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EXTREME WAVES CONDITIONS AT THE ENTRANCE OF CONSTANTA PORT

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ABSTRACT

The aim of this study is to obtain the extreme wave propagation at the entrance of Constanta maritime port area, as well as the impacts on port operations. The wave propagation modeling took into account the bathymetry of the harbor in the area of interest, updated port extensions layout, measurements and digitized bathymetric maps. For the selected offshore waves directions, considered for the harbor entrance area, the incident waves of maximum impact and the peak period values corresponding to the extreme heights of the significant wave at different return periods were calculated. For this study it was used a mild-slope wave propagation numerical model. The model provided quantitative evaluation of the vulnerability induced by the wave agitation on the port developing areas and an overview on hydrodynamic conditions which are the basis for various shelter facilities developments in Constanta Harbor, in extreme events circumstances.
Keywords: modeling, wave propagations, extreme conditions, return periods, Constanta port

AIMS AND BACKGROUND

The Black Sea basin is the main influencing factor of the coastal climatic regime, changing the thermal balance and the sea surface roughness. These conditions give a considerable variability to the atmospheric circulation patterns, the registered wind parameters (direction and speed) showing a high degree of instability, without the presence of the regular winds. The winds variability above the Black Sea generates waves field, which are strongly related to the local specificities (direction, duration and intensity of the local winds), especially in the coastal area. Extreme wind waves have an significant negative impact on the coastal and offshore structures (beaches, berths, piers, sea dikes, quay walls, drilling platforms) and can lead the pollution of waters in the coastal areas. In the design of marine structures, is very important to analyse the extreme wave parameters, especially the return periods of significant wave height (Bondar, 2007).

In recent years, many researchers have conducted studies on the Black Sea basin based on different models like SWAN, WAM and MIKE 21 SW. Based on the SWAN wave model forced with the CFSR winds, Van Vledder and Akpınar determined the wind and wave characteristics in the Black Sea and investigated ”the sensitivity of wave model forecasts due to variations in spatial and temporal resolutions of the wind field products” (Akpinar *et al*., 2016). Divinsky using the MIKE 21 SW spectral wave model, estimate that in the Black Sea, at the south of the Crimea Peninsula, ”the heights of maximum waves can reach 18—19 m” (Divinsky *et al*., 2020).

Gippius and Myslenkov using the SWAN model forced by the NCEP CFSR and NCEP CFSv2, simulated the wind waves and obtained that in the southwestern areas of the Black Sea the maximal significant wave heights exceed 8.5 m (Gippius *et al*., 2020). At the northeastern and southwestern coasts of the Black Sea and at the southern coast of the Crimean Peninsula, the maximal values of significant wave heights are over 6 m.

Islek using SWAN hindcasts over the Black Sea with two different wind fields, analysis the Long-term of extreme wave characteristics finding that the southwestern part of the Black Sea ”is exposed to greater significant wave heights, longer mean wave periods, and storm durations compared to the rest of the Black Sea” (Islek *et al*., 2021).

Bașaran and Güner evaluated the effect of wave climate change on longshore sediment transport in Southwestern Black Sea by using a third-generation wave model (MIKE21 SW), forced by the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim wind (Bașaran *et al*., 2021). Many researchers simulated the wind waves at the Romanian Black Sea coastal zone. Rusu realised the wave modelling at the entrance of ports, analysed the extreme storm events in the Black Sea considering the results of a ten-year wave hindcast and gave the prediction of extreme wave conditions in the Black Sea with numerical models (Rusu *et al*., 2011).

In this paper, we proposed to study, using PHAROS model, the wind waves of extreme conditions at the entrance of Constanta Harbor.

EXPERIMENTAL

Constanta Harbor is both maritime and river harbor, offering shelter facilities for large maritime ships and for river vessels, due to the Danube-Black Sea Canal. The Harbor of Constanta has a total area of 3,926-hectares with an annual operating capacity of approximately 120 million tons, being served by 156 berths, 140 being operational.

The harbor is structured in two main areas: Constanta North area which includes 12 basins with 7-14m depth, 15.5 kilometers of quay and 82 operational berths. South Constanta area is partially operational and includes 14.6 kilometers of quay, 74 operational berths for containers, ores, coal, phosphates, bitumen, laminates and general cargo, a RORO and ferry terminal that provides connections to the Black Sea and Mediterranean harbors.

The external channel toward the Constanta Harbor has a width of 3,900 m and a depth of at least 25m and is positioned on direction of 141° N - 319° N. The access corridor has a length of 6.4 nm, a width of 0.8 nm, a depth of 21m, on NW direction. The exact direction is 322 degrees and allows the safe navigation of ships in one direction. The internal channel has different sections and an average depth of 19m. This channel is parallel positioned to the north breakwater which has a length of 8.34 km. The harbor exit corridor has the general direction to SE, (142 degrees), (Fig. 1).

Fig. 1 Constanta Harbor (source Google Earth)

Marine storms at Romanian coast occur with a relatively high frequency. The Black Sea offshore area is characterized by the active storm regime. Over one year the storms from the northern sector are predominant. Storms from the southern sector have the highest frequency in spring, when the wind speed values reach up to 40 m/s.

In the summer months the short wind intensifications with speeds of 14-18 m/s are present. Due to these values of wind speed and direction in the northern and southern sectors, the offshore wave's heights can reach 5m and even more. The frequency of storm surges in the Black Sea is lower, but can cause great damage, as the magnitude of sea level rise is 7-8 times higher than the sea level changes due to other factors. (Mateescu *et al*., 2010), (Niculescu *et al*., 2017), (Omer *et al*., 2015).

Thus, the storm surges in the Black Sea area can lead to the coastal water levels increase, with up to 1.3 m, above the mean level (Fig. 2).

Fig. 2 The North Breakwater of Constanta Harbor during a winter storm, the waves from NE exceed the northern port jetty (image source: NIMRD Study)

For recurrence periods the calculation of data sets recorded nearshore by National Institute for Marine Research and Development "Grigore Antipa" and offshore from ECMWF, based on the WAM numerical model, the Extreme library and the Julia language were used https://jojal5.github.io/Extremes.jl/dev/, as well as MATLAB routines including the statistical calculation of the POT method (Pick Over Threshold). The analysis of the extreme values of data set related to the second quadrant was performed in three stages:

1. Defining the extreme values related to the data set, with three statistical methods: (1) the *Initial Distribution* (ID) method, using all the data available through the log-normal distribution and *Weibull distribution* approach, (2) the *Peaks Over Threshold* (POT) method using only maximum

values above a certain threshold, distributed asymptotically Pareto (*Generalized Pareto Distribution* or GPD), as well as (3) the *Annual Maximum Method* using the maximum values per year distributed according to the *Generalized Extreme Value* (GEV) distribution.

2. Determination of a trend line (distribution) for selected data with extreme values, which consists in adapting the corresponding distribution for the selected data (because the extremes values to be determined generally fall outside the range of observed/modeled values, requiring extrapolation).

3. Determination of recurrence/return values (e.g. 1/100 years) using an appropriate data extrapolation distribution. For the second quadrant sectors (90° - 180°) the distributions mentioned above were used for the selected values of the maximum values at the storm. The maximum values of the storm parameters were selected for all offshore regime conditions exceeding a limit value (threshold).

Storm maximum values were filtered such that the consecutive maxima were separated by a selected period:

- maximum values at the storm were selected for wind speed above the limit of 10 m/s;
- maximum values at the storm were selected for the wave height above the limit of 2m;
- for both wind and waves, a minimum period of separation between the maximum values at the 48-hour storm was applied.

In the analysis of extreme values, the limit (threshold) is estimated based on the stability of characteristic parameters estimates of data set, by successive adjustments, graphically represented:

a) the shape parameter ξ as a function of threshold;
b) generalized Pareto scale parameter reparametrized σ^* as a function of threshold;
c) the return value for the recurrence period defined as a function of the threshold value (Rusu *et al.* 2006).

RESULTS AND DISCUSSION

All calculated extreme values of the offshore waves hydrological parameters (at 44°N 29°E) resulting from the ECMWF/WAM model for the directions of the second quadrant, from 120°N and 180°N, defined as the most impactful, considering the opening to the SE of Constanta Harbor and the different recurrence periods are presented as follows (Fig. 3 – 10).

The maximum values of the independent events that are higher than the minimum duration established per event (48 hours) are the maximum values that exceed the determined limit (peaks over threshold), for the selected data set (Fig. 5 and 6).

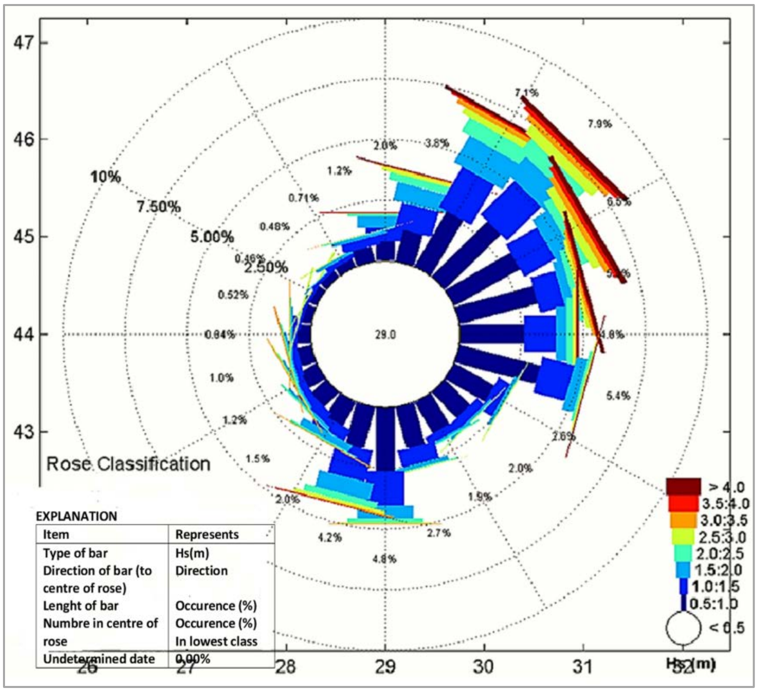


Fig. 3 Wave rose based on the WAM model multiannual data (1991-2002) in the coordinate point 44°N 29°E, approximately at 25 km off Constanta Port entrance

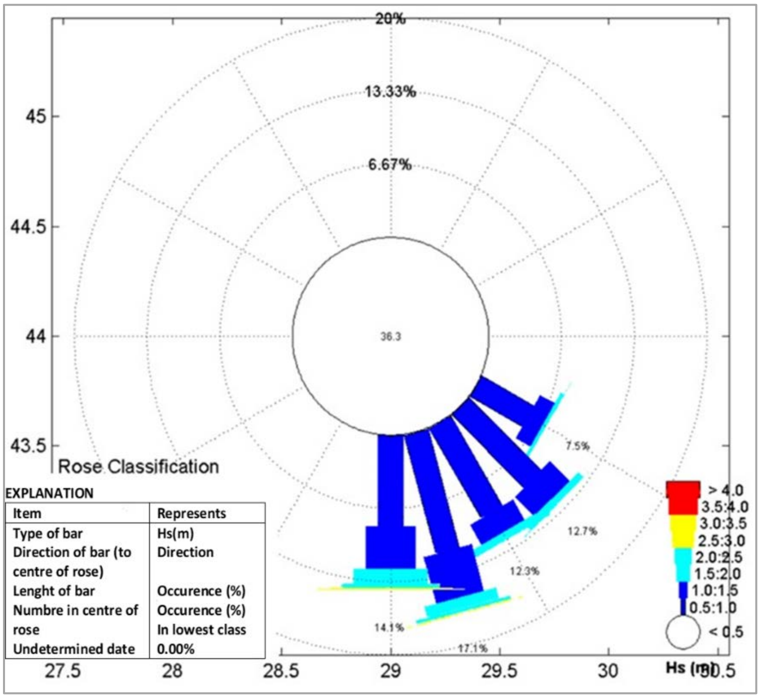


Fig. 4 WAM directional waves data set selection for second quadrant (120° -180° N)

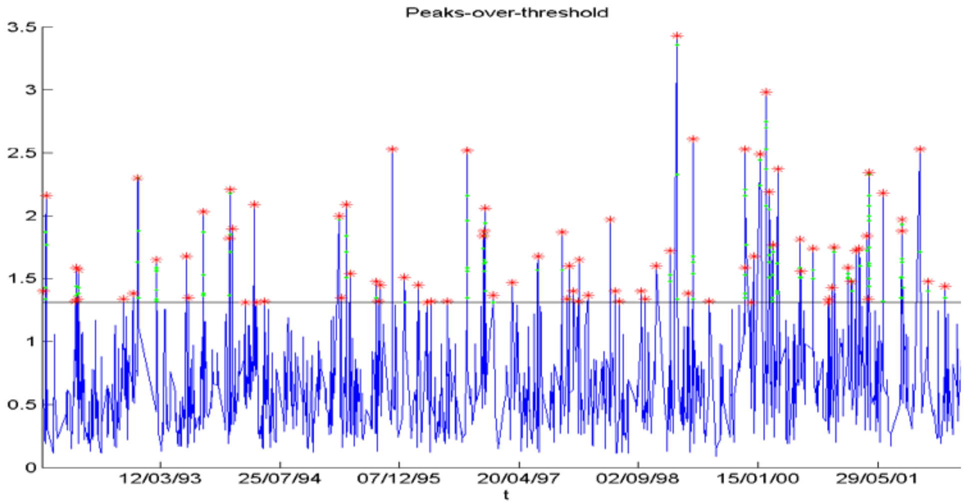


Fig. 5 Maximum values (above the threshold) for significant wave height, Hs (m), on y axis

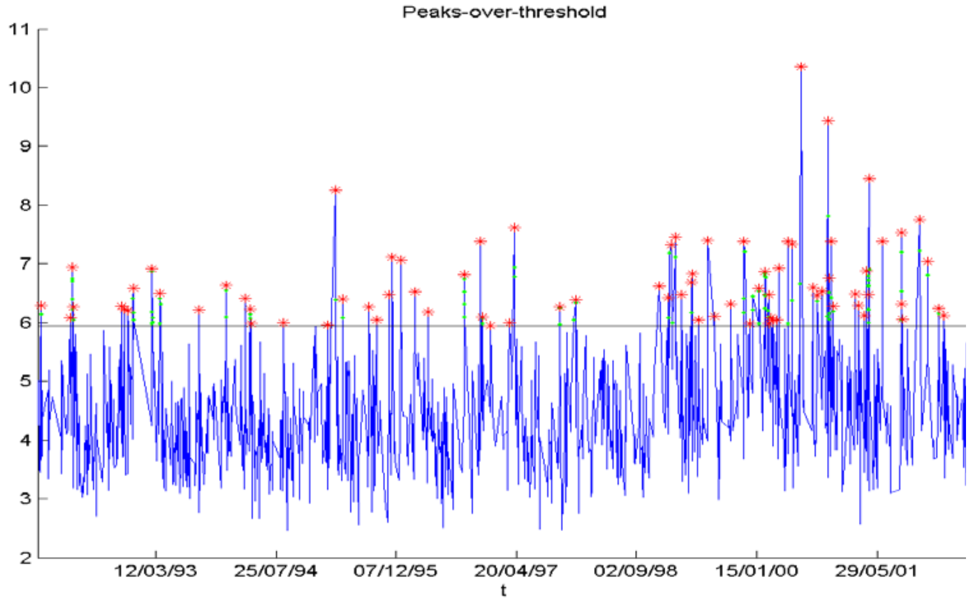


Fig. 6 Maximum values (above the threshold) of the wave period Tp (s), on y axis

The determined maximum values of the limits/threshold for the characteristic wave parameters were 1.3 meters for the significant wave height (Fig.7) and 5.95 seconds for the wave period (Fig.8). The three sub graphs shown in the figures 7 and 8 describe: a) the shape parameter ξ as threshold function, b) generalized Pareto scale parameter σ^* reparametrized as a function of threshold and c) the return value for the recurrence period defined as a threshold function.

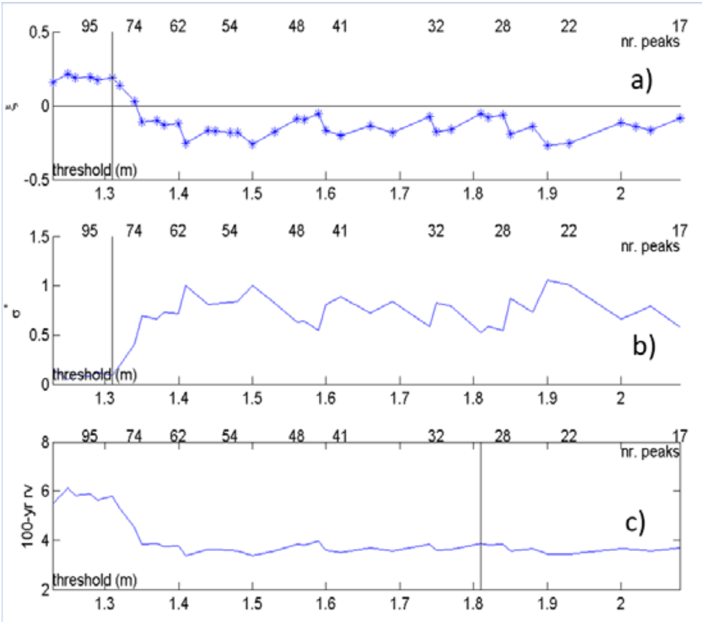


Fig. 7 Threshold values for significant wave height (Hs)

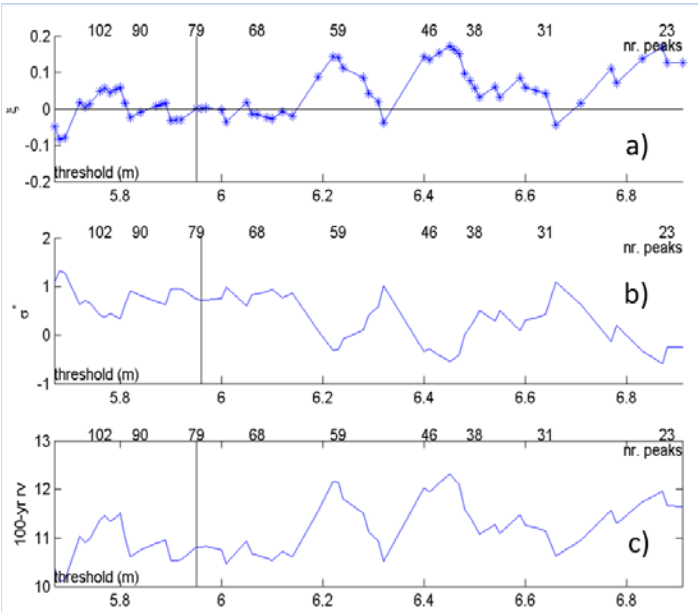


Fig. 8 Threshold values for the wave period (Tp)

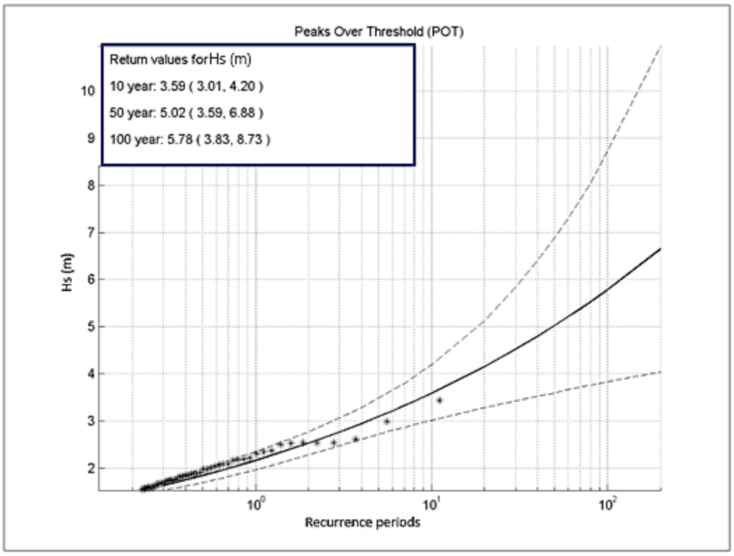


Fig. 9 Recurrence values for the significant wave height (Hs)

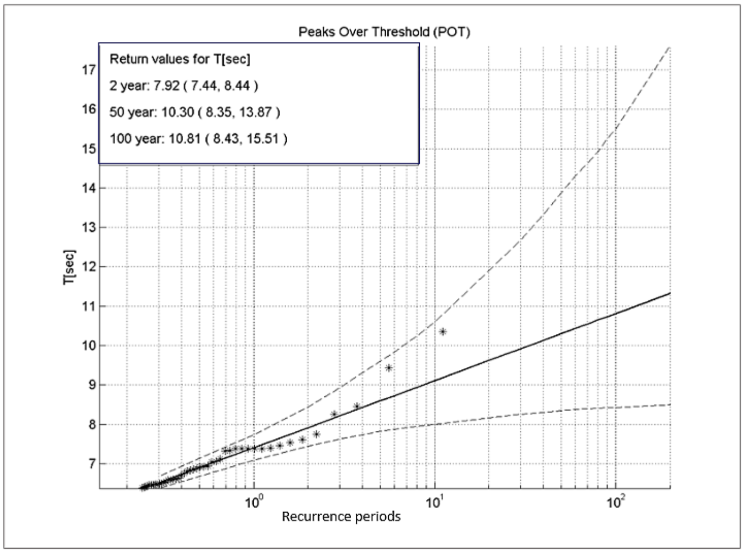


Fig. 10 Recurrence values for the wave period (Tp)

The return periods values result from studies (Table 1) will be used as input data for the running of wave propagation models within the harbor, selected in a JONSWAP wave spectrum, considered appropriate for the coastal conditions in the area of interest, as well as for several studies in the Black Sea (Rusu *et al*., 2006).

Table 1. Significant waves height and period for different recurrence periods for the second quadrant

Return periods (years)	Hs (m)			Tp(sec)		
	min	medium	max	min	medium	max
1	1.85	2.15	2.38	7.08	7.42	7.75
2	2.27	2.48	2.76	7.44	7.92	8.44
5	2.76	3.15	3.52	7.85	8.80	9.75
10	3.01	3.59	4.20	8.00	9.08	10.16
50	3.59	5.02	6.88	8.35	10.30	13.87
100	3.83	5.78	8.73	8.43	10.81	15.51

Taking into account the functions and configuration of the harbors, they will have to comply with the requirements of safe operation, which requires compliance with special requirements for harbor design, especially considering the mitigation of hydraulic conditions, but also the type of ships operations at the quay.

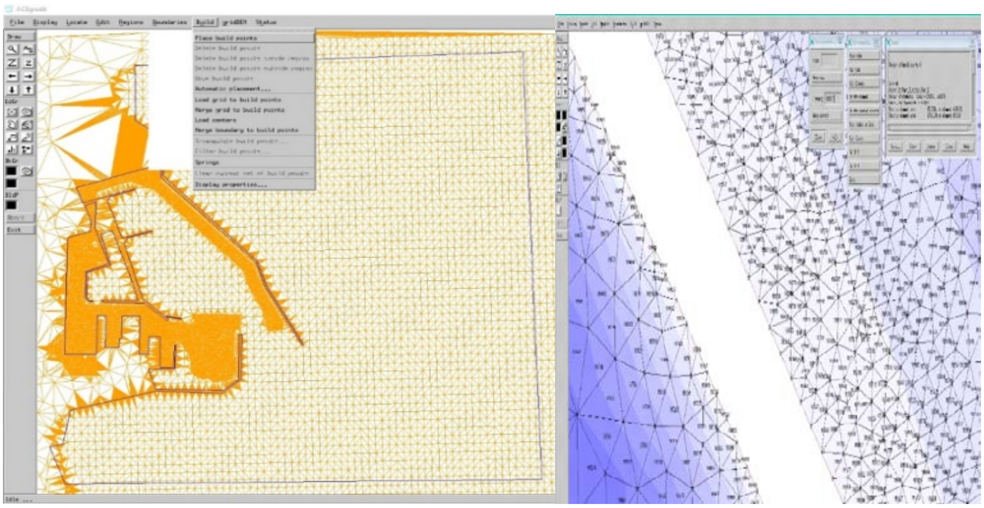
To observe the resonance effect of the basins, separated by the island of Constanta harbor and the reflective alignments with vertical quays, the PHAROS model developed by Deltares, Holland was chosen. PHAROS is an acronym for HARbor Oscillations software. The program solves the slight slope equation and includes the representation of the following hydrodynamic processes: refraction on an irregular depth profile, wave diffraction around structures, reflection or partial reflection through structures, transmission or partial transmission over (or through) structures, dissipation by wave breaking, bottom friction dissipation, propagation on a wind-induced current, directional scattering and spectral energy distribution.

The PHAROS model was implemented for Constanta Harbor to perform a simulation for wave propagation processes and basin resonance. The process governance equation used in the calculations is much more appropriate - mild-slope equation (eq. 1), used to describe the behavior of monochrome waves propagating in harbors in the presence of a wind-induced current (included optionally), considering the effects of energy dissipation (Kostense *et al.*, 1986):

$$\nabla \cdot \left(cc_g \varphi\right) + 2i\omega \cdot U \cdot \nabla_\varphi + \left(k^2 cc_g + \omega^2 - \omega_r^2 + i\omega\nabla \cdot U\right)\varphi = -i\omega_r W\varphi \quad (1)$$

where: ω is the monochrome wave pulsation (constant over domain) depending on depth, k is the wave number, c the wave velocity ($c = \omega/k$), c_g the wave group speed ($c_g = \partial\omega/\varphi k$), φ the complex potential of speeds, U the current velocity (U, V) T, W the energy source representing energy dissipation by breaking and rubbing the sea bed and ∇ is the horizontal gradient $(\partial/\partial x, \partial/\partial y)^T$, $(\partial/\partial x, \partial/\partial y)$.

The program has several modules, including pre-data and post-data processing modules, as well as four calculation modules, for specific hydrodynamic processes ("*long crested*", "*seiching*", "*directional spreading*", "*spectral*"), performed on associated Matlab compiler. To reduce the computing resources necessary for the development of the model, the propagation within the old harbor was blocked, following a focus on the area of interest, in development stage, according with the new port layout. The model grid was extended based on port new layout, with extended north jetty, but also port bathymetry, with accentuate nodes density for the access navigation channel and inner port developing areas (Fig. 11).



a) b)

Fig. 11 (a) Distribution and extension of boundary conditions after triangulation of bathymetric points and (b) the mesh nodes editing

The model was running for the selected critical directional waves and storm hydraulic conditions of calculated recurrence periods.

The JONSWAP spectrum was selected, using the gamma shape parameter and a corresponding adjustment of the frequency components contribution.

Thus, a JONSWAP spectrum was applied in combination with the cos-m expression for the directional width to create a wave energy spectrum - the directional stretching coefficient m was set at 8. The validation of the model results was done based on post event evaluations, or port authority recordings and field observation during a strong waves' penetration from SE direction inside the port. The wave heights in the areas of interest were estimated with the Pharos model as being the proper model to calculate the free-surface elevations associated with regular or irregular, long, or short-crested waves, including radiated or diffracted waves, over a mildly changing bathymetry.

The propagate free-surface elevations in the port entrance channel were estimate properly, considering the random nature of the sea waves, in particular the directional spread of wave energy in the critical direction of the second quadrant (120 degrees), the most impactful. As can be observed, the waves height decreases as the waves propagate further into the harbor basin. Near the harbor entrance the partial blocking effects of the dams are clearly visible, as well as the diffraction, including refraction, along the edges of the inlet channel (Fig. 12).

The model results provide the possibility to evaluate the wave penetration in the inner basin, and the widening of the influenced areas adjacent the new gap configuration after port extension, thus being feasible the assessment of the wave diffractions processes though the entrance. In association with this, the risk mitigation studies for port operations in a rapid changing wave climate, in the new climate change context, become possible.

It is considered the new improvements in term of complementary technical solutions for the wave's penetration control, in hazardous windy periods, including the use of the wave energy convertors, developed in different configurations, as mobile structures reducing the opening at the Constanta Port's entrance.

The diffraction patterns developed south, and westward areas shows a less significant perturbation of water-surface, and a good placement for a sheltered area, mandatory in the new developed maritime ports.

The propagation processes were observed from UAV in order to estimate the wave heights, as a validation method during the S-SE winds meteorological events. Despite the knowledge gaps to be filled with long term wave gauges installations in significant inner port area based on UAV observation can provide a quantitative model validation. A significant event of the wave propagation from SE direction was registered in 27^{th} June 2020, when waves of 1.2m height at the port entrance were produced wave of 0.8-0.9m height at the end of entrance channel, 6th km inside the inner first basin of Constanta harbor (Fig.13).

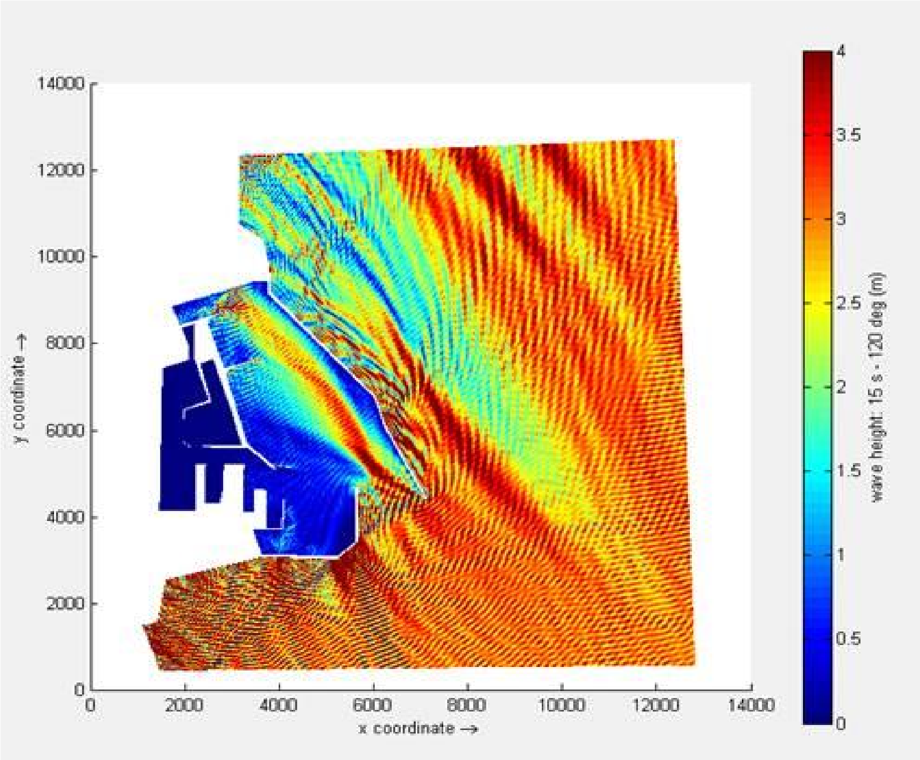


Fig. 12 Wave height spatial distribution in the area of Constanta Maritime Port, offshore direction 120°N – return period 100 yrs.

Fig. 13 Wave conditions with wind from the SE direction (in the area of Constanta's White Lighthouse)

CONCLUSIONS

Numerical simulations provide the offshore and nearshore waves climate for a better selection of harbor protection measures, establishing the hydrodynamic conditions/loads for various shelter facilities for ships in the storm, by establishing the average annual wave climate in different locations adjacent to the Black Sea North-Western basin.

The simulated results of the model provided a perspective on the performance of the northern dam extension of the harbor from the point of view of wave agitation.

The waves experienced in the berths related to the area of interest provides the necessary information for the quay dimensioning and the anchoring systems for different types of ships. Although a calm hydrodynamic regime inside a harbor cannot be completely characterized only by the height of the waves, this is the main aspect considered when the harbor expansion is planning. To validate the results of the numerical model applied in this study, it is necessary to perform *in situ* measurements of wave height, during winter storm periods, using Doppler current profiler, to calculate the wave reduction coefficient in the areas of interest with measured data. *In situ* and remotely observations with the UAV provided a qualitative assessment close for an estimate of this coefficient and the consideration of some covering reserves, considering the variability of the harbor hydrodynamic regime, accentuated by the new climate changes.

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