DEFORMATION OF COASTAL PROFILE DURING DIFFERENT STORM PHASES

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The aim of the work is to describe the mechanisms controlling the sediment transportation at different stages of the storm cycle including three main phases, namely development, stabilization and attenuation. The resulting morphological effect of the considered storm depends presumably not only on its strength, but also on the relative duration of the destructive and recovery phases. Two full-scale experiments conducted on the Bulgarian coast in 2016 and 2018 provided materials on the shore profile dynamics under conditions of storm waves. It proved that the profile deformations usually considered to be seasonal may happen in the course of a single extreme event of once a year frequency. Field experiment data analysis proved the concept that long mild waves move sediments onshore (cause accumulative profile) and short steep waves create erosional profile with sandbar. In studied case waves steeper than 0.02 create sandbars and milder than 0.02 – transport sandbars onshore. It was observed that in some cases accumulative phase corresponds to decrease of the peak period while mean period stays unchanged, which indicates narrowing of the wave spectrum.

Keywords: coastal profile, structure of storm event, underwater sand bar, beach recovery

INTRODUCTION

The problem actuality and the level of knowledge

The prediction of the sandy coast deformations by a storm is of considerable importance both from the scientific and practical points of view. The practical purposes most often consist in estimating the possible coast erosion at the maximum intensity of storm waves. At the same time, when dealing with the problems related to the coastal sediment budget we should take into account specific features of the recovery phase of storm noted for a dominance of the onshore sediment transport. When we state the problem in this way, we have to determine the mechanisms that control the sediment transport at different stages of the storm; or, to put it another way, not only the maximum erosion phase is to be estimated, but the entire structure of the storm cycle should be analyzed.

The structure of storm events is taken to mean the character of the wave energy distribution in time over the storm period (Yurkevich, 1977), or to put it another way, a relative importance of waves with different parameters, that is to say, the duration of individual phases of the storm (Dolotov, 1988). The storm includes three principal phases: development, stabilization, attenuation. The storm wave development is due to wind increasing in intensity, when the waves gain in height and steepness. The phase of the storm stabilization is noted for a steady wave regime. The wave attenuation is typically distinguished by a general decrease of the wave characteristics and the dominance of swell waves (Dolotov et al., 1982). At the phase of the storm development the sediments are transported seaward and the shore is subjected to destruction; while the storm attenuation may be attended with a part of the loose material to be returned to the beach (beach recovery). The resulting morphological effect of a given storm depends not only on its strength, but also on the chronological structure, that is on the distribution of different storm phases (destructive and recovery ones) over the time. The post-storm relief in the littoral zone depends heavily on the processes during the wave attenuation phase, the shore is being restored and the sediment balance formed.

The shore profile deformations during a storm cycle are comparable with seasonal changes. The concept suggested by V.V. Longinov is based on the observations of the seasonal changes in the wave regime; as stated by that author, the seasonal changes in wave regime “do not appear as an abrupt transition from low-energy wave regime in summer to higher-energy waves in winter, but proceed by way of gradual increase in wave energy in a series of subsequent storm events” (Longinov, 1963, p. 340). The influence of the seasonal wave climate on the shore profile morphology may be described by two limit states possible for the shore topography. F.P. Shepard (1950) having studied the processes on the California coasts described the two states as winter profile with one or a few sandbars (barred profile; Fig.1) and summer profile depleted of bars (non-barred profile). Later on, those observations have been repeatedly confirmed (Inman et al., 1993; Yates et al., 2009). In comparison with the winter profile, the summer one is distinct for a greater slope near the shoreline and is more advanced seaward.

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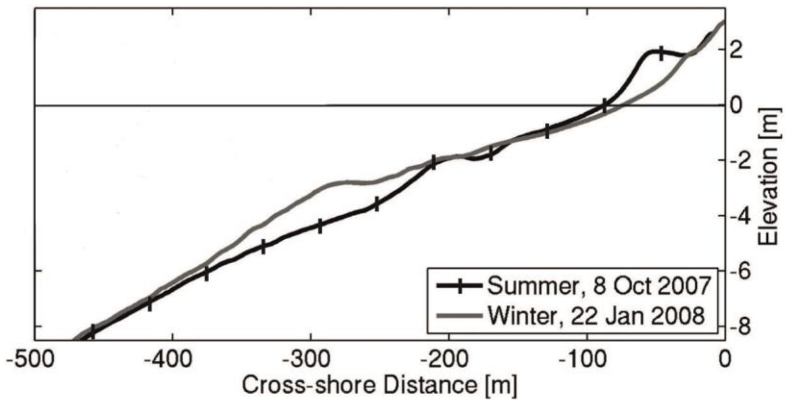

Figure. 1. Comparison between the summer and winter shore profiles (San Diego, California, the USA; Yates et al., 2009)

A conceptual model of the sandy shore evolution developed by Australian scientists (Wright, Short, 1984), the limiting positions of the beach profile are interpreted from the standpoint of the wave energy dissipation: the authors distinguish the dissipative beach profile (analogous to the winter – barred – profile) and reflective one (an analogue of the summer, or non-barred, profile). Intermediate states are marked by the stages in the submarine bar evolution: longshore bar (corresponding to a high degree of the wave energy dissipation); crescentic bar, joining the beach in places of protruding cusps; and a wave-built terrace adjoining the shore (the state closer to reflective one).

Unlike the oceanic coasts of Australia and California, the coasts of smaller water basins noted for shorter wave fetch distances and lesser wave energy are closer in the characteristics of the beach landforms to the intermediate states described in the above conceptual model (Wright, Short, 1984). In the case under consideration the beach profile bears a system of submerged bars; as to the seasonal changes, the dissipative component is dominant in winter and reflective one – in summer. The type of the coast morphology cannot be determined unequivocally, as dissipative and reflective elements vary along the beach profile. In this connection there has been suggested the notion of "bimodal state" (Goodfellow, Stephenson, 2005), describing the situation when the wave transformation results in oppositely directed processes on different morphological elements of the beach profile. The shore morphodynamics may vary depending on the stages of wave regime and is probably controlled by the state of the outer submarine bar; the mobility of the latter depends on a complicated combination of factors (bar dimensions, the sediment grain size, the bottom slope, and wave climate). Depending on the wave intensity, outer bars may either be displaced in relation to the coastline, or keep a relatively stable position. The outer submarine bars exert an influence on the transformation of lesser storm waves and control the system of inner – more mobile – bars.

As follows from the integrated studies of the coastal lithodynamic systems based on field data and mathematical simulation (Aleman, Robin et al, 2013, Gervais, Balouin, Certain, 2013, Price, Ruessink, Castelle, 2014), the systems bounded by the crescentic bar on the seaside are modeled to a considerable degree by the cellular circulation, the topographic changes in the littoral zone being mostly three-dimensional. The horizontal circulation gains in importance and the landward transport of detrital deposits proceeds easier even in case of not so strong storms. The key factor controlling the rate of beach recovery is the duration and characteristics of the storm attenuation stage. The studies performed strongly suggest that three-dimensional deformations of landforms gain in complexity under conditions of storm wave regimes varying in intensity and structure; the problem of their evolution forecast depending on those factors is still of current concern.

The considered investigations were aimed at the defining morfodynamic response during different storm phases. In particular, the task is to elucidate hydrodynamic factors responsible for the erosion of sandy coastal profile and recovery of beach relief bounded on the seaside by a submarine crescent-shaped bar.

Study site

The approach to the stated problem was based on results of two field full-scale experiments performed in October-November 2016 and October-November 2018 on the study site of the Nansen Institute of Oceanology, Bulgarian Academy of Sciences (Varna). The study site at Shkorpilovtsi settlement is equipped with a research pier 230 m long which permits to make measurements and observations at a depth up to 5 m at a distance of 200 m from the coastline. The experiments included synchronized instrumental measurements of the bottom topography changes and wave conditions.

The place where the stationary observations were performed is positioned on a relatively straight segment of the coastline oriented approximately from north to south and open to waves and winds. Typical of the region are depositional coasts, less common are erosional-depositional ones. The Kamchiya-Shkorpilovtsi beach was studied over a 13 km stretch; the beach is well developed and forms a wide continuous zone along the coastline.

The coast is composed of Quaternary deposits mostly of fluvial and littoral origin. In the region the sources of detritus are mostly sedimentary rocks; that accounts for the sediment particles being relatively fast involved into motion and then carried by waves. As a result, a thick sand series is formed at the base of the shore profile. The deposition is promoted by the input of alluvium by the rivers Kamchiya and Chairdere in the north and the Fundaklyiska near Shkorpilovtsi; the nearby sea cliffs eroded by waves present another source of material. Besides, a factor responsible for the deposition is a considerable width of the shelf in the region (~40 km) which attenuates the oncoming waves, hinders the sand removal from the beach and promotes its accumulation (Kaplin et al., 1991).

The beach near the study site is 30-50 m wide and adjoins the upper-lying coastal dune zone 100-200 m wide, which is the present-day marine terrace (fig.2). At present the zone is out of the wave action. There are preserved older landforms formed earlier by waves and then modeled by eolian processes. Median grain size of sand deposits on coastal profile - 0.3 mm (Keremedchiev, Trifonova, 2003).

Figure 2. Beach and the coastal dune zone in the region of the full-scale experiment

The submerged beach profile with a slope of 0.025 on average has a series of bars. The outer bar is distinctly crescentic in outlines, which is well readable in space images taken at different times (fig.3). The outer bar profile may vary notably depending on the wave climate in the preceding time interval. The same are reasons for its displacements with reference to the coastline and changes in configuration observed at different times. There is also an inner bar nearer to the shore that is a changeable landform and not always distinctly pronounced on the shore slope (fig.4). The inner bar dynamics controls development of cusps at the shoreline.

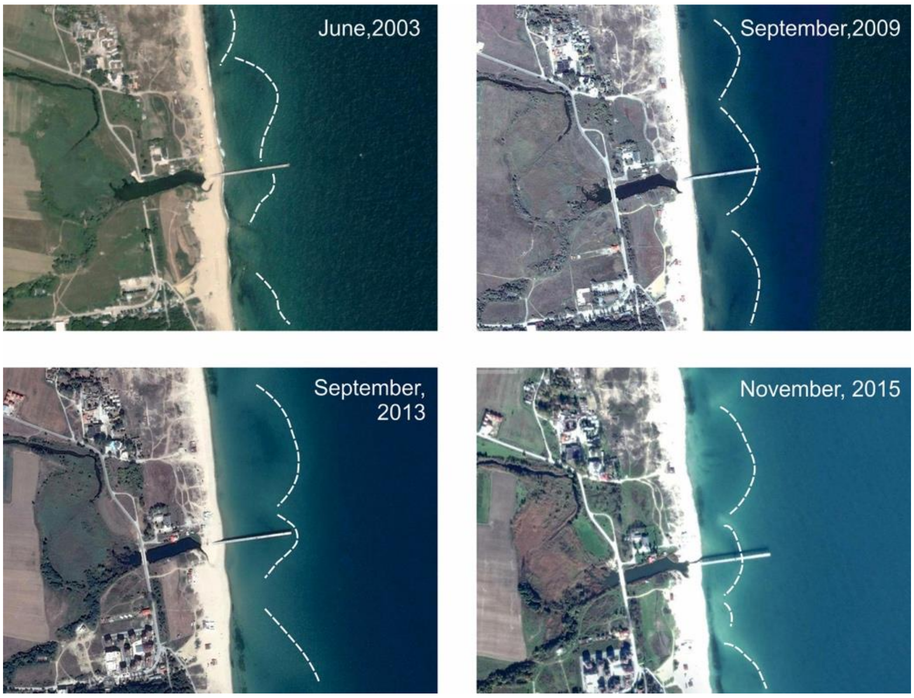

Figure 3. The site of the full-scale experiment. The research pier about 200 m long is in the center of the site. White dashed line shows crests of the outer bar seen in the aerial photographs.

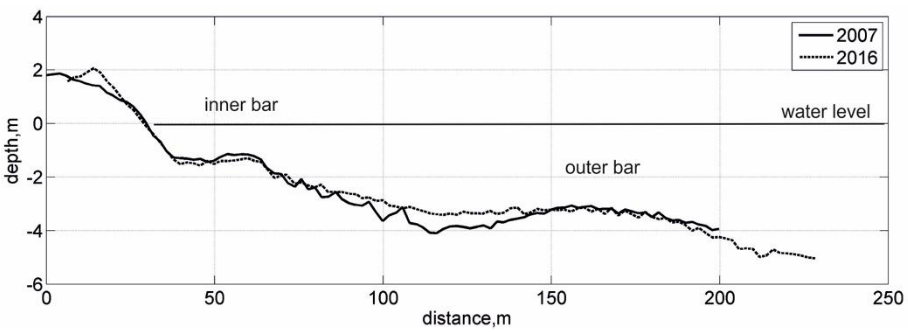

Figure 4. The shore slope profile measured from the research pier (measurements of 2007 and 2016)

Field experiments: description and methods

Synchronized instrumental observations of the changes in the sea bottom surface and wave regime was performed from October 7 to November 2, 2016 («Shkorpilovtsi-2016») and from October 10 to November 14, 2018 («Shkorpilovtsi-2018»). During first experiment the shore slope depths were measured using a metal pole and a plummet attached to the fishing rod. The measurements were taken 3 to 4 times a day at a disturbed sea and once a day under conditions of calm or slightly waving sea. The sea conditions were controlled using 16 wave gauge set along the pier and four of them installed at its end. During second experiment the spoondrift spotter wave measuring buoy (https://spoondriftspotter.co/) was used. It was deployed on 9 m depth in alignment with the research pier. Cross-shore bottom profile along the research pier was measured with plummet attached to the fishing rod. Relief measurements were held once or twice a day (depending on wave conditions). During both experiments wave breaking type and position was visually assessed in time with bottom profile measurements.

Wave parameters, such as Hs – significant wave height (m), Tp – peak wave period (s) and Tm – mean wave period (s) were determined from obtained wave chronograms.

Significant wave height (Hs) was defined as:

$$\mathrm{Hs} = 4\sqrt{m_0}, \qquad (1)$$

where $m_0 = \int Sdf$ (m_0 – dispersion), S – wave spectrum, f – frequency.
Peak period was defined as:

$$T_{peak} = 1/\gamma_{max}, \qquad (2),$$

where γ_{max} is frequency which corresponds maximum of spectral density.
The mean wave period (Tm) was defined as:

$$T_{mean} = \frac{\int Sdf}{\int Sfdf}, \qquad (3)$$

Wave steepness was defined as Hs/L, where L – deep water wave length:

$$L = \frac{gTmean^2}{2\pi}, \qquad (4)$$

Common conceptions that describe intensity and direction of cross-shore sediment transport are connected with relation between wave energy and median diameter of deposits. Generally, offshore sediment movement is connected with return flow. Dissipation of energy of steep waves leads to intensive disturbance of fine sand due to greater turbulence level in the surf zone. Dissipation of gentle waves leads to onshore sediment transport of coarse sand due to asymmetric wave currents. There is generally accepted concept that suggests separation of the bottom slope profiles into two categories: storm and normal. Storm profile is characterized by existence of the sandbar and flatter foreshore, when normal profile is steeper and nonbarred. There is also a number of criterions which allow to separate wave conditions leading to their formation. The simplest is proposed by M.Larson and N.Kraus (Larson, Kraus, 1989) and is as follows:

$$S_p = \frac{\overline{H_\infty}}{w_g T_p} \qquad (5),$$

where $\overline{H}_\infty$ is deep water mean wave height, T_p – peak period of wave spectrum and w_g – fall velocity. It was suggested that accumulative profile changes to the erosive profile when Sp exceeds 2. During field experiments we observe both types of underwater profiles, so it is possible to check how well the criterion is working.

DISCUSSION OF THE RESULTS

Field experiment №1 (October-November, 2016)

During first experiment one extremely strong storm occurred (October 17-18), with wave height up to ~4-5 m (the estimate is approximate, as no measurements had been taken at the storm maximum). When the storm was calming down, all the wave gauges resumed their work and the wave observations continued incessantly over the entire remaining period.

On the basis of the hydrodynamic conditions, the entire period of the experiment may be subdivided into two stages. The first one including the maximum wave intensity may be denoted as the phase of the storm development and stabilization (see the time interval between points «prof 1» and «prof 2» in Fig. 5a). The typical erosional profile developed during that interval is noted for a retreat of the water edge and the surface flattening within the swash zone; typically the material is carried out towards the lower part of the beach profile where the outer bar develops (Fig. 5b).

The second stage includes the whole period since the wave parameters began to lessen and up to the measurement termination on the site (November 2), when the wave height didn't exceed 0.1-0.2 m (see segment of curve between points «prof 2» and «prof 3» in Fig. 5a). This interval may be considered as belonging to the stage of wave attenuation (damping out). It should be noted that the process of wave parameter lowering was not continuous: there were recorded several intervals of increasing wave intensity. It may be seen that the wave attenuation stage is of complex structure and includes local peaks of wave parameters alternating with periods of steadying. Within the period of the storm attenuation the crest of the outer bar moved slightly landwards. A trough developed at the base of its inner side of an outer bar, and near the water edge an inner submerged bar formed; by the end of the attenuation stage the bar merged with the beach (Fig. 5b).

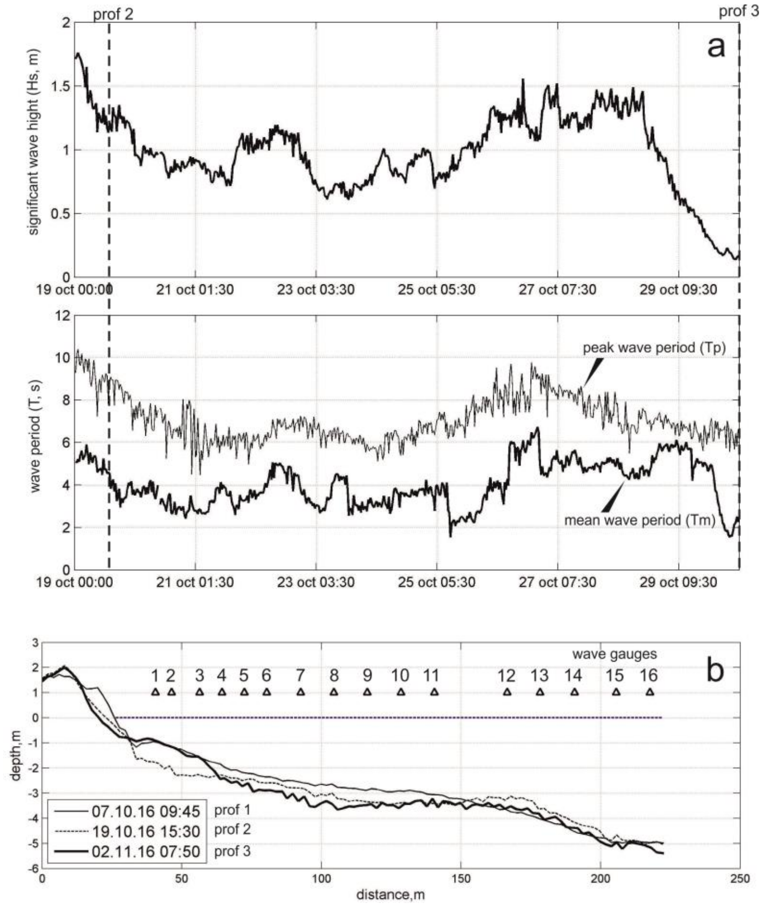

Figure 5. Measured wave characteristics from gauge at the end of the pier (gauge 16) in the course of the full-scale experiment (a) and the beach profile dynamics during entire period of experiment (b)

The considered changes in the shore profile morphology may be described as the transition from the summer profile (devoid of submerged bar and distinguished by a steep slope near the water edge) to the winter profile (noted for a pronounced outer bar and a gently sloping profile at the water edge). The suggestion may be supported by the fact that the observed extreme storm corresponds to the event of once a year frequency (0.14% probability of occurrence at 12 hours duration, Fig. 6); its consequences may be considered as seasonal.

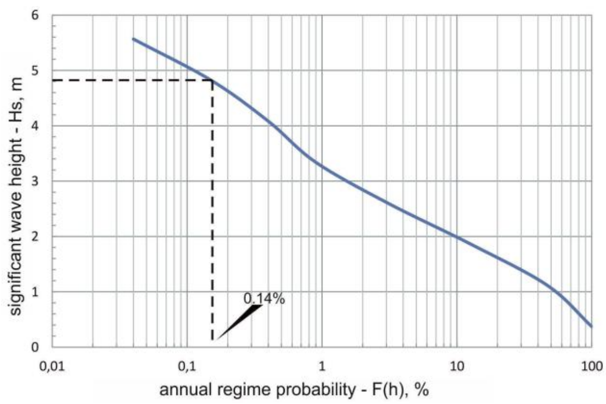

Figure 6. Value of wave height with frequency of occurrence at 12 hours duration. The curve of annual regime probability based on average wave data for west part of Black Sea (Russian Marine Register of Shipping, 2006)

Fig. 6 shows a probability curve of the significant wave height occurrence (Hs), based on the data from Russian Marine Register of Shipping (2006) on a region in the west of the Black Sea neighboring the study site. As follows from the curve, the storm wave regime of the 12 hours duration per year (0.14% probability of occurrence) corresponds to Hs values equal to 4.8 m; that is close enough to the wave height recorded at the extreme wave regime in October 17–18, 2018 at the storm maximum. The cited wave height is approximate, as the instrumental measurements could not be taken at the storm maximum; the estimates are based on forecasts published in open sources (http://193.7.160.230/web/esimo/black/wwf/wwf_black.php) and on visual observations over breaking waves coming onto the coast.

In respect to morphodynamics of the underwater slope, the most interesting is the stage of experiment, when a depositional terrace is being formed on the coastal profile after the main peak of storm passed and a series of lesser events of wave activity occurred. Two types may be identified in the changes of sea floor landforms during that stage. The first type of the shore profile evolution is noted for the depositional process dominance. In the second type dominant are erosional processes; in that case the erosional profile develops, or storm equilibrium profile with a submerged bar in the zone of wave breaking.

The first type (accumulation phase) was observed when sediments move landwards under conditions of continuously decreasing wave intensity after the main peak passed. In that case it would be reasonable to suggest a decisive role played by the wave transport, when smaller waves move sediment particles landwards from the crest of the bar built at the storm maximum (fig.7, fig.8a)

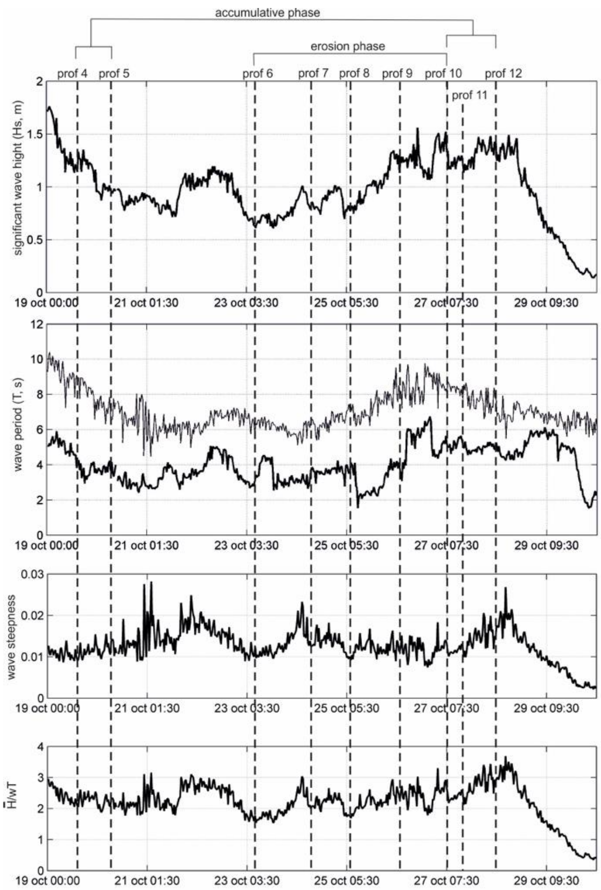

Figure 7. Wave process measured during the time of the full-scale experiments and the time intervals marked by a prevalence of depositional and erosional processes in the profiles (the profiles «prof 4»-«prof 12» are given in Figure 8).

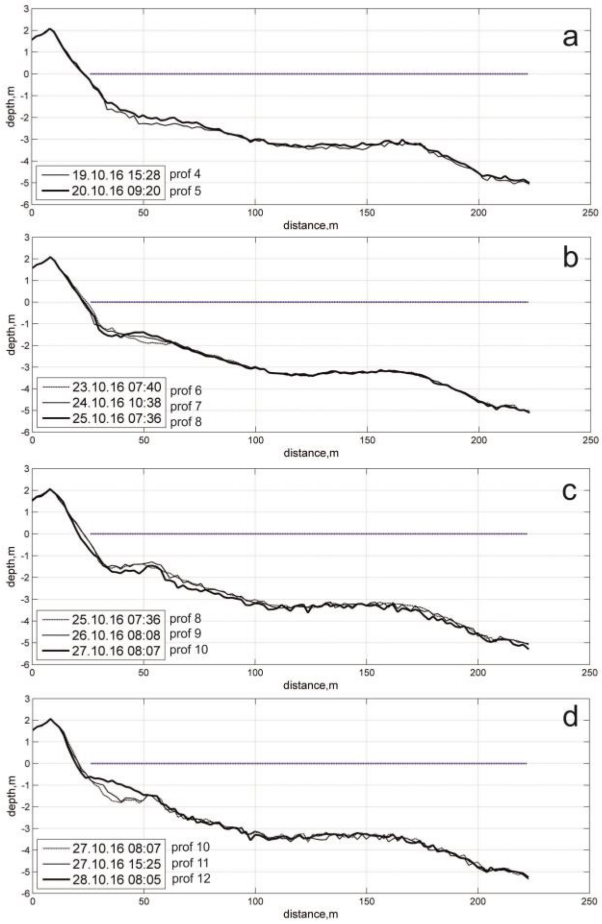

Figure 8. Shore profile dynamics over the time of the attenuation of a complete storm cycle

The second type of the beach evolution consists of development of a typical erosion profile, the shoreline receding and an inner bar being formed in the process (fig.8b,c). The described type of the shore profile evolution corresponds to the increase in the wave height and period; at a certain moment the wave height became stable, while the period reaches its peak and then begins to lessen. This moment marks the onset of the next depositional (accumulative) phase when the depositional terrace development in front of the inner bar, which may be described as the process of the bar adjoining the coast (fig.8d).

So the depositional phase was recorded twice during the full-scale experiments: at the dampening of the principal peak of the storm (see the interval between lines «prof 4» and «prof 5» in Fig. 6a; the behavior of wave parameters is shown in Fig. 7) and also at the phase of stabilization of the local peak of storm (see time interval between lines «prof 10» and «prof 12» in Fig. 6a).

In spite of the difference in the trend of the wave height changes within the two time intervals, the intervals have some specific features in common. The first feature to be noted is that both accumulative phases occur at the same values of wave height and period (Hs~1.2 m; Tp~8 s).In the first case (the interval between «prof 2» and «prof 3», Fig. 6a) two lines of wave breaking of the «plunging» type were recorded in the deposition zone. In the second case the breaking of largest waves occurred by “plunging” over the outer bar, while smaller waves were “spilling” over the inner bar.

Another distinctive feature of the accumulation phase on the profile consists in the reduced values of wave characteristics at the peak wave interval, while the medium period is relatively stable, so that the wave spectrum is narrowed.

The wave steepness characteristics were in the range between 0.01 and 0.02, and the Larson- Kraus index (Ω) was slightly above the threshold limit value (Ω=2) at which, according the theory, the deposition begins (Larson, Kraus, 1989).

In both cases the deposition on the profile is not accompanied with erosion on the adjoining parts. That suggests three-dimensional character of the deformations partly resulting from the cellular circulation within morphodynamics systems bounded by the crescentic submarine bar and partly – from the longshore sediment transport. As a hypothesis one may suggest that the deposition begins at a certain stage of the submarine bar evolution and a certain combination of the wave height and period, the material coming mostly from lateral deformations of the bottom landforms.

Field experiment №2 (October-November, 2018)

During field experiment that was conducted in October-November 2018 two pronounced storm events were captured. 10-day interval with 14 measured profiles was chosen for the analysis. Wave heights varied from 0.3 to 1.3 m and peak periods – from 3.3 to 8.5 s (fig. 9).

Full cycle of morphodynamic processes associated with storm events was recorded: in the end of the observations bottom slope profile returned to its original state (fig. 10).

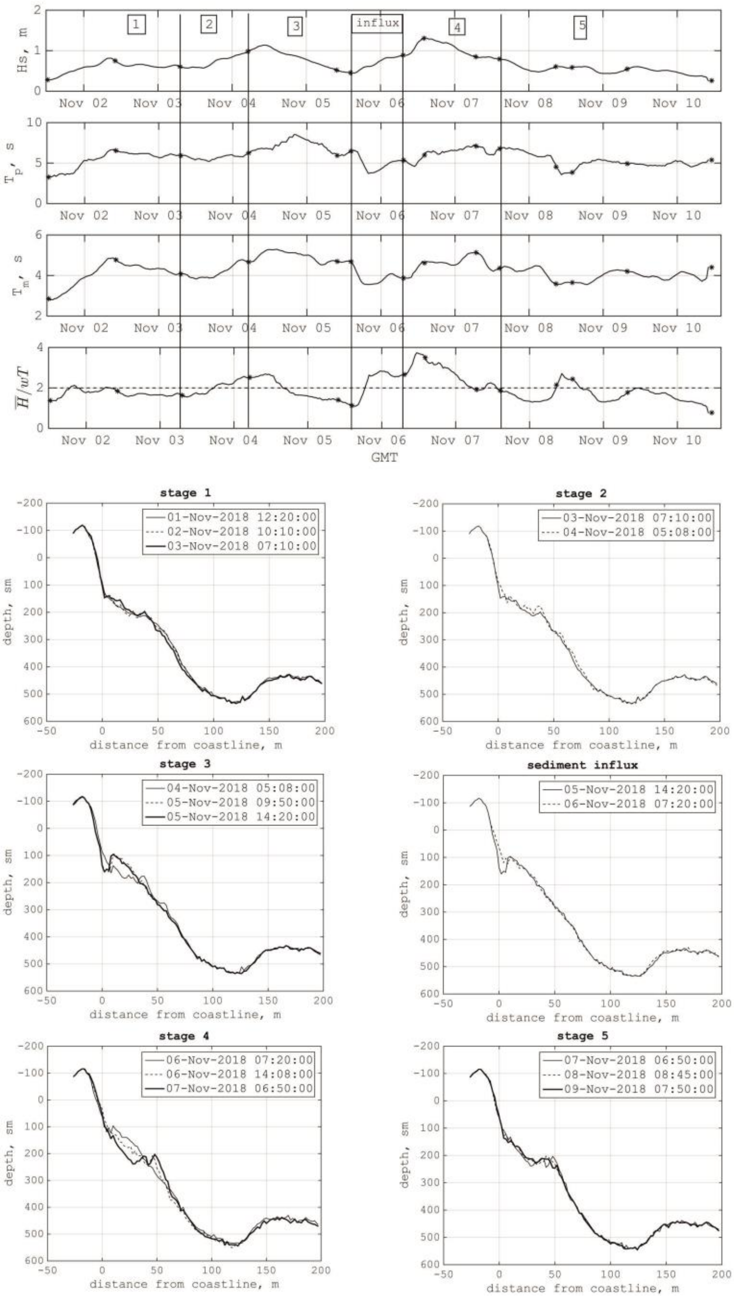

Figure 9. Wave parameters during considered storm events and corresponding stages of morphodynamic cycle

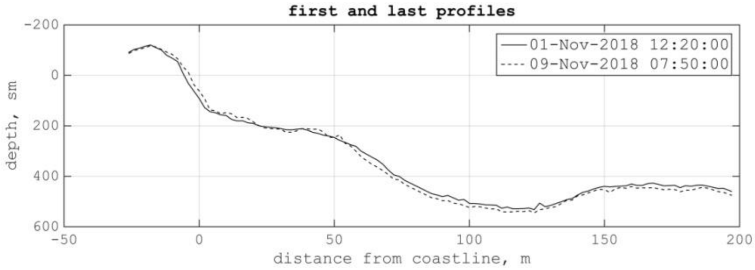

Figure 10. Bottom slope profile along the research pier for November 1 and 9, 2018

Cycle starts with accretion of the sandy deposits on the terrace adjacent to the beach face (stage 1, fig.9), then follows the formation of the sandbar (stage 2 and 4, fig.9) and its evolution (stage 3 and 5, fig.9): it moves onshore and disintegrates, adjoining the shore and recovering the initial profile.

Additionally, stage of sediment influx from the outside of the profile was distinguished between two measured morphodynamic cycles (stage «influx»). All changes in bottom topography were divided into those caused by 2d cross-shore sediment transport and caused by 3d processes. The division was made by summarizing differences between profiles neighboring in time and dividing it on sum of absolute values of differences (fig. 11). If this sum is nearly equal 0, then sediments are redistributed along the profile (which is associated with prevalence of cross-shore sediment transport influence), if it is negative, then sediments were removed from the studied profile and if the sum is positive – additional sediments came from outside (these two cases are related to 3d morphodynamic processes). Significant relief changes associated with redistribution of sediments along the profile occur between November 4 and 5, where sandbar is moving onshore, and between November 6 and 7, where sandbar is forming. Relief changes associated with 3d structure of sediment transport are clearly seen in November 3-4 (influx of sediments on the bottom slope), November 5-6 (filling of the trough on the inner slope of the sandbar with sand) and in November 6 between morning and evening measurements, where erosion of the former sandbar outer part takes place.

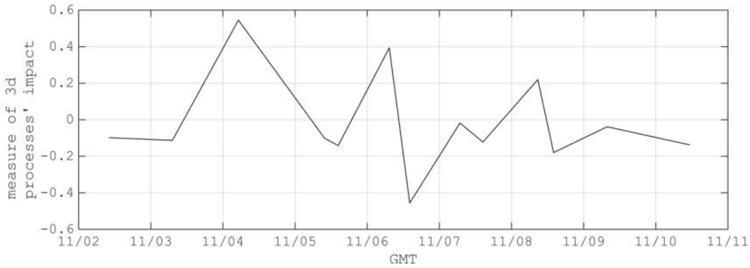

Figure 11. Relation between sum of differences between closest in time profiles and sum of absolute values of these differences. This value shows whether sediments are redistributed within profile or there is influx of outflow of sediments in longshore direction

Bar development takes place simultaneously with formation of the trough shoreward from it and is associated with erosional phase of storm morphodynamics. Degrading of the bar is happening together with its onshore movement and filling of the trough with sand, so this stage can be interpreted as accretive.

This cyclic process can thus be described in terms of crest position (fig.12). Sandbar position generally corresponds to changes of the wave height and thus wave breaking position. Bar formation occurs when wave height grows and wave steepness is relatively high (around 0.02), then, when storm is attenuating and wave height decreases together with wave steepness (in studied case it reaches 0.01), sandbar moves onshore for both observed storm events. But the difference of these two events is that in one case the sandbar moved long way nearly up to the shoreline and only disappeared after longshore sediment transport influx took place that filled the trough on the inner slope of the bar, and in another case the sandbar moved only slightly onshore and disintegrated in process. That can be because phase of storm attenuation in first case is characterized by very mild waves with steepness around 0.011, when for the second case during attenuation mild wave regimes are intermitted by very steep wave regimes. The Larson-Kraus index (Ω) works good for the studied situation if onshore sandbar movement is interpreted as return to "normal" nonbarred beach profile. The only exception are situations where influx of sediments to the profile from the outside is observed.

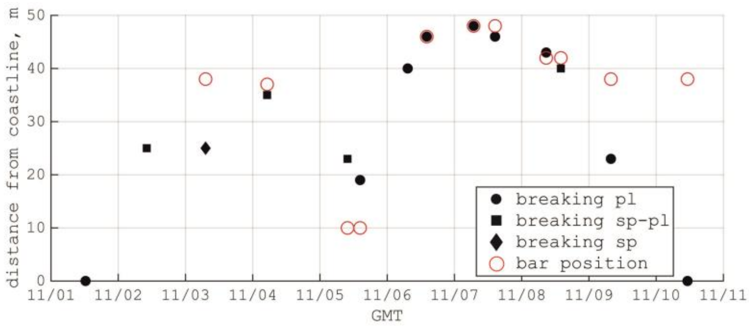

Figure 12. Sandbar position in comparison with wave breaking point and type

CONCLUSION

1. The shore profile deformations usually considered to be seasonal may take place during a single extreme storm event of once a year recurrence period.
2. Full cycle of storm-induced morphodynamic evolution of the beach profile that consists of bar formation, its onshore movement and disintegration with formation of terrace were registered during the experiment. Stage of onshore bar migration is associated with recovery stage of the underwater beach profile evolution.
3. During field experiment the concept that long mild waves move sediments in form of the sandbar onshore and steep short waves create storm profile with the sandbar was proved. In studied case waves steeper than 0.02 create sandbars and milder than 0.02 – transport sandbars onshore, which also means that criterion for distinguishing between storm and normal beach profile proposed by Larson and Kraus is true for the studied case
4. Significant role in the bottom profile morphodynamics play 3d processes that are not captured in 2d measurements of this experiment. These processes manifest in accumulation and filling of the trough during phase of storm development with steep waves where Larson and Kraus criterion predicts erosion and bar formation.
5. In case of the coastal morphodynamics system bounded by the crescentic submarine bar on the seaside, the depositional phase on its profile is not always related to any specific changes in the wave height and may occur both at its decrease and at its stabilizing. In some cases noted, that depositional (accumulative) phase is established to correspond to the decreasing peak period with the medium period staying unchanged, so that the wave spectrum is narrowed.

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