Cross-Shore numerical model CSHORE for prediction of sand beach and dune erosion – region of Coastal Research Station at Lubiatowo

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Circa 75% of the Polish coast is occupied by dunes. They form a natural flood and erosion barrier from marine processes. It is estimated that at the beginning of 21st century the mean rate of shore recession for the entire Polish coast was in the range of 1 ÷ 2 m/year and now tends to grow [11]. The Government will thus have to spend more money for coastal protection from erosion and floods (currently it is above € 10 million of public money per year, cf. Book of Law 2015, No. 0, item 1700, plus ca. € 100 million obtained from the EU between 2004 and 2015). On the other hand, it is estimated that large investments (such as a nuclear power plant, wind farm infrastructures and major gas pipeline from Norway and Denmark to Poland) will be located on dune coastal segments in coming decades.

For instances flood defence or protections against erosion are needed or when coastal infrastructures need to be constructed, the lacking knowledge about the rate and range of dune destruction due to extreme events, requires augmentation of the relevant safety factors of the planned structures, generating additional substantial costs. Apart from the negative financial implications greater safety factors, aimed at minimization of the probability of structural failure, achieved by such measures as increasing of dune crest elevation, artificial widening of a beach, deeper placement of pipelines, etc., is neither possible nor justified from the engineering point of view in the long-term perspective. Optimum solutions that harmonize structural safety and the assessment of failure risk of constructions located under beaches and dunes and in their hinterland primarily depend on the accumulated knowledge on physical processes occurring at sea – land interface.

RESEARCH GOAL

Based on the in-situ measurements carried out in natural conditions at Coastal Research Station Lubiatowo, the practical goal of the study includes adaptation and preliminary verification of numerical model CSHORE, based on phase-averaged equations of conservation of mass, momentum and energy, the phase-resolving wave and current models and morphological changes model. Adapted model is focused on theoretical reproduction of waves, currents, sediment transport, run-up phenomena and beach profile evolution of coastal zones.

The current state-of-the-art about morphodynamics of beach and dunes at a dissipative multiple bars coastal zones are far from comprehensive recognition. The modelling of morphological changes from the depth of seabed of ca. 1 m to the dune crest is done in a significantly simplified manner and the computational tools are mainly based on empirical formulations determined for local conditions. Since the paper is regarding to the prediction of rate and range of dune destruction, the review of state-of-the-art includes description of calculation methods of beach profile evolution processes.

STATE-OF-THE-ART

Bruun [3] proposed a method to assess the sea level rise induced shoreline retreat, based on the equilibrium profile concept. According to this approach, for sufficiently long high water level period, the cross-shore profile will change by retreating landward and the volume of eroded sediment will be deposited in such a way that sediment mass is conserved. Thus, long-shore shoreline changes are directly proportional to sea level rise. Edelman [9] refined the Bruun model; the updated equations required additional input parameters, such as an active dune width, depth of seabed for breaking waves before and during a storm, and the dune height relative of mean sea level. Dean and Maurmeyer [7] presented a model in which the dimensionless shoreline retreat was determined as the function of the storm surge and depth of seabed at a wave breaking location. The major difference between this model and the previous ones consisted in the fact that the previous models assumed instantaneous sea level rise and cross-shore profile adaptation, which in reality occurs much later. It resulted in vertical slope at the shoreline position of theoretical bathymetric profile, whereas the latter model produced a nearly triangular profile shape. Vellinga [31] further enhanced and improved this approach and Van de Graaff [29] adapted it for design of the required dune height on the Dutch coasts using probabilistic methods. Next, Kobayashi [14] proposed a new model combining mass conservation equation and empirical sediment transport formulas. As a result of this he came up with a partial differential equation, solvable for simple profile geometry. Kriebel et al. [16] presented an analytical model describing the volume of material eroded from the dune as the function of storm surge and dune geometry (dune height, its foot elevation and crest width). In this approach the main parameter generating the dune erosion is seawater level.

The main characteristic assumption of all those models was a discreet rise of sea level that remains constant during the entire storm duration. Sediment, eroded from the dune, is deposited on cross-shore profile in the vicinity of wave breaking location occurring for mean sea level conditions. The majority of models also assume that the retreating dune face takes a vertical shape and the profile tends to achieving new equilibrium configuration. In reality morphological changes are much slower than the underlying hydrodynamic regimes and storm duration is usually too short to generate new equilibrium configuration. A typical example of this kind of modelling was the Dutch model DUNE [8], adopted in Poland since mid 1990-s for the assessment of safety of dune beaches. This model, like all those that base on the equilibrium profile concept, overestimates the actual rates of dune erosion/degradation.

Fisher and Overton [10] and Nishi and Kraus [19] came up with different reasoning. In their models the total dune erosion is determined as a sum of impacts of waves running-up the beach. Hence, the total erosion during a storm depends on the frequency and intensity of individual waves. The wave impact was mathematically described as the change of momentum in a wave hitting the dune face. The volume of sediment eroded from the dune for a single wave was determined in wave flume tests [21, 22, 23]. The contributions by Fisher and Overton [10] were summarized in an analytical model by Larson et al. [17]. Its use requires the adoption of empirical coefficients adequate for site-specific conditions of a given coastal segment.

The latest methodology of determination of dune erosion is featured by the XBeach (*eXtreme Beach behavior model*) and CSHORE models. The XBeach model was tested in Delft Flume [24, 29] as well as in natural conditions [18, 25]. It has been widely used nowadays for computations of foreshore and backshore evolution of coastal segments with dunes [1, 4, 5, 12, 27, 32].

The details of the CSHORE model are available in [15]. The combined wave and current model operates under the assumption of longshore uniformity and includes the effects of a wave roller and quadratic bottom shear stress. The numerical integration of the depth-averaged energy, momentum and continuity equations results in predictions of wave height, water level and wave-induced steady currents. The development of physically defensible sediment transport algorithms for a nearshore breaking wave environment has been focused of the research efforts. The model accounts for wave and current interaction, bedload, suspended load and wave-related sediment transport. The CSHORE model represents total suspended sediment volume V_s with the expression (1)

$$V_s = \frac{e_b D_b + e_f D_f}{\rho g\,(s-1)\,w_f} P_s \tag{1}$$

where:
e_b – the empirical efficiency of breaking,
D_b – dissipation due to wave breaking,
e_f – the empirical efficiency of bottom friction,
D_f – the dissipation due to bottom friction,
ρg – the unit weight of water,
s – the sediment specific gravity,
w_f – the grain fall velocity,
P_s – the probability of sand suspension related to local turbulence levels.

The cross-shore and longshore suspended sediment transport rates q_{sx} and q_{sy} are expressed as

$$q_{sx} = a\bar{U}V_s \tag{2}$$

$$q_{sx} = a\bar{V}V_s \tag{3}$$

where:
$\bar{U}$ and $\bar{V}$ – the cross-shore and longshore averaged velocities
a – an empirical suspended load parameter.

Throughout the adaptation of the CSHORE model, the hydrodynamic and morphological change predictions have been preliminary verified based on data gathered at CRS Lubiatowo.

SITE INVESTIGATION
– COASTAL RESEARCH STATION AT LUBIATOWO

Topography of the coastal zone

The sand beach and dune under analysis are located on the South Baltic coast at Coastal Research Station Lubiatowo (Choczewo Community, Pomeranian Voivodeship), (Fig. 1). The seashore in this location is characterized by a gently inclined seabed (β ≈ 0.015). It is composed of fine-grained quartz sand with an average grain diameter of $d_{50} \approx 0.22$ mm. The thickness of sand sediments in the backshore zone is 3-5 m. In the seashore pro-

Fig. 1. Location of the sand beach and dune under analysis

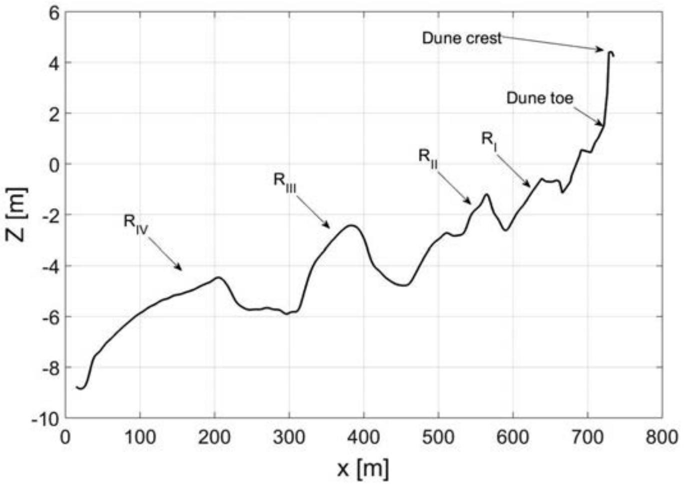

Fig. 2. Typical profile in the area of investigation

files, 3-4 nearshore bars occur. The first of them, R$_I$, is located at a distance of about 50 ÷ 70 m from the shoreline, the second (R$_{II}$) at about 100 m, the third (R$_{III}$) at about 300 ÷ 350 m, whereas the fourth (R$_{IV}$) and possible fifth at about 450 ÷ 550 m (Fig. 2). A significant proportion of the coast section under analysis is built of regular dune crests with height approx. 4.5 m. The dune toe ordinate in the profile analysed is about 1.5 m (Fig. 2), and the beach is about 70 m wide. The dunes in this region are protected by twig fences and reinforcing plants (Fig. 1) [20, 26, 28].

Nearshore zone hydrodynamics

Wave climate measurements at the site have been performed since 1997 by IBW PAN using the directional wave buoy located at depths of 16 ÷ 20 m. Tabl. 1 shows that waves from the western sector (SW, W and NW) occur over 50% of the year,

Tabl. 1. Root mean square wave height occurrence [in %] for different wave height classes and wave directions

Root mean square wave height H_{rms} [m]	N	NE	E	SE	S	SW	W	NW	Total
0.0 ÷ 0.5	3.06	6.84	5.72	0.32	1.31	0.38	8.35	3.19	29.18
0.5 ÷ 1.5	5.90	12.60	2.75	0.11	0.18	0.04	21.74	4.00	47.32
1.5 ÷ 2.5	3.06	3.22	0.02	0.00	0.00	0.00	10.94	2.23	19.47
2.5 ÷ 3.5	0.99	0.20	0.00	0.00	0.00	0.00	1.73	0.50	3.42
> 3.5	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.61
Total	13.5	22.9	8.50	0.43	1.49	0.41	42.76	10.03	100.0

Tabl. 2 CSHORE wave and morphological parameters identified for CRS Lubiatowo site

Shallow water ratio of wave height to water depth	Sediment diameter [mm]	Specific gravity	Suspension efficiency due to breaking	Suspension efficiency due to friction	Suspended load parameter	Bedload parameter
$\gamma = 0.5$	$D_{50} = 0.3$	$\gamma_s = 2.65$	$e_b = 0.003$	$e_f = 0.01$	$slp = 0.3$	$blp = 0.001$

those from the eastern sector (NE, E, SE) over ca. 32% and those from the shore normal sector over ca. 13.5%. The most frequent waves are those from the 0.5 ÷ 1.5 m height class, occurring over ca. 47% during a year. Tabl. 2 presents the rates of occurrence [%] for significant wave heights for given height classes and azimuths of wave direction [24].

Sea level (storm surges)

In most seas, tides are the key factor responsible for sea levels. In the Baltic Sea, the tides are insignificant, in the range of a couple of centimetres so the Polish maritime area is defined as a non-tidal region. The representative water levels corresponding to given probability of occurrence for the CRS Lubiatowo are adopted from the nearby mareographic station at Ustka Port [2]. The long-term mean water level amounts to about 500 cm. The absolute maximum and minimum of seawater levels at CRS Lubiatowo (Ustka Port) from mid 19th century until 2007 are [2]:

- absolute maximum – 668 cm, recorded on 15th Dec. 1898,
- absolute minimum – 396 cm, recorded on 10th Feb. 1897.

PRELIMINARY CALIBRATION OF CSHORE MODEL

In order to carry out a preliminary verification of CSHORE model, the following research methodology was applied. At the depth of seabed of ca. 20 m a wave buoy DWR-7 Mk. III was positioned (Fig. 3). This instrument is capable of measurements of wind waves parameters – their height, period and angle of approach from offshore directions. The waves running from offshore directions encounter shoaling sea bottom with nearshore bars on their way to the shore. This causes their transformations (changes of geometry) and, after passing of critical depth, breaking. In order to measure the changes of wave geometry in the area from the depth of ca. 4.5 m (point D2 on Fig. 3) through 2.5 m (point D1 on Fig. 3) up to 0.5 m (point D0 on Fig. 3) (corresponding to the offshore distances of 450 m, 250 m and 50 m respectively) the parameters of wind waves were recorded in that area. Due to the technical limitations the data obtained at D0 point were not used for the calibration investigations. Fig. 3 presents the measuring set located in the nearshore region.

The measurement period between Sep. – Nov. 2016 was used for preliminary verification of the CSHORE. The detail description of measurements carried out at CRS Lubiatowo 2006 could be find at [13]. Fig. 4 and 5 presents the comparison of the measured and calculated wave heights at locations D1 and D2. A comparison of CSHORE results with the observations (Fig. 4 and 5) shows that with the nominal formulations of the physics, the average RMS error is about 15% of the incident significant wave height for both D1 and D2 locations. In particular, modelled wave height during storm events is temporarily and short-term overestimated. Nevertheless, the agreement between numerical model and in situ measurements results is certainly sufficient.

The calibration of seabed evolution module was based on bathymetric surveys and tachymetric records done in Sep. 2015. Those measurements were done on 4th and 16th Sep. 2015 and included both bathymetric and tachymetric measurements of the nearshore zone and emerged beach at CRS Lubiatowo. Those measurements were done, using GPS Leica VIVA, along 400 m long coastal segment; the bathymetric profiles were evenly spaced every 25 m and reached the depth of seabed of 7 ÷ 8 m, some 700 m offshore. On land the tachymetric records included the dry beach up to the dune crest. The computations were based on the mapping of stormy conditions occurring in the same period (4th – 16th Sep. 2015 – Fig. 6, 7 and 8). For that purpose wave parameters were set at the offshore boundary of computational numerical grid. Those hydrodynamic parameters were provided by the directional wave rider buoy with the time step of 1 hour. The computations also included sea water level changes, which varied with the same time step of 1 hour.

Figure 9 contains the calculated and measured changes in beach and seabed at the centrally located bathymetric/tachymetric profile of the investigated coastal segment. Both the measured and calculated quantities demonstrate their high similarity.

Tabl. 2 presents the values of CSHORE parameters determined during the preliminary calibration of the numerical model.

The analysis of results points out that the following conclusions:

- due to low rise of sea water level during the storm both the measured and calculated changes of beach elevations practically did not vary from initial beach configuration,
- disintegration of beach berm, located in shoreline vicinity, was much less pronounced in the calculations than in reality,
- the seabed portion in close shoreline proximity, up to ca. 100 m offshore, was modelled accurately; the results of computations closely matched the actual seabed evolution during the investigated storm,
- the results of computations in the vicinity of the innermost bar indicates it should have retained its stability; in reality the crest of that bar moved 5 – 10 m offshore,
- the changes of seabed in the trough between the 1st and the 2nd bar were modelled fairly accurately,

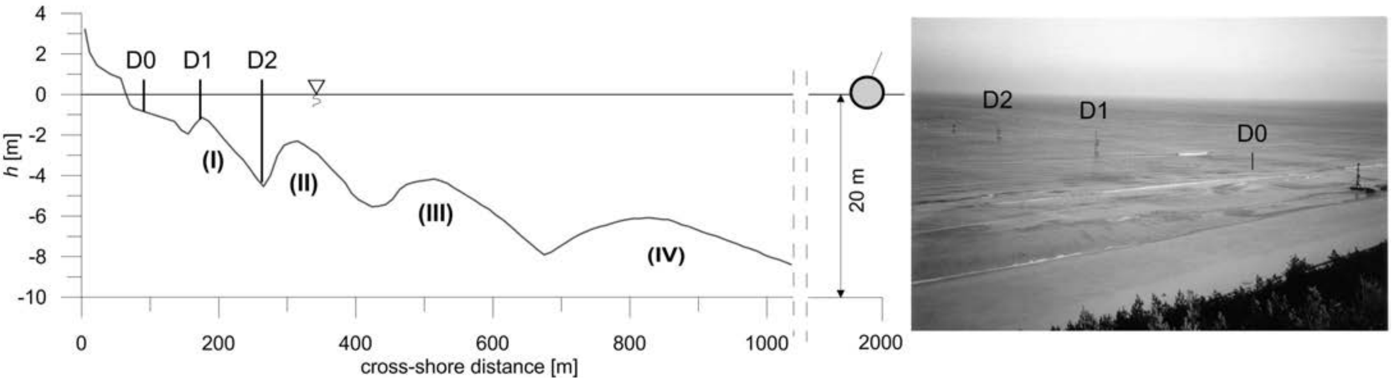

Fig. 3. Measuring set (wave parameters) located at CRS Lubiatowo, D0, D1 and D2 – location of waves recorded

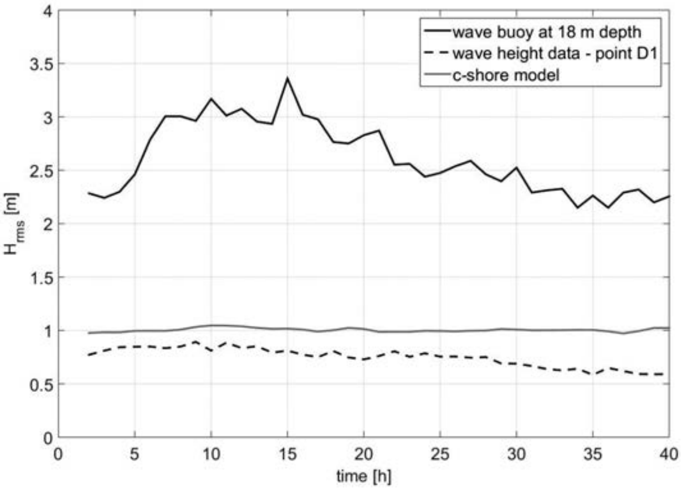

Fig. 4. Comparison of the time series of the root mean square wave height H_{rms} at location D1

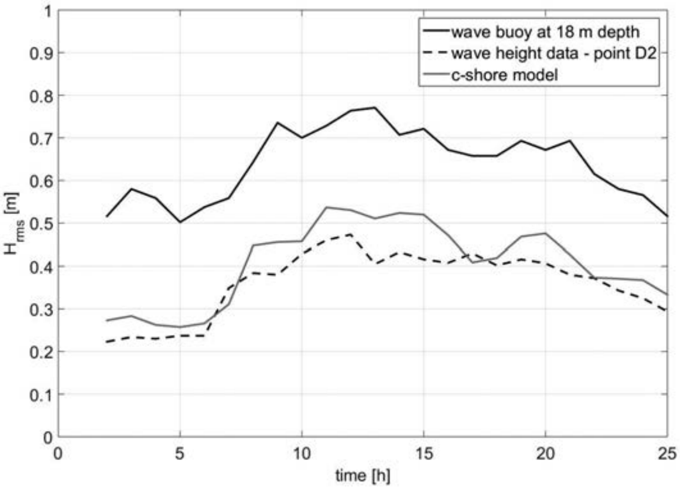

Fig. 5. Comparison of the time series of the root mean square wave height H_{rms} at location D2

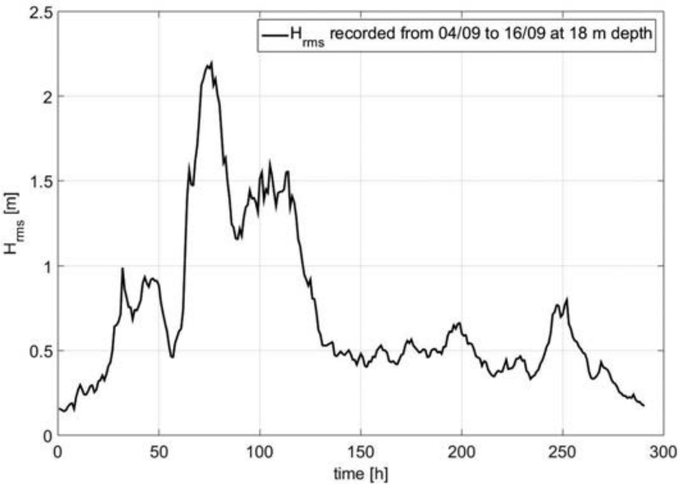

Fig. 6. Root mean square wave height H_{rms} [m] recorded during a period 4th ÷ 16th Sep. 2015

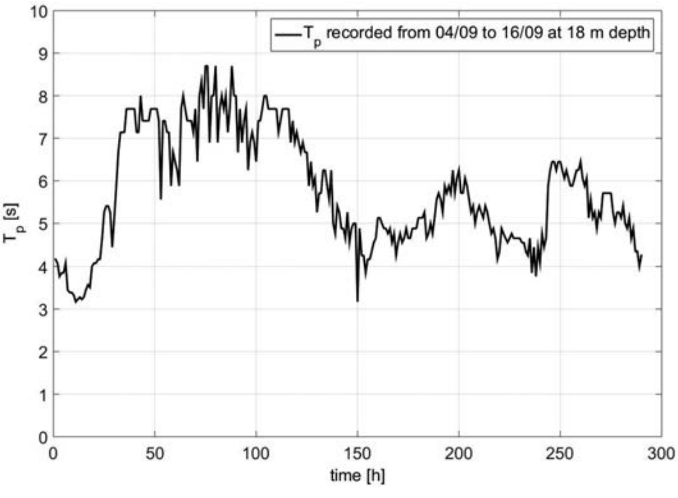

Fig. 7. Wave peak period T_p [s] recorded during a period 4th ÷ 16th Sep. 2015

– the calculated reduction of the height of the 2^{nd} bar was 0.2 – 0.3 m greater than the actual change of seabed there,

– for the region more than 400 m offshore both the calculated and measured changes of seabed were very close to each other.

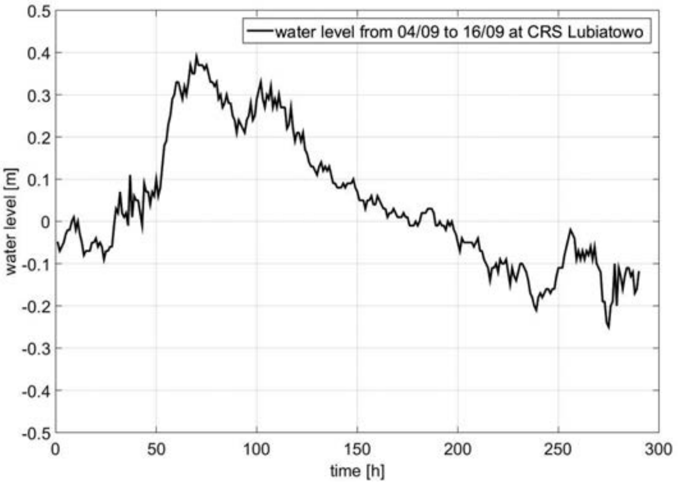

Fig. 8. Water level recorded during a period 4th ÷ 16th Sep. 2015 at CRS Lubiatowo

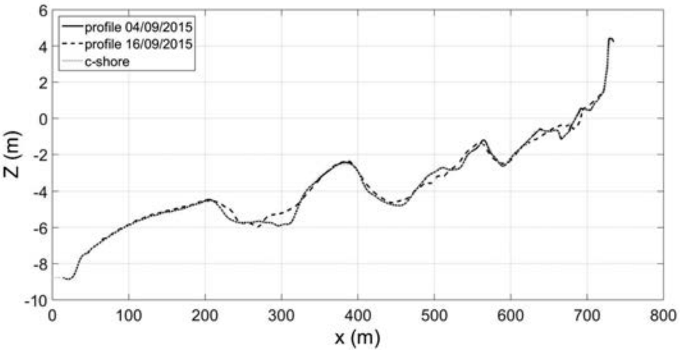

Fig. 9. Comparison of measured and calculated seabed changes between 4th and 16th Sep. 2015

CONCLUSIONS

Based on the measurements and wave climate calculations, done for Sep. – Nov. 2006, and bathymetric/tachymetric seabed and beach records, done twice in Sep. 2015, the credibility of the CSHORE mode is difficult to be clearly assessed. Despite fairly accurate reproduction of the wave climate in dissipative nearshore zone with multiple bars, typical for the south Baltic Sea region, interpretation of the results produced by the seabed evolution module is not straightforward. This ambiguity can be related to three phenomena. First, multiple bars generate multiple wave breaking processes in the nearshore region. They may produce a number of nonlinear and quasi-random processes that cannot be captured by the numerical model. Next, the studied storm was featured by fairly low surge and rather averaged wave conditions, so those phenomena have contributed to rather insignificant fluxes of wave run-up energy. This prevented a serious study on storm induced dune damage or destruction. Fairly accurately predicted changes in the depth of seabed in the region of more than 400 m offshore could result from rather low energy waves and currents that were unable to produce substantial seabed evolution in that region. The repetition of computations for more intensive or significantly longer high energy hydrodynamic events should allow for fully credible model validation. Third, the remainders between the measured and computed morphological changes are related to a number of physical parameters of the sediment, such as diameter, specific gravity and buoyancy, which interact with a number of textural properties including compaction, sorting, grain shape and roundness. Seabed roughness and viscosity at seabed-water interface contribute to additional complexity. This multitude of parameters can produce much different transport rates of apparently similar sediments, set in motion by the same hydrodynamic forces. Therefore, the transport of marine sediments is a highly random process, as both sediment distribution over the seabed and hydrodynamic forces are random as well. A certain remedy to this complexity is the approach suggested by Callaghan [6] in which it is assumed that since some theoretical assumptions of Navier-Stokes equations cannot be satisfied in the shallow water region ranging from the depth of ca. 2 m up to the run-up region, deterministic modeling of water motion there is not feasible. Callaghan [6] postulates this region should be described using a stochastic-probabilistic approach. Such approach is based on the analysis of the measurements of past seabed bathymetries and beach topographies contrasted with the corresponding records of hydrodynamic regimes. Using that information a probabilistic scale and range of seabed changes is constructed for given hydrodynamic conditions. This approach has not yet been verified for the conditions of south Baltic Sea coasts. It should be verified whether the application of such a probabilistic concept shall provide more precise description of seabed and shoreline evolution for shallow water depths less than 2 m up to the zone of wave run-up.

Despite the above critical remarks, the preliminary verification of CSHORE model indicates that this model can be applied to computations of wave transformation and seabed evolution at dissipative, nearshore zones of the south Baltic Sea coast that contain multiple bars.

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