

MODELLING SUITABLE LAYOUT FOR A SMALL ISLAND HARBOUR: A CASE STUDY OF RUHNU IN THE GULF OF RIGA, EASTERN BALTIC SEA

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We explore the complexity of various drivers and local constraints from the viewpoint of developing a feasible re-design of a small harbour that is affected by ultra-refraction of storm waves. Waves propagating towards the Port of Ruhnu on a small island in the central part of the Gulf of Riga are systematically redirected by underwater features so that saturated waves in virtually all storms propagate almost exactly into the harbour entrance. A new design of the port entrance and associated set of breakwaters is largely steered by the location of the port and options for the fairway into the port. The re-design of the breakwaters and possible relocation of the entrance considers the specific features of the local wind, wave, and water level climate, including period-depending refraction of storm waves. We present systematic analysis of these aspects using recorded and modelled wind and water level time series. Wave properties are reconstructed using the WAVE module (SWAN) of the Delft3D suite forced with ERA5 and local wind information. Phase-resolving modelling of waves (REEF3D software) reveals the presence of a bi-modal wave field in the interior of the port and provides alternatives for the design of effective protection options that suppress single wave components. On many occasions, greatly simplified models and local one-point wind properties provide even better match with recorded wave properties than sophisticated models and global data sets.

Keywords: *Breakwater design, Delft3D, port planning, REEF3D, SWAN model, wave modelling.*

1. INTRODUCTION

A harbour has to provide protection for the vessels against the impact of wind, waves and currents, and sometimes against large variations in the water level. This is usually achieved by a combination of choice of the layout of the harbour and characteristics of its structures. However, the situation gets more complicated when there is a possible sediment movement nearby. Wave and current-driven sediment transport can turn a perfectly sheltered harbour or water-

way into an expensive maintenance project (e.g., [1]–[3]). Additionally, several other conditions (accessibility on land and on water, man-made objects etc.) must be considered for an optimal harbour design ([4], [5], among many others). As virtually every port is unique, modern port design covers a wide range of different aspects of planning, and management and case studies offer great insights to understand them.

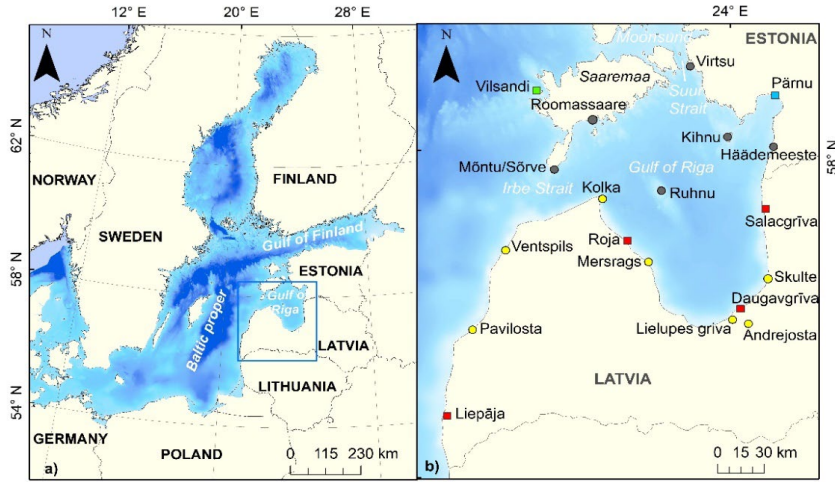


Fig. 1. Location scheme of the Gulf of Riga in the eastern Baltic Sea (left) and the island of Ruhnu in the Gulf of Riga (right). The right panel shows the locations of water level stations in Latvia (red and yellow) used in the analysis.

The Port of Ruhnu (called Port of Ringsu or colloquially Ringsu harbour in the past [6]) is situated on the southern tip of a small island of Ruhnu in the middle of the Gulf of Riga (Fig. 1). Wave fields in this water body are mostly locally generated and follow the wind patterns [7]. Only a small amount of wave energy generated in the Baltic proper penetrates into the Gulf of Riga through Irbe Strait and affects to some extent the northern part of the gulf. The “climate” of waves of appreciable height is driven by a two-peak wind regime in this region. Moderate and strong winds blow

usually either from the south-west (SW) or (less frequently) from the north-north-west (NNW) [8], [9]. The port is sheltered against waves from the NNW by the island itself. It is protected against waves from the SW and refracted waves from the northern directions by two rubble mound breakwaters. To enhance the protection, the tip of the southern breakwater is turned to the south-east. The entrance and waterway to the port are oriented to the south-east (SE). This is the direction from where winds are infrequent and weak [8], [9].

Despite this careful design that consid-

ers the directional structure of predominant moderate and strong wind, inconveniently high waves often penetrate into the port interior that also suffers from rapid changes in the water level. The situation is especially difficult in the narrow entrance channel where a vessel entering the port may experience strong bow waves. Undesirable wave conditions often occur even during westerly and northerly winds against which the harbour is geometrically protected. A likely reason for such conditions is refraction of wind waves. Namely, waves excited in the Gulf of Riga at wind speeds of 10–15 m/s eventually undergo extensive refraction on underwater slopes of the island of Ruhnu and possibly its neighbouring shallow area. This process systematically redirects waves so that intense waves may propagate directly into the entrance of the Port of Ruhnu during virtually any strong wind event as described in detail in [6].

The refraction-induced rotation of wave propagation direction is relatively mild for weak winds but becomes more effective for strong winds [6]. This feature simply reflects an increase in the wave period and length under stronger winds as longer waves are more affected by refraction.

Interestingly, the range of wave approach directions converges around 120° (clockwise from the North) for a wind speed of 15 m/s. This is exactly the orientation of the fairway that enters the port [6]. Such ultra-refraction is not unique and is known, e.g., for SW swells propagate into San Francisco Bay [10].

Another long-term issue for the Port of Ruhnu has been an accumulation of sediments (sand) at the harbour entrance. It is not clear where the sand is coming from. An estimate of sediment transport based on archive documents about coastal processes, the appearance of morphology of the beaches next to the port and nearby coasts concluded in the 1990s that the fine sand was coming from the north along the eastern coast of Ruhnu [11] (Fig. 2). Hence, an extension of the northern breakwater was proposed. However, due to costs, it was built shorter than necessary and sand accumulation continued. The port authorities addressed the problem by dredging the sand and placing it to the west of the port where a sandy beach was located (Fig. 3). As sand accumulation continued, it was hypothesised that sediment transport from the west could also be its possible reason.

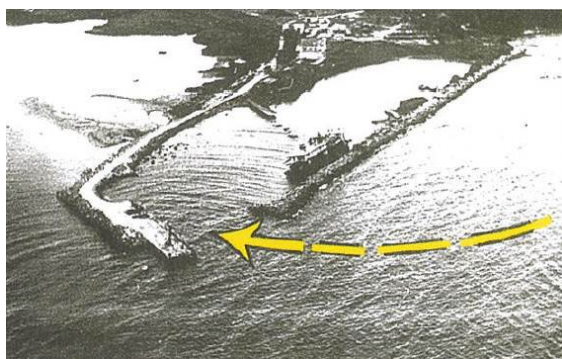


Fig. 2. A possible pathway of the inflow of sand from the north. The photo shows the configuration of breakwaters of the Port of Ruhnu in the 1990s [10].

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Fig. 3. A sandy beach is located to the west of the contemporary configuration of the Port of Ruhnu (base map: Estonian Land Board, 2020).

In this article, we address possible solutions to both described issues. The goal is to better understand their reasons and to employ this understanding to develop options for a new layout of the Port of Ruhnu. We start with a description of in situ wave measurements in the vicinity of the port entrance and validation of the SWAN wave model forced with different winds based on recorded time series of wave properties. Wave simulations using a phase-average model are employed

to analyse suitable layouts for the port. We first analyse properties of waves in different scenarios to specify eventual new layouts of the port. This analysis is complemented by more detailed, phase-resolving examination of wave propagation in a prospective new layout using the 3-dimensional hydrodynamic model REEF3D. Finally, we evaluate the design wave parameters for this layout, by using extreme value analyses of wind properties and reconstructed water level time-series.

2. DATA, METHODS AND MODELS

2.1. Wave Measurements

Time series of wave properties were measured at and near the Port of Ruhnu in the period of 2021–2023 with pressure-

based devices (Table 1) and directional waveriders (Table 2).

Table 1. Measurement Periods and Locations of Pressure Sensors

No	Name	N°	E°	Depth, m	Start date	End date	Data points	max H_s
1	PR_CTRL	57.7787	23.2753	4.6	01.05.2021	26.06.2021	5472	0.86
2					28.06.2021	22.08.2021	5376	1.47
3					24.08.2021	11.10.2021	4704	1.40
4	PR_ENTR	57.7796	23.2724	3.3	01.05.2021	26.06.2021	5472	1.13
5					28.06.2021	22.08.2021	5376	1.64
6					24.08.2021	12.10.2021	4700	1.49
7					13.10.2021	25.11.2021	4224	1.18
8					04.08.2022	08.09.2022	3456	0.41
9					26.09.2022	03.11.2022	3744	1.09
10	PR_PORT	57.7806	23.2701	1.6	01.05.2021	27.06.2021	5472	0.24
11					28.06.2021	23.08.2021	0	0
12					24.08.2021	27.08.2021	384	0.28
13					13.10.2021	26.11.2021	4320	0.27
14					04.08.2022	24.09.2022	4992	0.31

Table 2. Measurement Periods and Locations of Waverider Buoys

No	Name	N°	E°	Depth, m	Start date	End date	Data points	max H_s
1	LP_PORT	57.7782	23.2753	4.6	03.05.2021	17.11.2021	9516	1.64
2	LP_SEA	57.7695	23.3420	19	03.05.2021	17.11.2021	9516	2.45
3	LP_PORT	57.7785	23.2768	4.6	04.11.2022	30.04.2023	11622	2.02

The loggers manufactured by the Centre of Biorobotics of Tallinn University of Technology recorded continuously pressure fluctuations with a frequency of 5 Hz in three locations (Fig. 4) with water depths of 1–4 m. The length of each measurement session (1.5 months) was limited by the capacity of the batteries. The measurements were only performed in spring, summer and autumn 2021 and 2022 due to problems with winter maintenance of the instruments. The pressure data saved locally on the instrument was first converted into water level fluctuations and then into significant wave heights H_s , and 15-minute-interval periods were calculated with MatLab scripts from [12].

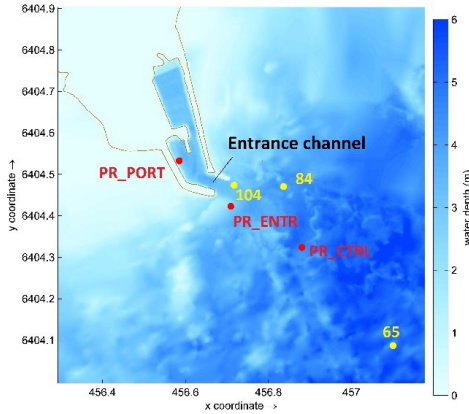


Fig. 4. Locations of pressure sensors in 2021 and 2022 (red) and calculation points (yellow) in [6]. Brown line indicates the waterline.

In 2021, two waveriders were deployed near the port entrance to validate the wave models and quantify the refraction-driven changes of wave propagation directions (Fig. 5) suggested by the numerical analysis [6]. In winter 2022/23, one waverider was set near the port entrance at point LP_PORT (Table 2).

The correlation coefficient between H_s recorded with the waverider and pressure sensor at LP_PORT and PR_CTRL (Fig. 4), respectively, was 0.91. The wave heights evaluated from pressure data were smaller

The directional waverider called LainePoiss® produced by WiseParker Ltd is a spherical buoy with a diameter of 32 cm, a height of 22 cm, and a weight of 3.5 kg. The output stream of LainePoiss® was validated through (i) sensor tests, (ii) wave tank experiments, (iii) a field validation against a Directional Waverider, (iv) an intercomparison of several buoys in the field, and (v) field measurements in the Baltic Sea marginal ice zone [13]. The bias of H_s was 1 cm, with a correlation coefficient of 0.99 and a scatter index of 8 % against the output of similar devices. The mean absolute deviation of mean wave direction was 70 °.

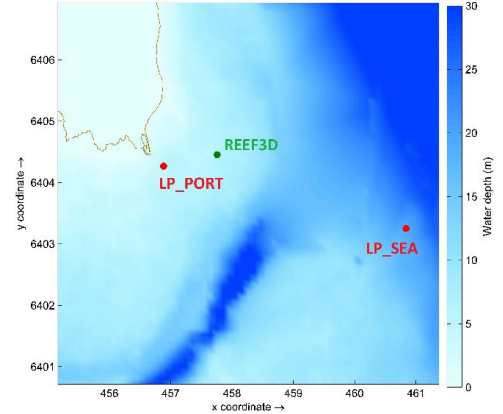


Fig. 5. Locations of waverider buoys in the period of 2021–2023 (red) and calculation point for REEF3D (green). Brown line indicates the waterline.

(bias -0.19 m; root mean square deviation (D_{rms}) 0.22 m, maximum difference 0.82 m). The bias is apparently because of a relatively large water depth (4.6 m) in the location of the pressure sensor. The wave periods recorded by the waverider were 2 – 4 s. These periods are characteristic in this area [7], [14]. As pressure fluctuations generated by such short waves rapidly decay in the water column, the pressure sensor is not able to register some part of shorter waves. As a result, the average and instantaneous H_s may be underestimated even though the

highest single waves may be recorded adequately.

The damping effect of the port structures was assessed by comparing the H_s recorded in- and outside of the port (Fig. 4). The H_s in the interior of the port was at least two times smaller than H_s outside the port during measurements performed in 2021. The difference (and thus the protection offered by the breakwaters) increased with the decrease of the wave height. In cases when $H_s > 0.5$ m outside the port, this ratio

was about 4 and increased to >10 for very low wave conditions ($H_s < 0.2$ m outside the port). A slight change in the measurement location in 2022 led to slightly different values of this ratio. The core message from the measurements is that the significant wave height at the ferry berth in the port interior is less than 25 % from the wave height outside the port, whereas H_s in the entrance channel is about 50 % of the H_s outside the port.

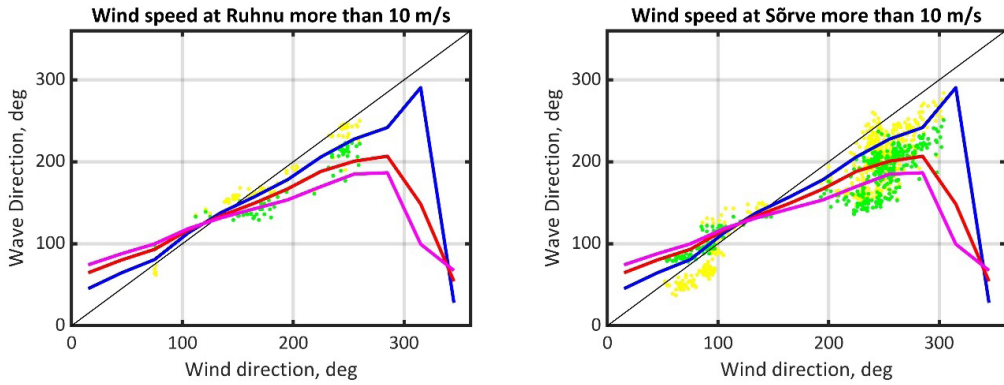


Fig. 6. Comparison of wind and wave directions hindcast using wind information from Ruhnu (left) and Sõrve (right). Note that the wind measurement location on Ruhnu may be shadowed by the forests on the island. Blue, red and magenta lines show the modelled directions of waves for points 65 (Fig. 4), 84 (fairway) and 104 (entrance channel) with constant wind speed of 10 m/s (evaluated as in [6]). Yellow and green dots indicate the recordings at LP_SEA and LP_PORT (Fig. 4), respectively.

The modelling exercise in [6] demonstrates that refraction of waves is the strongest and redirects the waves directly into the port entrance when the wind speed is 15 m/s. Such wind speeds did not occur during the measurement campaigns. For this reason, we compare wave directions for all

wind speeds ≥ 10 m/s at Ruhnu and Sõrve (Fig. 1). Figure 6 confirms that refraction clearly redirects waves in the vicinity of the port entrance even though the rate of change in the wave direction is in some occasions smaller than evaluated in [6].

2.2. Wave Models and Wind Data

The waves were modelled using the SWAN (version 40.11) wave model [15] in Delft3D suite (WAVE module). SWAN is a third-generation phase-averaged spectral wave model developed at Delft University of Technology. A more detailed description of the particular implementation of

this model for the study area is provided in [6] and [16]. We used a four-level nested scheme of regular rectangular model grids. Even though only very limited amount of wave energy created in the Baltic proper enters the Gulf of Riga, propagation of specific swells into the gulf and their refraction

along underwater sandy features near Cape Kolka towards Ruhnu cannot be excluded. For this reason, a coarse model was run for the whole Baltic Sea on a grid with a step of 5000 m (251×271 grid points). The second level grid covered the Gulf of Riga with a step of 1000 m (171×181 grid points). The third level grid (Fig. 3) covered the neighbourhood of Ruhnu with a step of 100 m (211×171 grid points). The innermost (finest) model focused on the Port of Ruhnu (Fig. 3) with a resolution of 3 m (300×300 grid points). The resolution of the third- and fourth-level grids is evidently fine enough to replicate detailed properties of waves in the vicinity of Ruhnu and Port of Ruhnu. The bathymetry was taken from the databases of Estonian Transport Administration, Baltic Sea Bathymetry Database by the Baltic Sea Hydrographic Commission [17] (<http://data.bshc.pro/legal/>) and Saarte Liinid LLC.

We compared the output of the SWAN model with estimates produced by a semi-empirical fetch-based wave model, called SPM-method [18] and denoted as SPM. The idea was to see how a very simple model compares with a sophisticated contemporary numerical model. We followed the procedure given in [19]. For each measurement site we measured the fetch with a 20° step. Wave models were forced with wind speed and direction from nearby meteorological stations. We calculated wave parameters (H_s and peak period T_p) with 1 h time step.

The SWAN and SPM models were forced with wind information from several sources. The aim was to select the most suitable source of wind in terms of the match of modelled and recorded data. We used measured wind data from Ruhnu, Kihnu, Sõrve and Vilsandi (Fig. 1) and modelled ERA5 winds [20], [21]. The ERA5 dataset is the fifth-generation global atmospheric reanalysis produced by the Euro-

pean Centre for Medium-Range Weather Forecasts (ECMWF) [22] from 1940 to present. We use the ERA5 data from 2021 and 2022 since the data from 2023 has not been available yet. This wind data realistically represents spatio-temporal variations in the wind properties with a time step of 1 h and spatial resolution 0.25° (about 30 km). The recorded wind properties are used to construct one-point homogeneous unidirectional non-stationary wind fields with a temporal resolution of 1 h. Such conditions (referred to as SWANhom) are used for modelling waves in extreme conditions with long return periods. ERA5 wind data was not used in SPM models.

Ruhnu, Kihnu, Sõrve and Vilsandi meteorological stations (Fig. 1) are operated by the Estonian Environment Agency. Automatic systems were installed in all stations in 2003. The Ruhnu station, active since 1958, is located on the southern part of the island, about 200 m from sea. It is open to all directions, except to the north and north-east (NE) where the forest grows. Its data set is not homogeneous. Initially measurements were carried out four times a day, then eight times. No measurements were performed in the period of 1987–1996, and thereafter only two recordings a day were taken. The Kihnu station is sheltered by the forest in the north and east. It has been operating since 1931. Digitised records are available since 1958 when the wind speed and direction were measured four times a day. The Sõrve station is located at the tip of the Sõrve peninsula and is open to all directions. It is somewhat influenced by the peninsula to the north of the station. The measurements commenced in 1866. The digitised records are available from 1961.

Vilsandi meteorological station is located on a small island, to the west of the island of Saaremaa (Fig. 1). The data from Vilsandi is often used as a standard, high-

quality representation of wind properties in the northern Baltic proper. The wind data at Vilsandi is highly reliable except for easterly winds [23] that are generally less frequent and weaker than SW or NNW winds in this region. The station has been operat-

ing since 1865. The digitised records are available since 1947 when the wind speed and direction were measured four times a day. Starting from 1966, the measurements were performed eight times a day.

2.3. Validating the Wave Model

The comparison of the modelled wave heights and periods with recorded data covers the whole time period of measurements (Table

3) and includes a detailed assessment of wave conditions during the most severe recorded events (Tables 4 and 5; Figs. 7 and 8).

Table 3. Comparison of Modelled H_s with the Recorded ones during 3 May 2021–17 November 2021 (The positive bias means that the modelled H_s are higher than the recorded H_s . D_{max} (m), D_{rms} (m), and R denote the maximum difference, root mean square difference and correlation coefficient, respectively, between measured and modelled values.)

No	Wind	Type of model	PR_ENTR H_s , m				LP_PORT H_s , m				LP_SEA H_s , m			
			bias	D_{max}	D_{rms}	R	bias	D_{max}	D_{rms}	R	bias	D_{max}	D_{rms}	R
1	ERA5	SWAN	0.18	0.83	0.23	0.89	0.06	0.69	0.14	0.92	0.02	0.80	0.15	0.93
2	Ruhnu	SWANhom	0.03	1.02	0.16	0.80	-0.20	0.76	0.25	0.86	-0.38	2.15	0.47	0.76
3	Vilsandi	SWANhom	0.02	1.10	0.24	0.50	-0.12	1.30	0.28	0.55	-0.23	1.67	0.44	0.55
4	Ruhnu	SPM	-0.08	1.17	0.21	0.66	-0.25	1.23	0.32	0.71	-0.45	2.22	0.57	0.62
5	Vilsandi	SPM	-0.03	1.09	0.24	0.42	-0.19	1.43	0.33	0.46	-0.37	2.22	0.54	0.47

Table 4. Comparison of Modelled H_s with the Recorded ones during 19 October 2021–24 October 2021 (The positive bias means that the modelled H_s are higher than the recorded H_s . D_{max} (m), D_{rms} (m), and R denote the maximum difference, root mean square difference and correlation coefficient, respectively, between measured and modelled values.)

No	Wind	Type of model	PR_ENTR H_s , m				LP_PORT H_s , m				LP_SEA H_s , m			
			bias	D_{max}	D_{rms}	R	bias	D_{max}	D_{rms}	R	bias	D_{max}	D_{rms}	R
1	ERA5	SWAN	0.31	0.83	0.36	0.84	0.19	0.44	0.24	0.93	0.11	0.59	0.23	0.88
2	Ruhnu	SWANhom	0.06	0.60	0.25	0.71	-0.19	0.49	0.28	0.86	-0.51	1.32	0.61	0.71
3	Vilsandi	SWANhom	0.24	1.10	0.36	0.52	0.05	0.63	0.27	0.65	-0.08	1.21	0.41	0.62
4	Ruhnu	SPM	-0.09	0.84	0.25	0.57	-0.35	0.95	0.40	0.76	-0.70	1.81	0.78	0.69
5	Vilsandi	SPM	0.01	0.86	0.25	0.50	-0.22	1.00	0.36	0.53	-0.57	1.75	0.71	0.40

Table 5. Comparison of H_s with the Measurements during 17 August 2021–21 August 2021 (The bias indicates that the modelled H_s are higher than the measured H_s . D_{max} (m), D_{rms} (m), and R denote the maximum difference, root mean square difference and correlation coefficient, respectively, between measured and modelled values.)

No	Wind	Type of model	LP_PORT H_s , m				LP_SEA H_s , m			
			bias	D_{max}	D_{rms}	R	bias	D_{max}	D_{rms}	R
1	ERA5	SWAN	0.07	0.40	0.15	0.96	0.05	0.46	0.18	0.95
2	Ruhnu	SWANhom	-0.26	0.76	0.29	0.94	-0.44	1.18	0.49	0.90
3	Vilsandi	SWANhom	-0.23	1.12	0.39	0.60	-0.36	1.62	0.57	0.55
4	Ruhnu	SPM	-0.47	1.20	0.52	0.79	-0.69	1.74	0.77	0.71
5	Vilsandi	SPM	-0.41	1.43	0.56	0.34	-0.65	2.00	0.81	0.31

As expected, recorded wave properties have the best match in terms of the correlation with those modelled using spatially varying ERA5 wind information. However, the bias between the modelled and recorded data was larger for this data set than in other models during the whole modelled period

in 2021 and in October 2021. The SWAN model forced with ERA5 winds overestimates wave heights during relatively severe seas (Fig. 7). The use of one-point homogenous wind based on Vilsandi data overestimates wave heights in October, but underestimates in August 2021.

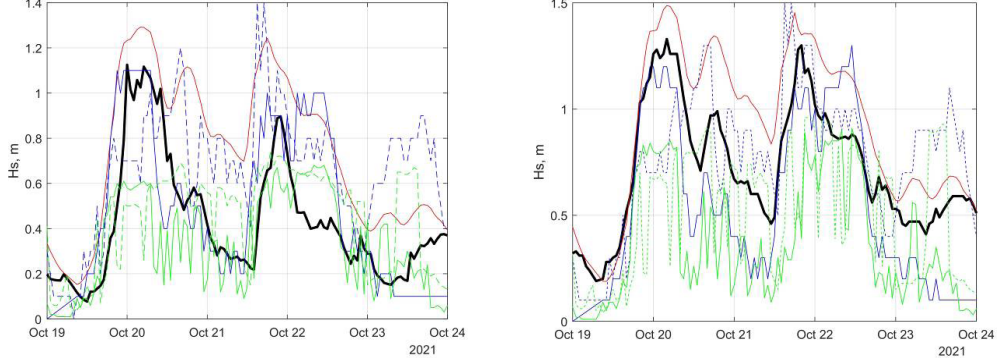


Fig. 7. Recorded H_s in October 2021 (black line) in point PR_ENTR (on the left, Fig. 4) and point PR_PORT (on the right). Red line indicates the modelled H_s with ERA5, blue H_s modelled with homogenous wind from Ruhnu (continuous) and Vilsandi (dashed), and green H_s modelled with SPM with wind from Ruhnu (continuous) and Vilsandi (dashed).

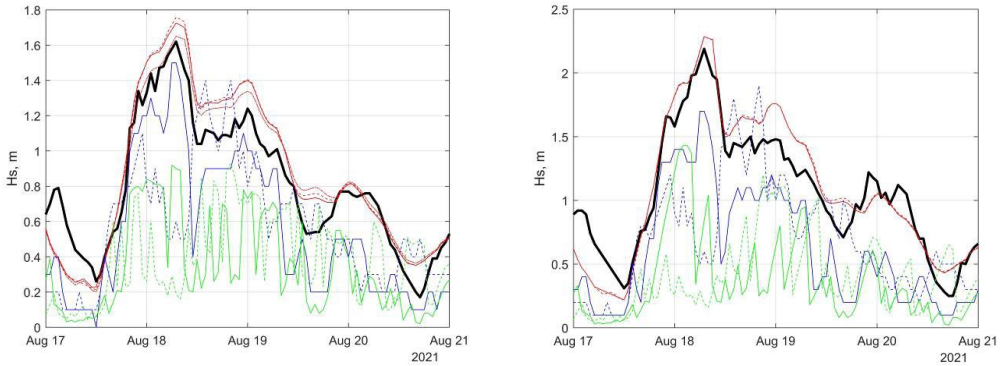


Fig. 8. Recorded H_s in August 2021 (black line) in point PR_ENTR (on the left, Fig. 4) and point LP_PORT (on the right). The colour and line type code is the same as for Fig. 7.

Somewhat surprisingly, the best match of the recorded and modelled wave properties at the entrance of the port (point PR_ENTR, Fig. 4) provides the combination of the SWAN model and one-point homogenous wind forcing based on wind recordings from Ruhnu. The relevant bias and D_{rms} are smaller than similar values for other simulation exercises (except for August 2021). We also checked the wave directions by

comparing refraction described in [6] with measured directions. The modelled results had a good correspondence with the measured results. As no strong winds occurred during the measurement campaign, it was not possible to detect strong refraction-driven effects. Based on this analysis, we use SWAN wave model with homogenous wind forcing from Ruhnu to evaluate design wave parameters for the port structures.

2.4. Water Level

Water level was observed visually at Ruhnu two to four times a day in the period of 1945–1988. Measurements resumed after a long pause with an automatic device in 2012. As water level information is crucial

for structural design, we fill the water level data for missing years using recordings at the coastal stations in Estonia and Latvia. These data are converted into the European Vertical Reference System, EVRS.

Table 6. Comparison of Reconstructed Water Levels Based on Two Different Stations (WL1 and WL2) with Measured Values at Ruhnu in the Period of 2012–2020 (D_{max} (cm), D_{rms} (cm), and R denote the maximum difference, root mean square difference and correlation coefficient, respectively, between measured values at Ruhnu and constructed values.)

No	WL1	WL2	Weight of WL1	Weight of WL2	D_{max} , cm	D_{rms} , cm	Bias, cm	R
1	Roja	Salacgriva	0.5	0.5	26.8	5.5	0.7	0.91
2	Roja	Salacgriva	0.6	0.4	27.3	5.7	1.4	0.91
3	Roja	Salacgriva	0.7	0.3	28.5	6.0	2.1	0.90
4	Liepaja	Daugavgriva	0.5	0.5	45.8	12.1	7.7	0.69
5	Liepaja	Daugavgriva	0.4	0.6	39.1	10.4	5.8	0.74
6	Liepaja	Skulte	0.5	0.5	41.3	12.3	9.2	0.77
7	Liepaja	Skulte	0.4	0.6	31.7	10.4	7.5	0.83
8	Liepaja	Skulte	0.6	0.4	50.8	14.4	10.8	0.69
9	Liepaja	Skulte	0.3	0.6	34.3	15.3	13.9	0.85
10	Liepaja	Skulte	0.5	0.7	43.2	10.9	-6.8	0.82
11	Liepaja	Skulte	0.5	0.6	32.6	8.3	1.2	0.80

The most complete datasets in terms of hourly measurements among Latvian water level recordings are at Liepaja and Daugavgriva [24]. To a first approximation, we assume that the water level changes linearly between any two stations. It is likely that this approximation is adequate for stations that are located along relatively straight coastline segments. This is the case for Latvian water level measurement locations on the Baltic proper shore and in the Gulf

of Riga [24]. To validate this assumption, we compared the outcome of this simple model with the measurements at Ruhnu in the period of 2012–2020 (Table 6). The strongest correlation, lowest bias and smallest D_{rms} are reached if this model is fed with recorded water level values from Roja and Salacgriva with equal weights. The resulting estimates of water level at Ruhnu are thus used below for calculating return periods for extreme water levels near the port structures.

3. MODELLING THE HARBOUR LAYOUT

3.1. Choosing the Layout Based on Wave Modelling

The properties of wave climate form just one criterion for the (re)design of the harbour layout. One must also consider

the current fairway for the ships that may potentially make a port call, variation of water depths in the sea, and access roads

and structures in the port. Several these constraints cannot be adjusted within a reasonable budget, efforts and time even for small ports, such as Ruhnu.

Most likely it is not possible to radically change the location of the entrance to the Port of Ruhnu as this is the only relatively deep-water location around the island that is maintained by the existing hydrodynamic loads. The idea of possible new openings in the eastern or western quays and breakwaters seems unrealistic because of likely very large costs of repeated dredging even

if a re-design of structures is not considered. To a first approximation, the feasible solution would be to improve protection of the entrance channel, by relocating and/or extending the breakwaters.

We start this analysis from rough estimates of extreme wave conditions near the port entrance under strongest winds from different directions with different return periods. The goal is to select the configuration of breakwaters that provides, on average, the best protection of the port interior in theoretically possible worst conditions.

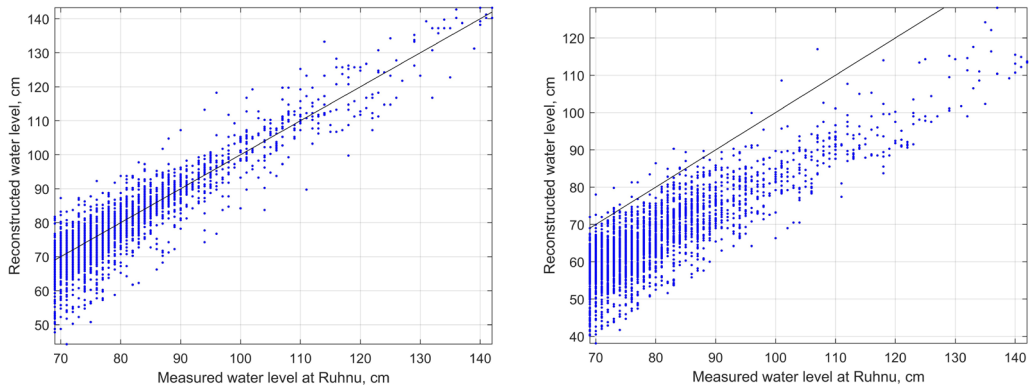


Fig. 9. Comparison of reconstructed water levels from Roja and Salacgriva (left panel, line 1 in Table 6) and Liepaja and Skulte (right panel, line 9 in Table 6) with measurements at Ruhnu in the period of 2012–2020.

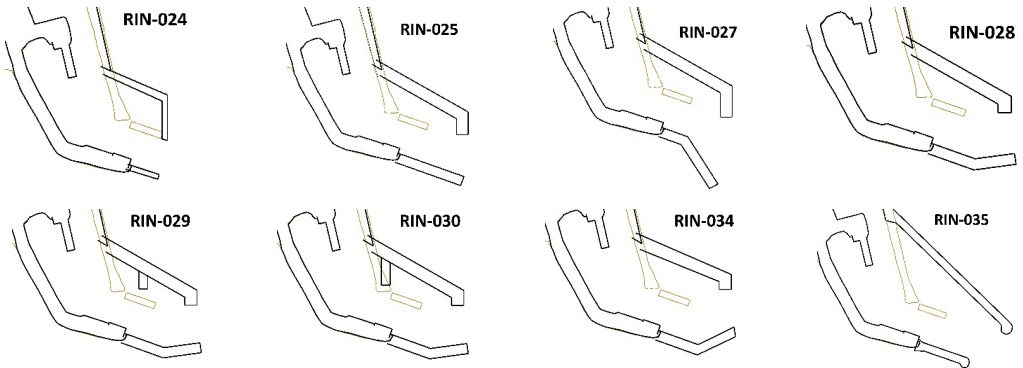


Fig. 10. Modelled new layouts (black thick line). Thin brown line indicates the current layout.

The SWAN wave model in Delft3D suite (see above) was forced with homogeneous unidirectional stationary winds over the entire Baltic Sea from 12 directions with a step of 30° . For every direction, extreme

wind speeds with return periods of 2, 5, 10, 20, 50 and 100 yr were applied. These wind speeds were calculated from time series of wind properties recorded on Ruhnu by applying peak-over-threshold method [25], [26].

Wind speeds corresponding to different percentiles of strong winds were used to mimic more frequently occurring severe wave conditions. For every return period, the runs were performed for a selection of elevated water levels with a step of 30 cm. Doing so may lead to certain overestimation of the impact of extreme wave conditions because for some directions high water levels and severe wave conditions do not necessarily occur simultaneously [27]. For example, strong easterly winds are not

associated with substantially elevated water levels at Ruhnu. Doing so still gives some indication of properties of possible worst-case scenarios.

This approach was applied to eight potential new layouts built around the existing interior of the port and the fairway out of the port (Fig. 10). The spatial distributions of differences of were assessed visually and based on virtual wave recorders in key locations in the port (Fig. 11).

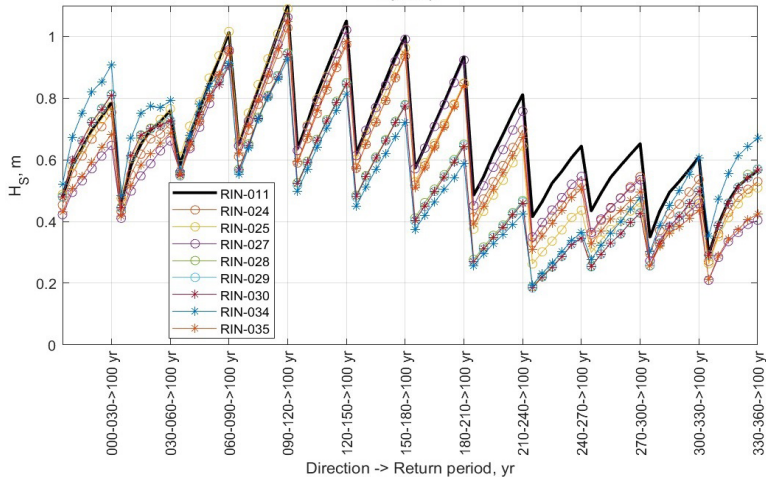


Fig. 11. Modelled H_s in the port interior (point 5 in Fig. 17) for breakwater layouts shown in the legend of Fig. 10. The layout RIN-011 reflects the current situation. The markers show values for extreme wind speeds with return periods of 2, 5, 10, 20, 50 and 100 years with a directional resolution of 30 °.

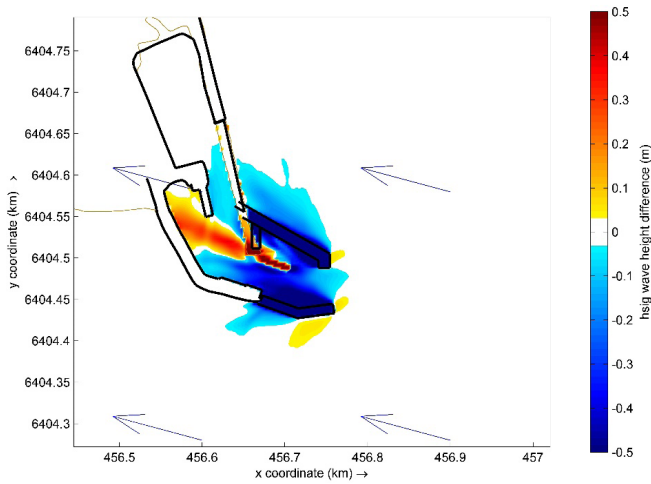


Fig. 12. Differences of H_s in an east-south-eastern storm that occur in the port area with layout RIN-030 compared with H_s that occur in the current (RIN-011) layout. Negative values mean that the wave heights are lower in RIN-030 layout. Blue arrows show the wind direction.

Consultations with the harbour owner (personal communication, January 2023) led to a conclusion that the best layout was RIN-030 (Fig. 12). It (i) reduces wave heights in the entrance channel and (ii) makes the entrance channel wider which is important for ship manoeuvrability. Also, (iii) small inner breakwater reduces the waves compared with other solutions and (iv) this layout is a cost-effective solution. A drawback of this solution is that wave

heights will be larger at the present berthing area in strong storms. This feature was not deemed a big problem by the owner. From the owners' viewpoint, the most problematic issue was moving a ship into the harbour through the narrow entrance. Wave reflection coefficients for obstacles are given in Section 3.2. We take this layout (called new (breakwater) layout for simplicity) as the basis of further analysis.

3.2. Phase-Resolving Modelling

Significant diffraction of wave energy often takes place around breakwaters, creating extremely complicated wave regime inside the port. This (often nonlinear) diffraction is challenging for phase-averaging models but can be captured by more local phase-resolving models. For this reason, the phase-resolving fully nonlinear potential flow model REEF3D::FNPF [28], [29] within the open-source hydrodynamics code REEF3D [30] was used to investigate the wave propagation inside the port for both the old and new breakwater layouts with various offshore wave directionalities.

The REEF3D::FNPF code solves the Laplace equation and nonlinear boundary conditions for the velocity potential and free surface elevation using the parallelized geometric multigrid preconditioned conjugate gradient solver provided by the *hypre* library [31]. High-order discretisation methods were used to further ensure the accuracy and stability of nonlinear and steep waves. For example, 5th-order WENO spatial discretisation [32] and 3rd-order Runge-Kutta temporal schemes [33] were used for the simulations. The code utilised a message-passing interface (MPI) for parallel high-performance computations, allowing multiple-processor large-scale simulations. A novel coastline algorithm

and robust breaking wave algorithm were introduced to the code to resolve most of strongly nonlinear coastal wave transformations [28]. A relaxation method [34] was used for wave generation and numerical beaches in the presented study.

The numerical domain focuses on the Port of Ruhnu and its offshore area to the SE, with east-west/north-south dimensions of 1250 m and 1000 m, respectively. The objective was to investigate what happens in both the old and new breakwater layouts and the effectiveness of the improvements. For each layout, three offshore wave directions were investigated, approaching from the east (90°), SE (135°) and NE (45°) waves. These waves propagate in directions roughly aligning with the port entrance and fairway and were thus specifically chosen as potential extreme scenarios associated with intense wave refraction in strong storms from other directions [6]. The new harbour layout is better represented in the numerical wave tank than the old layout thanks to the improved data fidelity especially around the new breakwaters and the western beach coastlines. However, the most relevant structures are sufficiently resolved to investigate the influence of the wave propagation and transformation in both scenarios.

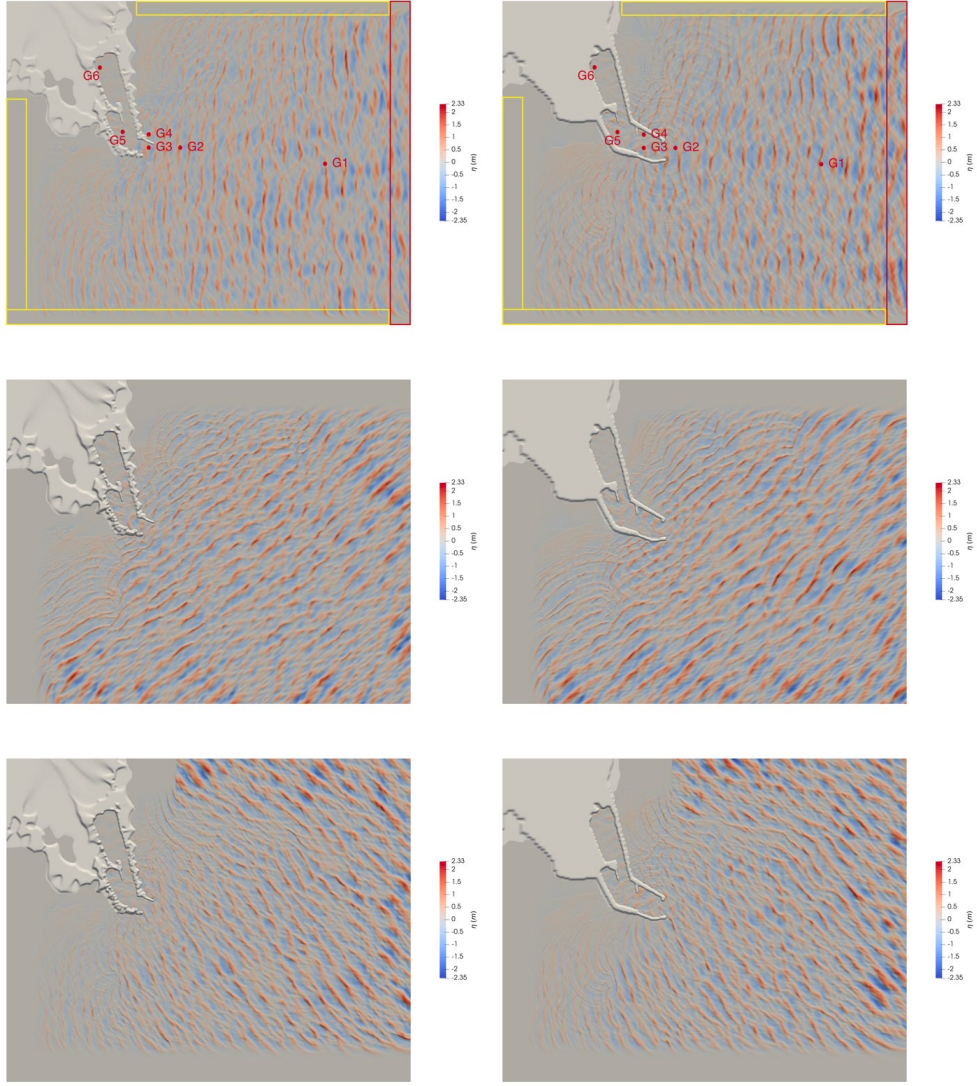


Fig. 13. Simulated wave surface elevation at the last simulation time step for both the old (left) and new (right) breakwater layouts with three offshore wave principal directions – East (top), SE (middle) and NE (bottom). The numerical wave gauges (nodes) are indicated as red circles in the uppermost panels. The red boxes are wave generation zones, and the yellow boxes are numerical beaches for the eastern wave case. The wave generation zones are allocated at the income wave boundaries with numerical non-reflecting beaches allocated on the opposite boundaries for the SE and NE waves.

Six numerical wave gauges (called (wave) nodes below) were arranged from the offshore area to the inner harbour (Fig. 13). The maximum H_s and the corresponding T_p were chosen based on the offshore SWAN simulation at node (Fig. 4) which was located at the eastern boundary of the phase-resolving computational domain, resulting in the

input irregular wave with $H_s = 2.2$ m and $T_p = 6.3$ s. A cell size of 2 m was used after a 2D grid convergence study, which ensured over 30 cells per wavelength corresponding to the peak period. The DNV(Det Norske Veritas)-recommended JONSWAP spectrum and a Mitsuyasu directional spreading function (e.g., [35]) with a shape factor 28

were used as input for the narrowly spreading short-crested multi-directional irregular wind-wave simulations. While 3.5 hours of simulations were performed for each scenario, the last 3-h time series was used for processing statistical properties of the wave

field. With 128 cores on the local computing station, each simulation took about 4 to 5 hours to complete. The numerical wave tank (NWT) configurations and the simulated free surface elevations for all scenarios are presented in Fig. 13.

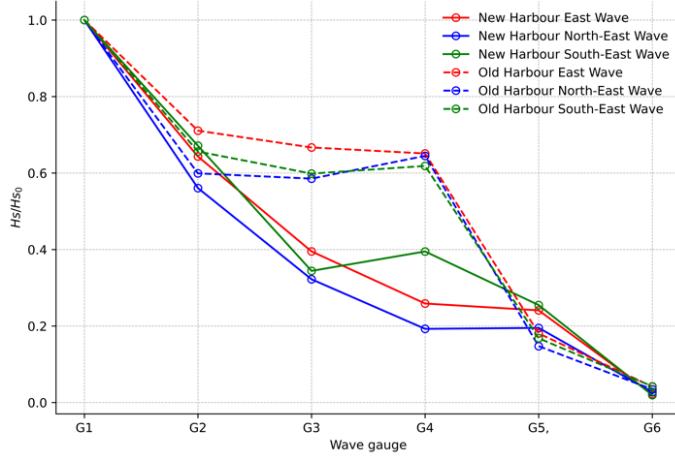


Fig. 14. Variations of H_s/H_{s0} from offshore to the inner harbour.

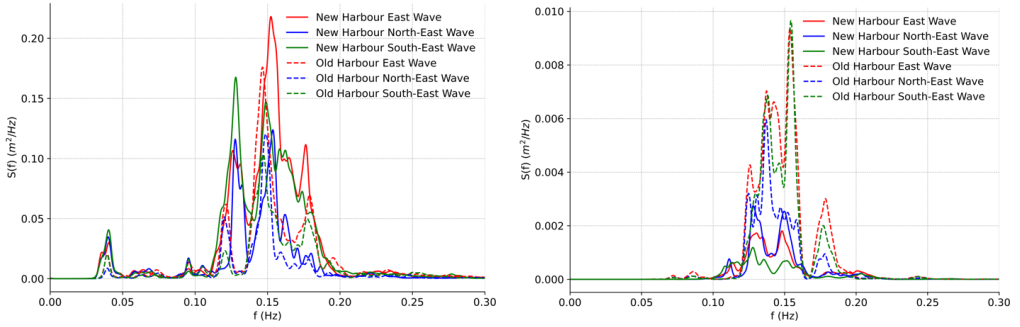


Fig. 15. Wave spectra at numerical wave gauges (nodes) 5 (left) and 6 (right) for the old and new breakwater layouts with various offshore wave directionality.

The H_s correlation factors to the input waves at the wave nodes for all scenarios are shown in Fig. 14. The extended harbour layout provides extended sheltered areas, as can be seen from the much-reduced waves at nodes 3 and 4. This is beneficial for the ferry navigations along the narrow entrance. The highest waves along the fairway are observed for southeast waves, as the H_s at

node 4 indicates, which is expected since the wave direction aligns with the harbour opening. The wave height reduction for the inner harbour area is less obvious when comparing H_s . To further illustrate the effect of the extended harbour, the wave spectra at nodes 5 and 6 at the inner harbour were compared in Fig. 15. Though the new layout reduces the H_s along the navigation

channel significantly, the wave heights and spectra at node 5 near the berth are quite comparable to the old layout. This feature is to some extent alarming; however, the significant wave height is about 0.2 m that is on most occasions not dangerous.

The wave spectra show a four-peak pattern for both layouts, which could be a result of the reflections from the compactly configured breakwaters. Such reflections might create resonance, standing wave patterns and infra-gravity waves which may be indicated by the increased low frequency peak around 0.04 Hz (25 s). Only about half

the energy is able to propagate towards the inner harbour at node 6 with the new layout in comparison with the old configuration. A four-peak spectrum pattern was also observed with the old harbour layout, especially a high-frequency peak near 0.175 Hz (about 5.7 s) containing a significant amount of wave energy. The new extended layout constrains the wave energy in a predominantly two-peak spectrum near the peak frequency. This bi-modal wave behaviour makes it simpler to avoid modal resonance when designing coastal structures.

3.3. Evaluation of Design Parameters for the Breakwaters

The design parameters of hydrodynamic loads to coastal engineering structures are commonly evaluated based on critical combinations of wave loads and water levels. The properties of these combinations may substantially vary depending on the wind direction in strong storms in the study area [27]. To comply with this feature, the reconstructed water level time series at Ruhnu (Section 2.4) was binned to different sectors according to the instantaneous wind directions at Ruhnu with 30 ° step. The resulting subsets were employed to evaluate very high-water levels with different return periods that are associated with different wind directions. As single projections of extreme water levels may have substantial uncertainties in the Baltic Sea basin [36], we use several versions of extreme value distributions to construct an ensemble of projections. These distributions are theoretical limiting distributions for maxima or minima (extreme values) of statistically independent and identically distributed samples [25].

We use the so-called block maximum method (e.g., [25]). To remove correlations between single maxima, one should consider only values that are sufficiently

separated in time. Monthly maxima and minima are often serially correlated in the Baltic Sea because of inertia of the formation of Baltic Sea water levels [37], [38]. Therefore, longer blocks are necessary for an application of this method. Even annual values could be correlated to each other. For example, the highest values of two subsequent years could occur during a windy period that involves December and January. Eelsalu et al. [36] compared extreme water level projections based on annual and so-called stormy season maxima (from July to June next year, [24]). The extreme water levels projected using the maxima over stormy seasons were usually higher than those based on the annual maxima. Following a conservative view, we rely on maxima of stormy seasons.

A large variety of empirical distributions of recorded water level data and the presence of outliers in the neighbourhood of the study area [9] suggest that none of the classic extreme value distributions perfectly estimates extreme water levels for longer return periods. It is reasonable to assume that the errors of projections made using single distributions are randomly distributed [36]. This assumption justifies

the concurrent use of several distributions to form an ensemble. Thus, we include results obtained using a general Generalized Extreme Value (GEV) distribution and its limiting case, a Gumbel distribution, into such an ensemble (Fig. 16). To provide an estimate of the lower limit of extreme water levels, we also included the 2-parameter Weibull distribution into the ensemble. It is likely that the average of such an ensemble

provides a sensible estimate of the true value of extreme water levels that is necessary for coastal design and management. The spreading of projections adds information about their possible bias and variability of these projections that are also needed in the assessment of engineering applications. We used a freely available general-purpose software tool *Hydrognomon* [39] for specification of parameters of these distributions.

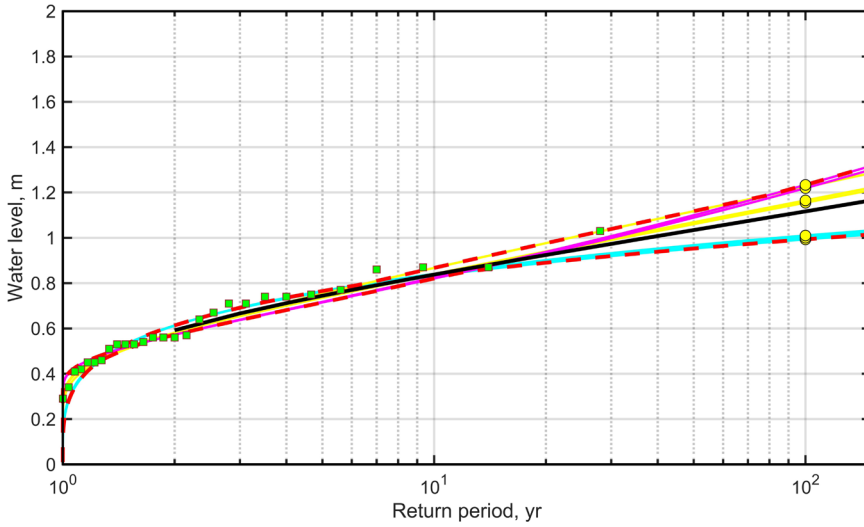


Fig. 16. Return periods of extreme water levels associated with wind directions 120–150 ° according to different projections at Ruhnu. Green rectangles show stormy season maxima and yellow circles depict water levels with return period of 100 yr for different projections. Yellow lines: projections using the Gumbel distribution; magenta – GEV distribution; cyan – 2-parameter Weibull distribution; black – weighted average of projections.

The developed ensemble for Ruhnu (Fig. 16) signals that the projections of extreme water levels form a narrow (width less than 0.2 m) corridor for return periods up to 30 yr. This time scale characterises half of the length of the underlying time series. For even longer return times the projections spread considerably. This spreading reaches about 0.3 m for a 100 yr return period, i.e., for the time interval that is almost twice as long as the time series.

The wind climate in the study area has greatly varying probability of strong wind

speeds from different directions [8]. We address this feature by addressing separately extreme wind speeds and their return periods for winds from different 30 ° wide sectors. To avoid serial correlation of maxima, we only included winds ≥ 10 m/s into the set of block maxima, thus concentrating on the events that dominate the extremes. It is likely that such samples are identically distributed. Extreme wind speeds from single sectors and their return periods are evaluated using a Gumbel distribution that is well suited to evaluate wind speed maxima [25].

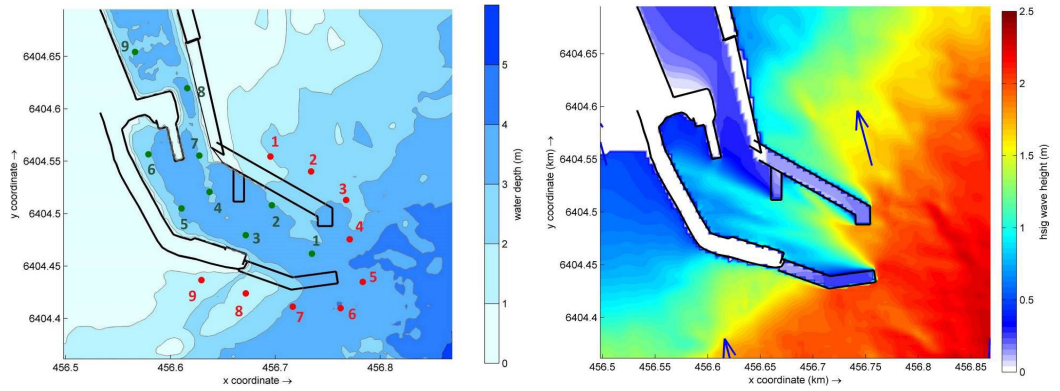


Fig. 17. Virtual wave gauges (nodes) of the Delft3D (SWAN) runs forced with stationary extreme wind conditions used for the final design of breakwaters (left panel). Black lines indicate the water line of the new layout. An example of the distribution of corresponding to extreme wind properties from south-south-east with 50-yr return period (right panel; wind direction is shown with blue arrows).

The projections of extreme water levels with different return periods were applied to describe increased water depths in the above-described four-level nested wave model SWAN (Section 2.2). This model was forced with homogenous unidirectional stationary winds from single sectors. Wave conditions were evaluated using extreme wind speeds with return periods of 2, 10, 50 and 100 yr until saturation of the wave field. The parameters (H_s , T_p , T_m , directions, etc.) of the resulting saturated wave conditions were analysed in several locations (virtual wave gauges or nodes) around the breakwaters and in the port interior. Following the recommendations from [40], the points were selected at a distance about 5

times H_s away from the toe of breakwaters (Fig. 17). These combinations of water level and wave properties were used to specify the design parameters of hydrodynamic loads to the elements of the proposed new layout of breakwaters. The resulting wave parameters were used to design the cross-sections of breakwaters. Wave parameters for navigation season (from April till October and possibly November) were calculated in a similar fashion. A map of significant wave heights in the vicinity of the port and in the harbour interior during the worst of analysed wave conditions attacking the harbour (Fig. 17) signals that the new layout provides sufficient protection for the inner harbour.

4. DISCUSSION AND CONCLUSIONS

The performed wave measurement campaigns, first of all, demonstrate that a kind of ultra-refraction that translates storm waves from virtually any direction into a wave system that propagates directly into the entrance of the Port of Ruhnu [6] is a highly interesting and instructive feature of the local environment and not just a spuri-

ous result of a wave modelling exercise. Still, a few multi-week measurement campaigns over past 3 years are not yet enough to exactly quantify all transformations of waves caused by strong (higher than about 15 m/s) winds. An appropriate quantification of these transformations requires much longer measurement campaigns.

However, the wave measurements provided vital data for validation of the wave models. As expected, the best match with the wave recordings obtained using several pressure sensors and two directional waveriders provided the 3rd generation wave model SWAN which was forced with the modelled ERA5 winds. Notably, this model systematically overestimated wave heights in the measurement locations.

Interestingly, wave properties modelled using homogenous one-point wind recorded in the local meteorological station on Ruhnu had comparable and in several occasions even better match with the recorded wave properties. This feature is similar to the outcome presented in [41] and encouraged the use of this kind of computationally much less expensive modelling exercises to analyse different layouts of the port and to calculate design parameters.

The correct specification of design parameters could not be done without proper water level data. The local water level recordings had long gaps. To address this shortage, it was necessary to reconstruct a “synthetic” time series of water levels by using the data from other water level stations in the Gulf of Riga and even on the Baltic proper shore of Latvia. This exercise showed that the best results were yielded by a linear combination of recordings from Roja and Salacgriva that are located at almost opposite sides of the Gulf of Riga.

The adequate design of harbour breakwaters has to take into account not only waves, water level and sediment movements, but also suitable fairway, bathymetry, access roads and other limiting structures in the harbour. These aspects set major restrictions for the improvement of the geometry and layout of breakwaters. Thus, the analysed layouts were focused on

improving and extension of the current layout. To evaluate advantages and disadvantages of 11 different layouts (out of which eight were presented above), wave and water level parameters for different return periods were modelled with the SWAN wave model, and resulting wave heights in key points in the interior of the port were compared. Although the phase-averaged SWAN wave model is not designed to be used in small basins, the comparison of its results with the output of phase-resolving REEF3D showed that it gave reasonable results and could be used in similar studies.

It is likely that, for any reasonably extension of breakwaters, the intrusion of sand into the port entrance will continue. It is likely that this issue could be mitigated using appropriately placed submerged breakwaters [42] that slow down sand motion similarly to the impact of tombolos [43]. The situation would still need regular monitoring of sediment transport and accumulation.

Perhaps the most instructive lesson from the variety of measurement, design and modelling exercises is that a combination of greatly different methods and approaches is needed to gather progress in solving a seemingly simple problem of re-design of breakwaters in such a complicated environment. Another lesson is that surprisingly simple models provide very good information in environments that possess extensive small-scale variability in geometry and bathymetry. However, they are not able to highlight particularly intricate features, such as the formation of a bi-modal wave system in the port interior. This information can be used for fine-tuning the breakwater configuration to provide better protection in the port interior by suppressing one mode instead of addressing the entire wave spectrum.

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