 1 for measuring wave-induced forces on the captive vessel, particularly in the measured moments. Building on that premise, he then ascribes the discrepancies between measured values and results from his computations, both for open water situations and with the schematic port basin, mostly to those hypothesised inaccuracies in the scale model measurements. Figure 11 shows an example of his results for the situation with the schematic port basin, H_s = 3 m, T_p = 10 s, $\cos^2$ directional spreading.

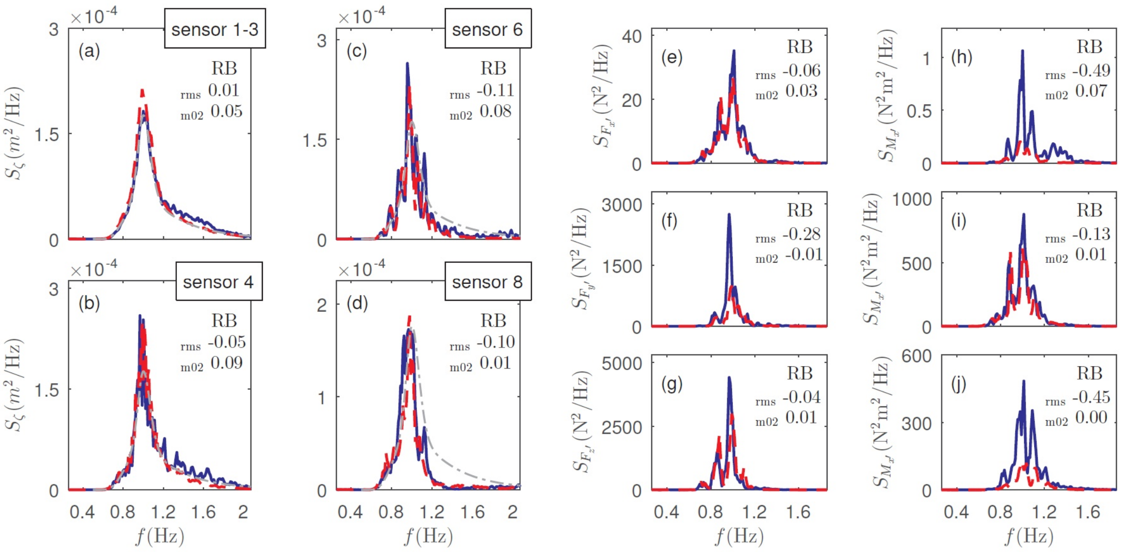


Figure 11: Predicted (red line) and observed (blue line) spectra of the surface elevation S_ζ(a), and the forces S_F (b-d) and moments S_M acting on the ship (e-g) for a condition with the schematic port basin (from Rijnsdorp, 2016). See Figure 1 for the location numbers.

This general expectation of a limited accuracy of the force probe measurements is contradicted by the findings from both De Jong *et al.* (2005) and from Van der Molen (2006), described above, which showed quite a good agreement between computed and measured times series of the three forces and of the pitch and yaw moments (Figure 7 and Figure 8). The good agreement reported in those studies, based on two different computational methods, indicates that fundamentally the measurements of those degrees of freedom – i.e. aside from the known issues for the roll measurement – did not particularly suffer from low accuracy as a result of the scale model setup. This means that the cause of the discrepancies identified in Rijnsdorp (2016) for degrees of freedom other than roll should be sought in other (numerical) modelling aspects, either in the description of the wave conditions in SWASH, in the approach used for representing the vessel inside the computational domain or in his method for deriving the resulting wave forces and moments acting on the vessel. Those alternate possible causes are only briefly considered in Rijnsdorp (2016), mentioning the possible influence of leaving out the bulbous bow in the representation of the vessel in the numerical wave model and the coarse vertical resolution applied in the SWASH schematisation.

---

[5] We cite here the PhD Thesis of Rijnsdorp. These same results have also been published as part of: Rijnsdorp, D.P. and M. Zijlema (2016): Simulating waves and their interactions with a restrained ship using a non-hydrostatic wave-flow model, *Coastal Engineering*, 114, 119–136.

4. COMPARISON OF VALIDATION STUDIES USING DATASET 2

Three studies have so far considered (parts of) Dataset 2. Here we use one specific wave condition and layout to illustrate typical results, which has been considered in all three studies. It involves Layout Hm1 (top right panel in Figure 5), which resembles the present situation, aside from the lacking extension of the main breakwater. The selected wave condition has an incident wave direction of 80°N and is represented with a JONSWAP spectrum with a peak period of T_p = 7 s, a peak enhancement factor of γ = 3.3, a significant wave height of H_s = 2.5 m and a directional spreading of σ = 31.5°.

Reijmerink (2012) modelled the port layout in the numerical wave models SWAN (Booij *et al.*, 1999) and PHAROS (Berkhoff, 1972, 1976, De Jong and Borsboom, 2012a,b). In absence of full modelling of diffraction, SWAN is generally known to have limited applicability inside small and confined port layouts, even more so in case of longer incident wave periods. Nevertheless, the spectral wave model SWAN was considered by Reijmerink (2012) as a reference and to assess up to which point (possibly conservative) SWAN results (not reproduced here) may still be acceptable in practice. The mild-slope model PHAROS of Deltares includes full modelling of diffraction and therefore was expected to provide more accurate descriptions of wave penetration. The mild-slope formulation results in a practical and computationally efficient numerical wave model, which in essence is a linear modelling approach but PHAROS includes parameterised descriptions representing the effects of wave breaking and of bed friction that can optionally be activated. Wave conditions relevant for wave penetration computations, often focussed on operational wave conditions, will typically correspond to quite low resulting wave heights inside port basins, supporting the use of a linear wave model. Directional spreading and frequency spreading can be represented efficiently in this model by a weighted sum of separately computed wave components that together make up the full wave spectrum.

The reflection values in the model schematisation applied in Reijmerink (2012) were taken from earlier references cited in his report, without further optimisations or calibrations. Incoming wave boundary conditions were prescribed as-is, i.e. without any tuning, calibration or amplifications.

Figure 12 depicts the results from PHAROS for the selected wave condition. The coloured circles in the panels of this figure indicate the measured values at each probe location using the same colour scale as applied for plotting the numerical results in that panel. A matching colour inside and around each circle therefore indicates a good match between measured and calculated results.

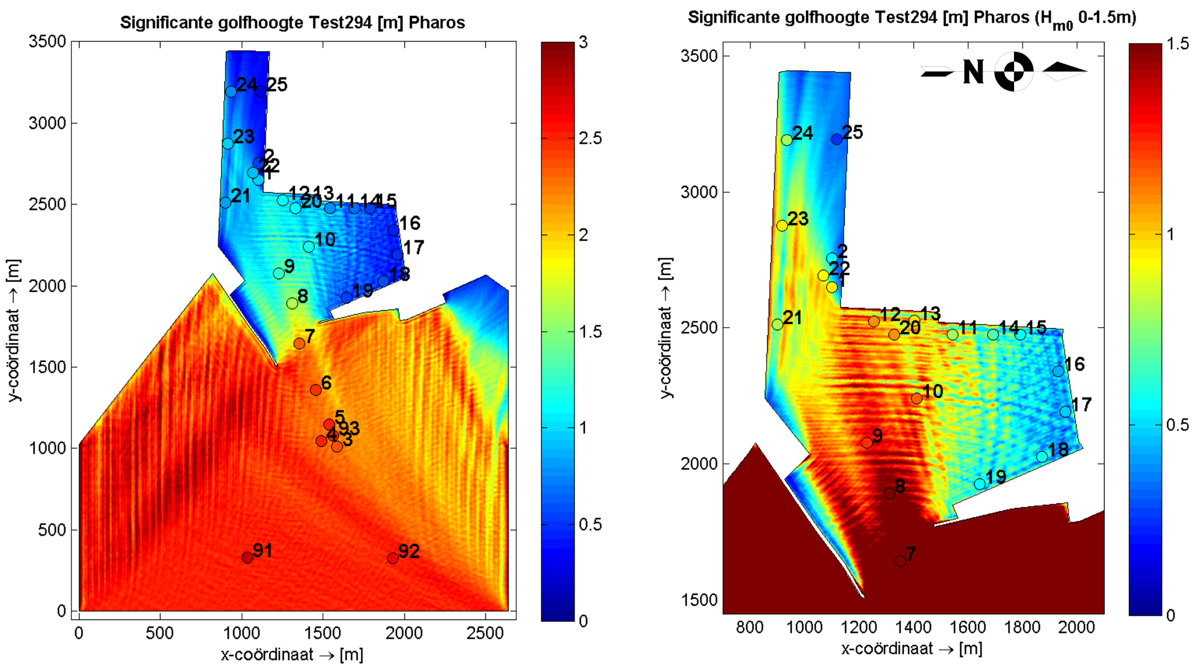


Figure 12: results from the PHAROS model for Limassol (from Reijmerink, 2012). Left panel: overview of the computational area; right panel: same results, now for a zoom of the port area. Note the difference in colour scale between both panels.

The figure shows that the agreement between measured and computed values is rather good. Detailed analyses of the computed results described in Reijmerink (2012) indicate that at most locations the calculated wave heights for this condition (averaged within a circle with a diameter of the wave length around the main location to account for the rather outspoken standing wave height pattern in the numerical wave model[6]) are typically accurate within about 5-10%, although a few specific locations showed higher relative deviations. Larger relative deviations were found typically for locations furthest into the port layout, i.e. in case of low absolute wave heights.

Van Vledder and Zijlema (2014) considered the same wave condition and layout in the numerical wave model SWASH. Contrary to other studies using this test case (Reijmerink, 2012 and Adytia, 2014, considered below), they specified only one reflection characteristic along the breakwater and quay walls in the harbour. However, apparently this has not decisively influenced the computational results. This is striking, since wave heights inside port basins often depend strongly on such reflection values. Why it does not prove critical in their computations is not discussed by Van Vledder and Zijlema. We hypothesise that it may be related to the specific shape of the port and that the uniform settings at least describe with sufficient accuracy the quay sections within the port that dominate local reflection.

The computations in SWASH by Van Vledder and Zijlema (2014) included the default value for bottom friction. They report that the incoming boundary conditions in the SWASH model had to be tuned using the output locations closest to the wave maker to obtain suitable results inside the computational domain. From this calibration it followed that the SWASH model *underestimated* the incoming wave conditions at the model boundary and the model had to be forced with a wave height of around 2.9 m, i.e. about 15% enhancement of the actual value (Figure 13), to achieve comparable wave heights at the observation locations within the computational domain. This observed model characteristic is striking, since the computations in SWASH by Dobrochinski (2014), using Dataset 1, indicated that SWASH apparently *overestimated* the measured wave heights for those conditions, which was (likely unfoundedly) compensated in the computations by Dobrochinski (2014) by using an amplified bottom friction in the SWASH model.

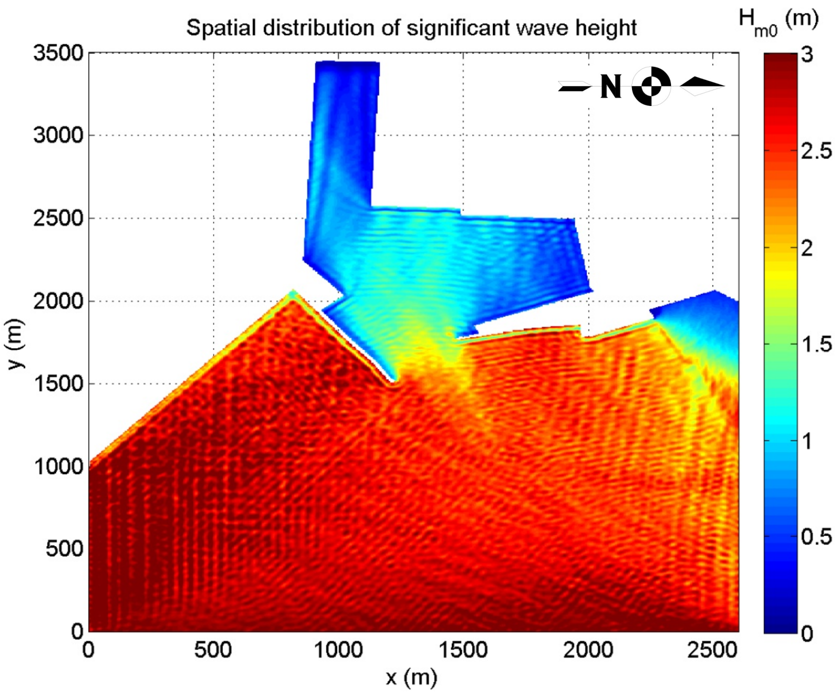


Figure 13: results from the SWASH model for the considered wave condition at the Port of Limassol (from Van Vledder and Zijlema, 2014). Note the unequal scales of the axes, resulting in a horizontally stretched plot of the layout.

[6] Since the work by Reijmerink (2012), Deltares has developed an efficient and accurate wave splitting method specifically aimed at analysing output of phase resolving wave models such as mild-slope models, see De Jong and Borsboom (2012a,b). This tool is presently part of the PHAROS software package. Applying this post-processing tool removes the requirement of spatially averaging computed wave heights.

Adytia (2014) modelled the same layout and wave condition in an Optimised Variational Boussinesq-type wave Model (OVBM). In that paper he states that this numerical model is a relatively efficient version of a Boussinesq-type model that includes less complex derivative terms than many other Boussinesq-type wave models. The output of the non-linear OVBM is expressed in Adytia (2014) as the linear fraction (percentage) of the incoming wave height. Figure 14 shows the results for the main wave condition considered from Dataset 2. Adytia (2014) reports that typical deviations between computed and measured values at the observation locations are within 5-10%. This would certainly be within a practically suitable accuracy.

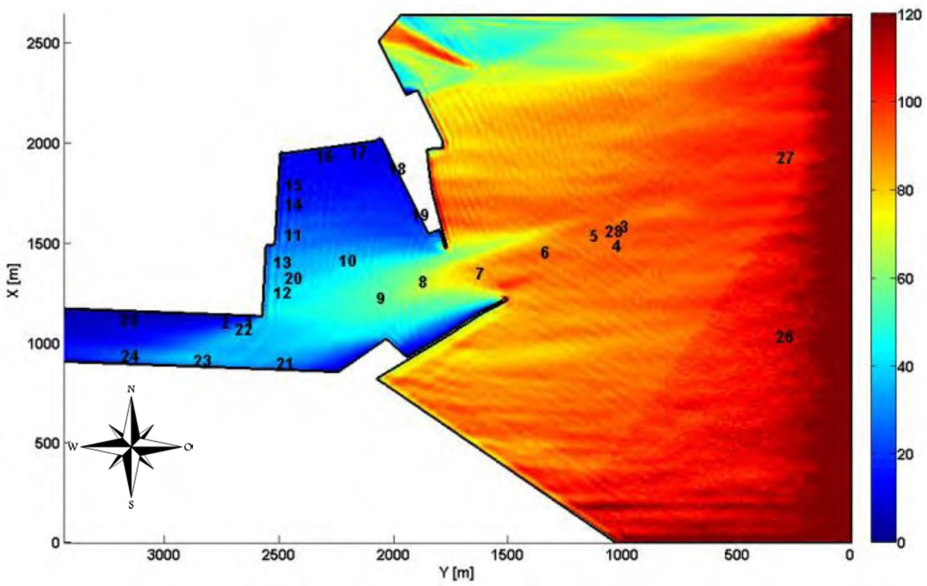


Figure 14: results from the OVBM wave model for Limassol (from Adytia, 2014). Wave heights are expressed as percentage of the incoming wave height.

Adytia describes how the dispersive properties of the Boussinesq-type model (i.e. the description of the phase speeds of waves of different period) were optimised for this particular targeted wave condition prior to making the calculation. A wave generation region of 4 wave lengths (increasing in strength from the boundary inward from 0 to 1, i.e. up the full incoming wave height) was included in the modelled domain of the considered case. How generic these settings and modelling choices will be is not reported in Adytia (2014).

Furthermore, as is also briefly noted by Vledder and Zijlema (2014), the wave height at the incoming boundary of the modelled domain in the OVBM appears to include a similar enhancement (of over 20%, Figure 14) as Vledder and Zijlema (2014) reported to be required for the SWASH model (15%). Such an enhancement was apparently required to achieve the reported computed values at the measurement locations inside the computational domain. The detailed causes of this numerical model behaviour are not analysed in the cited papers. We hypothesise that it may be related to model formulation-specific aspects such as numerical damping caused by the applied calculation schemes, but this remains to be verified.

Both Vledder and Zijlema (2014) and Adytia (2014) do not consider how the observed characteristics of their numerical wave models will influence the practical use of those models, including cases where no measurements will be available for detailed model optimisation and boundary condition calibrations, and when results are typically required to be provided quickly and indisputably (e.g. for consultancy).

5. COMPARISON OF VALIDATION STUDIES USING DATASET 3

The application of Dataset 3 is only briefly considered here, since only a very limited part of this dataset has been considered so far and because a separate publication is foreseen on this test series.

So far this dataset has been considered in a number of master studies at Delft University of Technology (Van Mierlo 2014, Monteban, 2016 and Wong, 2016). They all used the same selection of wave conditions from Dataset 3 to validate and compare different numerical wave models (PHAROS, TRITON, SWASH and Mike21 BW). Overall, their findings seem to confirm general conclusions from earlier studies cited above: wave penetration can typically be modelled with a practical accuracy, whereas long waves and resonant modes are generally computed with less accuracy. Remaining attention points mentioned in these MSc reports include: requirements for data analysis methods (e.g. spectral resolutions), reflection settings in the numerical models, stability of the numerical models (most notably related to the use of SWASH and Mike21 BW) and practical aspects related to performing physical scale model tests. This shows that there is still ample work to be done on validating and improving numerical wave penetration models to enable application of such models in daily practice.

6. CONCLUSIONS

This paper introduces a collection of benchmark datasets by Deltares that is made available for validation of numerical wave penetration models and related tools such as methods for calculating wave-induced forces on moored vessels. Since datasets for validation of such numerical methods are quite scarce we have already received and honoured several requests for use of these datasets. This paper gives a summary of the typical findings from a selection of those studies and for the first time provides an inter-comparison and an overarching analysis of those different results.

Even though already several studies have used the presented datasets, these data still form a valuable collection for future work. This is because several parts of the available datasets have not yet been exploited in model validation studies, and because so far only a few specific models (model types) have been considered. Furthermore, parts of the validation outcomes obtained so far have been inconclusive and still require further analyses for reaching complete and definitive conclusions. In addition, in the future we expect to expand the open data collection by adding other physical scale model projects by Deltares.

Overseeing the discussed selection of publications that used the open datasets by Deltares to this date, we conclude that identifying the causes of differences between computed and measured values is often not straightforward. Hypothesised causes in one study may be refuted (implicitly) in others. This shows that there is still quite some work to be done in this field and that cooperation between different organisations will remain essential to reach proper conclusions. Therefore, researchers and advisors working on related topics are encouraged to contact Deltares to explore cooperation possibilities. Together we will continue to show the large added value that physical scale model tests provide in engineering, consultancy and research, including calibration and validation of numerical methods.

ACKNOWLEDGEMENTS

The authors acknowledge O.M. Weiler as developer/originator and project manager of the physical scale model tests performed in 2003 (Dataset 1). His foresight on preparing and generating that large and still very relevant dataset has proven invaluable. We thank the authors that have used the described datasets to this date for their interest in these data and their willingness to confront their numerical model results with these measurements. M.J.A. Borsboom is acknowledged for commenting on an earlier draft of this paper. His suggestions on document structure that were processed for this final paper version are much appreciated.

REFERENCES

Adytia, D. (2014), Simulations of Short-crested Harbor Waves with Variational Boussinesq Modelling. Proc. 24th Int. Ocean and Polar Engineering Conference. ISOPE-I-14-451.

Berkhoff, J.C.W. (1972), Computation of combined refraction-diffraction, *13th Int. Conf. Coastal Eng.*, pp. 471-490.

Berkhoff, J.C.W. (1976), Mathematical models for simple harmonic linear water waves, wave diffraction and refraction, Delft Hydraulics Publication No. 163.

Booij, N., R.C. Ris, and L.H. Holthuijsen (1999), A third-generation wave model for coastal regions, Part I, Model description and validation, J. Geoph. Res., 104(C4), 7649-7666.

De Jong , M.P.C., O.M. Weiler, M.J.A. Borsboom and A.R. van Dongeren (2005), A phase-resolving analysis technique for short-crested wave fields, Paper presented at the 5th International Symposium on Ocean Wave Measurement and Analysis, WAVES 2005, held in Madrid, Spain, 3-7 July 2005. - Paper number: 026.

De Jong, M.P.C. and M.J.A. Borsboom (2012a), A practical post-processing method to derive design wave parameters from wave model results, PIANC-COPEDEC VIII, February 2012, Chennai, India, pp. 345-356 (ISBN : 978-93-80689-06-7).

De Jong, M.P.C. and M.J.A. Borsboom (2012b), A practical post-processing method to obtain wave parameters from phase-resolving wave model results, *International Journal of Ocean and Climate Systems*, **Vol.3**, Number 4, December 2012, pp. 203-216, ISSN 1759-3131

De Jong, M.P.C., S.P. Reijmerink, A. Capel and A.J. van der Hout (2016), Combining numerical wave models for efficient design of port layouts and entrance channels, PIANC-COPEDEC IX, Rio de Janeiro, Brazil.

Dobrochinski, J.P.H. (2014), A combination of SWASH and Harberth to compute wave forces on moored ships, MSc Thesis, Delft University of Technology (repository.tudelft.nl).

Janssen, T.T., A.R. Van Dongeren and C. Kuijper (2001), Phase Resolving Analysis of Multidirectional Wave Measurements. Proc. Waves 2001, San Francisco, CA, U.S.A., 377-386.

Monteban, D. (2016), Numerical modelling of wave agitation in ports and access channels - A comparison study between SWASH and MIKE 21bw, MSc Thesis, Delft University of Technology (repository.tudelft.nl).

Reijmerink, S.P. (2012), Wave boundary conditions inside ports – application limits of numerical models (in Dutch), MSc Thesis, Delft University of Technology (repository.tudelft.nl).

Rijnsdorp, D.P. (2016), Modelling waves and their impact on moored ships, PhD Thesis, Delft University of Technology (repository.tudelft.nl).

Van der Molen, W. (2006), Behaviour of Moored Ships in Harbours, PhD Thesis, Delft University of Technology, ISBN-10: 90-9021264-7, ISBN-13: 978-90-9021264-7 (repository.tudelft.nl).

Van der Ven, P.P.D. (2016), Benchmark tests of wave penetration in harbours - Measurement report, Deltares Technical Report, reference 1209490-000-HYE-0001.

Van Mierlo, F.A.J.M. (2014), Numerical modelling of wave penetration in ports, MSc Thesis, Delft University of Technology (repository.tudelft.nl).

Van Vledder, G.Ph. and M. Zijlema (2014), Non-hydrostatic wave modelling in partly sheltered areas, Proceedings of 34th Conference on Coastal Engineering, Seoul, Korea, 2014, Editor: Patrick Lynett, ISBN: 978-0-9896611-2-6.

Wong (2016), Wave hydrodynamics in ports - Numerical model assessment of XBeach, MSc Thesis, Delft University of Technology (repository.tudelft.nl).

Zijlema, M.; Stelling, G.; Smit, P., (2011). SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. Coastal Eng. 58, 992-1012, doi:10.1016/j.coastaleng.2011.05.015.