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Hydrodynamics and Lithodynamics of Dissipative and Reflective Shores in View of Field Investigations

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Abstract

The paper presents a comparative analysis of physical processes occurring at two different coasts, which belong to two different European seas. The first coast under examination comprises the sandy shore nearby Lubiatowo, located at the south Baltic Sea in Poland. The second site is represented by the sandy coast in Shkorpilovtsi, located at the west Black Sea in Bulgaria. Both sites are equipped with field research facilities ensuring extensive and precise *in situ* investigations. The study is focused on differences and similarities of hydro- and lithodynamics as well as the nearshore morphology between the above coastal zones. The present analysis is based on the results of the field campaigns carried out in recent years at the research facilities in Lubiatowo and Shkorpilovtsi. Considering the way in which wave energy transforms on the cross-shore profile, the sea shore at Lubiatowo is found distinctly dissipative while the shore at RB Shkorpilovtsi has a reflective character. This fact implies some differences in the features of wave-current motion and sediment transport.

Key words: cross-shore profile, waves, currents, grain size distributions, sediment transport

1. Introduction

Solution of practical coastal engineering problems is facilitated by the knowledge of physical processes occurring on a shore under consideration. Although ruled by the same laws independently of the location, these processes are site-specific and the detailed findings concerning a particular coastal segment can rarely be useful for other parts of the coast. Some general but very important parameters of the coastal phenomena and coastal systems, however, can be common for shores located in a certain vast area. These parameters comprise the inclination and shape of the cross-shore profile, features of seabed sediment, and the offshore wave climate. The climate, together with the coastal bathymetric layout (including bars), gives rise to the occurrence of specific nearshore patterns of water circulation, resulting from wave transformation and the appearance of wave-driven currents. Water flows affect the seabed and cause sediment motion, the intensity and quantitative characteristics of which depend on seabed grain sizes.

According to various field observations reported by Pruszak et al (1999), the nearshore seabed inclination, grain diameters and number of bars are mutually dependent. At the same time, the above characteristics are in a conjunction with the wave-current climate. This conjunction is certainly associated with the nature of the equilibrium of hydrodynamic and morphodynamic factors that is achieved after a rather long-term impact of waves and currents on the shore. Although the shores of different European seas, influenced by different long-term hydrodynamics, have in general distinctly various slopes and seabed sediments, a question arises if the short-term hydrodynamic forcing typical of those sites is also significantly different.

Clarification of the above doubts can be greatly assisted by field measurements and observations, which are usually difficult and require expensive equipment to be used. Surveys *in situ* are therefore organised as field campaigns with participation of a few research teams, frequently international. It is much easier to carry out observations and measurements of coastal processes having an organised technical infrastructure, well established recording devices, easily available equipment close to the measuring site, and finally, facilities ensuring accommodation and appropriate living conditions for the staff conducting the experiments. That is why several coastal research laboratories have been created in different parts of the world, including two important European coastal research facilities, located at two totally different sites: the Coastal Research Station in Lubiatowo (the Baltic Sea, Poland) and the Research Base in Shkorpilovtsi (the Black Sea, Bulgaria).

The major and overall aim of the activities that led to establishment of the field laboratory in Lubiatowo in 1970 was to provide high quality field data to be used for validation and verification (sometimes also for calibration) of theoretical models developed at the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN). Indeed, the results obtained by many of these models, comprising coastal hydrodynamics and sediment transport, have been compared with the field data provided by the IBW PAN Coastal Research Station (CRS) in Lubiatowo. The Research Base (RB) near the village of Shkorpilovtsi, 50 km south of Varna, was established by the Institute of Oceanology of the Bulgarian Academy of Sciences (IO BAS). The building and the pier were built in the period from 1980 to 1983. Multi-aspect field investigations carried out in various time-spatial scales at CRS Lubiatowo and RB Shkorpilovtsi have provided enormous amounts of data and observations regarding the Baltic and Black Sea coastal zones. This knowledge, obtained under undisturbed, natural conditions, makes it easier to verify many theoretical considerations as well as to identify features characteristic of the south Baltic and west Black Sea sandy coasts.

Considering the way in which wave energy transforms on the cross-shore profile, one can distinguish two basic types of sea shores: dissipative shores, at which most of wave energy dissipates because of the wave breaking in the surf zone; and reflective shores, at which waves are subject to reflection from the nearshore slope. The shore character depends on the shoreface slope and features of the representative wave. In assessment of the shore type, a so-called surf scale parameter is useful, see e.g. Komar (1998):

$$\varepsilon = \frac{2\pi^2 H_b}{gT^2 \tan^2\beta}, \tag{1}$$

where:

H_b – breaking wave height;
T – wave period;
β – angle of mean sea bed inclination.

The higher the parameter ε, the more dissipative the shore is. It is very difficult to determine the boundary value of ε indicating a transition from the reflective shore to the dissipative shore. According to Komar (1998), this difficulty is related to the shape of the local bottom profile and wave parameters permitting e.g. the outer surf zone to be dissipative in character while the steep beach face of the inner zone is more reflective. Further, determination of the breaking wave height H_b and the representative wave period T is to a large extent arbitrary and thus problematic. Nevertheless, a comparison of two shores by means of the surf scale parameter ε seems to be useful.

The average nearshore bottom slope (about 500 m seawards from the shoreline) at CRS Lubiatowo amounts to $\tan\beta = 0.012$. Assuming the long-term mean height of the breaking wave for the south Baltic coast to be about 0.3–0.6 m and the wave period of 3.5 s, one obtains $\varepsilon \in (342; 684)$. The average sea bed nearshore bottom inclination (about 500 m seawards from the shoreline) at RB Shkorpilovtsi is steeper than at CRS Lubiatowo, with $\tan\beta = 0.025$. Further, owing to the greater depth of the Black Sea, the wave climate is more severe than in the Baltic Sea. The assumption of the long-term mean height of the breaking wave for the west Black Sea coast equal to about 0.8 m and the wave period of 6 s yields the parameter ε equal to 72. This value denotes that the Black Sea shore at Shkorpilovtsi has a much more reflective character than the Baltic shore at Lubiatowo.

The present study of the above two different coastal sites is based on the results of measurements taken at CRS Lubiatowo during international thematic field campaigns in the years 2001–2006 and an international field experiment carried out at RB Shkorpilovtsi in the autumn of 2007.

2. Study Area I

The study area of CRS Lubiatowo is a typical South Baltic sandy coast, situated some 70 km northwest of Gdańsk (Fig. 1) with the laboratory building at the coordinates 54°48’42”N 17°50’26”E. Relatively mild winters, warm summers and fairly high air humidity characterise the climate at Lubiatowo. The mean air temperature is about +7.5°C and varies from –1.2°C in February to +16.5°C in July. The mean monthly water temperature varies from +1.2°C in February to +17.8°C in August. Ice at the shoreline is present for an average of about 20 days/yr, but there are some winters when the sea shore is totally frozen for 2–3 months. Water salinity amounts to about 7.5 PSU. The vegetation period lasts about 200 days, usually from the beginning of April until early November. Most of precipitation, amounting to 650–690 mm/yr, is discharged in summer and autumn. Usually, there are 130 rainy days a year. The area is dominated by westerly and south-westerly winds, which are strongest in autumn and winter.

Fig. 1. Location of CRS Lubiatowo on the Baltic coast

The station in Lubiatowo is a unique field research facility of this type in Europe, with a row of cable-connected measuring towers stretching 250 m offshore, modern equipment (ensuring also autonomous operation of recording devices) and a laboratory building close to the sea shore. Parameters of physical processes measured *in situ* are registered and initially processed by computers in the laboratory.

The shore in the vicinity of CRS Lubiatowo is an open and natural beach built of sediment with a density of $\rho_s = 2650$ kg/m^3, composed predominantly of quartz sand. The cross-shore profile is characterised by a gentle slope (about 1–2%), with the sediment median diameter oscillating about the average of $d_{50} = 0.22$ mm. The shore is relatively stable, although a very gentle erosive tendency has been observed over the last years. The beach width varies in time and space from about 15 to about 60 m (sometimes up to 100 m). The beach is bounded by dunes overgrown by grass and bushes. At some shore segments, the upper edge of the eroded dune slope adjoins the forest. The shoreface features multi-bar cross-shore profiles, which usually show 4 stable bars (see Fig. 2) plus an ephemeral one, near the shoreline. This bar interacts with the shoreline, supplying or removing the sediment and simultaneously preventing the shore from wave action. In extreme situations of a storm or long calm period this bar seldom exists. Under stormy conditions it is washed away by moving the material offshore, and during quiet periods it moves onshore until it arrives on the shoreline. This causes the beach build-up and berm formation.

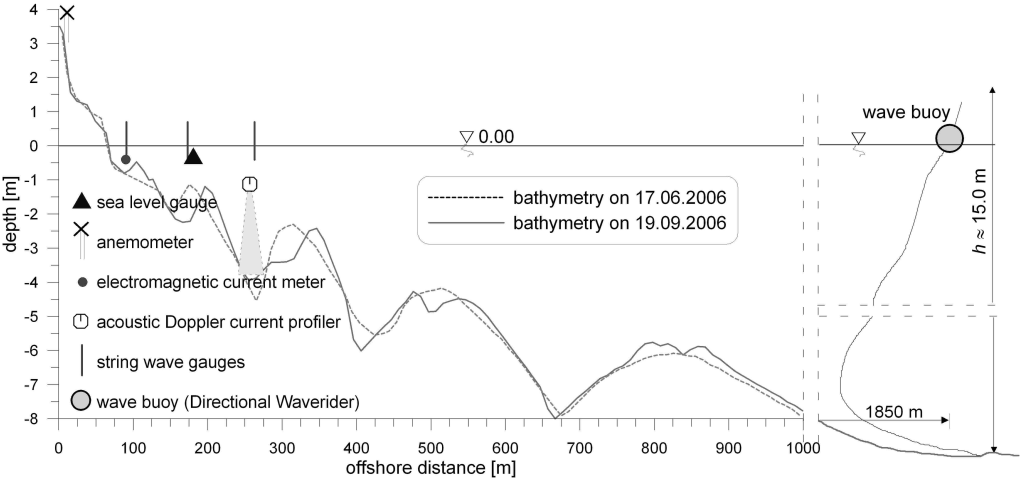

Fig. 2. The measuring profile at CRS Lubiatowo and equipment layout during a field survey in 2006

The resultant long-term wave energy flux is directed obliquely to the shoreline, thus generating eastwards net longshore sediment transport.

In recent years, a wide range of coastal processes and features have been investigated at CRS Lubiatowo, e.g. wind speed and direction, wave transformation (including breaking) from deep water to the shoreline, spectral characteristics of waves, wave run-up, wave-driven currents, sediment concentrations, variability of grain size distributions in time and space (including vertical and horizontal sorting of size-graded sand), short-term cross-shore profile evolution (with the dynamics of bars), long-term shoreline migration and changes in the topography of the dune system.

3. Study Area II

The field coastal research base in Shkorpilovtsi is well prepared to carry out studies on the wind-wave climate and wave transformation in shallow water, as well as coastal morphodynamic and lithodynamic processes. It can provide conditions for work and accomodation for 35 persons. The base is suitable for training students and holding scientific meetings.

During most of the year the climate in the study area is relatively warm and arid. Air temperatures above 10°C occur only 200–210 days of the year from April to November. The average annual temperature varies between 11.5 and 12°C, while the average temperature in July is 20–22.5°C, which highly contributes to tourist activities. Other climatic parameters characteristic of the area include a relatively low atmospheric moisture content (65–70%), average summer precipitations (112.5–130 mm) and medium cloudiness in July from 0.3 to 3.5 octans (*Reference book*... 1979).

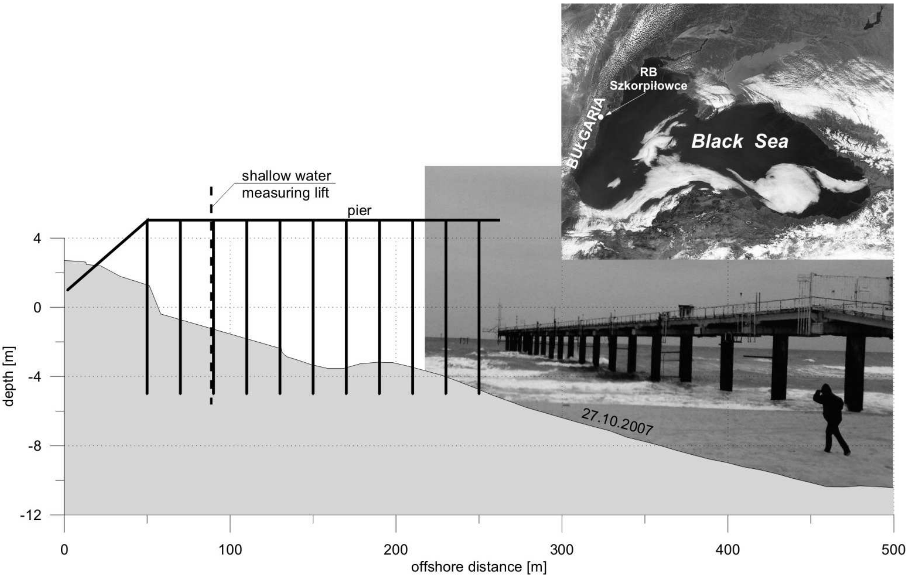

Fig. 3. The location of RB Shkorpilovtsi on the Black Sea coast and the layout of the pier on the measuring cross-shore profile

The shore of the Black Sea at RB Shkorpilovtsi is built mainly (in 96%) of quartz sandy sediments, which have a density of ρ_s = 2650 kg/m^3. The remaining 4% is constituted by fine shell particles (aragonite – $CaCO_3$) having a density of ρ_s = 2720 kg/m^3. The median grain diameter amounts to about d_{50} = 0.4 mm. The beach is 30–50 m wide, bounded by a zone of grass-overgrown dunes. The shoreface usually features 1 bar only. At some locations, there can be 2 bars at the maximum or no bars at all. Most waves approach the shore perpendicularly and generate intensive cross-shore water circulations compared with relatively weak longshore wave-driven currents. A pier of about 230 m in length is the basis of the measuring infrastructure of RB Shkorpilovtsi. The pier reaches the depth of about 4 m and is equipped with lifts, to which measuring devices can be mounted. The pier deck is about 7 m above the mean sea level. Such installation ensures safe maintenance of the measuring instruments and effective surveys under all hydrological and meteorological conditions. The pier is cable-connected with the laboratory building. The location of RB Shkorpilovtsi on the Black Sea shore, a view of the pier, and the measuring cross-shore profile are shown in Fig. 3. The pier covers the most dynamic part of the coastal zone. During the field experiment in 2007, the main hydro- and lithodynamic measurements were carried out at a nearshore location where the water depth varied from 1.2 to 1.5 m. This place is marked in Fig. 3 as the "shallow-water measuring lift".

The lift was equipped with a special carriage, on which two devices were installed, namely an electromagnetic current meter and a laser-type particle size analyser. Moreover, water surface elevations were recorded using a string wave gauge close to the lift.

4. Analysis and Results

4.1. Nearshore Bathymetry

Bathymetric measurements have been carried out near CRS Lubiatowo since 1987 along a 2600 m long shore segment, every time reaching a water depth of at least 7 m (600–700 m offshore). In the beginning, traditional geodetic equipment was used for boat positioning, and an echo-sounder was attached to a boat. Since the mid-1990s positions of the boat along each profile have been controlled with GPS technique (two sets comprising base and rover stations). Corrections for the water level and the placement of a GPS-integrated echo-sounder in the boat are made routinely. Sea bed profiles, equally spanned every 100 m, are surveyed close to the shoreline, using land geodetic equipment (electronic total station). The spacing of records in a profile is kept constant at about 10 m.

Seasonal variability of an exemplary cross-shore transect observed at CRS Lubiatowo is shown in Fig. 4a. It can be seen that the coastal zone in Lubiatowo has four distinct bars in the time span from early summer to late autumn. A detailed analysis of all the archival data collected near Lubiatowo has revealed a number of bars amounting to at least 3 independently of location or season. Thus, the bar system in this region seems to be very stable.

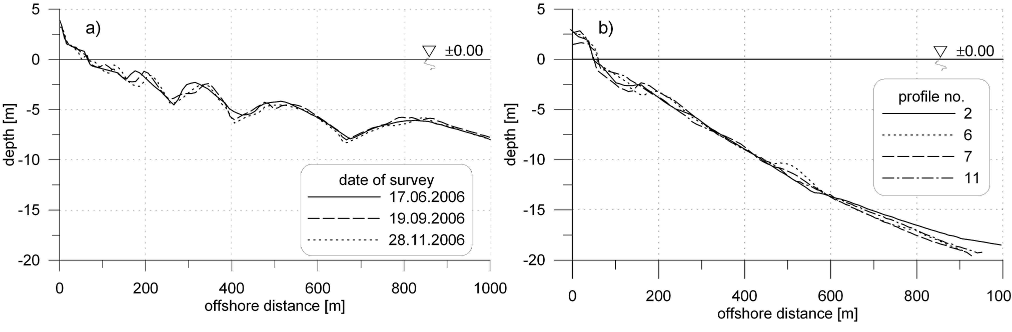

Fig. 4. Cross-shore profiles at a) CRS Lubiatowo (2006) and b) RB Shkorpilovtsi (2007)

A bathymetric survey carried out during the field campaign "Shkorpilovtsi 2007" showed that there is a typical single-bar coastal zone at Shkorpilovtsi. The bar is located about 150 m from the shoreline, mostly at the depth of 2–3 m. Rarely, the second bar appears farther from the shoreline (about 400 m seawards), at the depth of about 10 m. Exemplary cross-shore profiles measured near RB Shkorpilovtsi are plotted in Fig. 4b.

4.2. Waves and Currents

In Lubiatowo, owing to the existence of a few bars, waves approaching the shore from deep sea are subject to considerable transformation in the surf zone and most of wave energy is dissipated as a result of multiple wave breaking. If the significant wave height H_s at deep water exceeds 1.5–2 m, the mean wave energy dissipated at the cross-shore profile with three offshore bars amounts to about 80% of the input deep water wave energy. This denotes that in such cases not more than 20% of wave energy reaches bar I and even less reaches the shoreline. For deep water waves of smaller heights ($H_s < 0.5$–1.0 m), the amount of wave energy reaching the vicinity of bar I and the shoreline increases up to 30–50% of the deep water wave energy. In addition, because the mean wave energy flux is directed obliquely to the shore, only a part of total wave energy acts perpendicularly to the shoreline. Therefore, a small percentage of deep water wave energy reaches the nearshore region and directly affects the shoreline and the beach, causing their change.

Wave measurements at CRS Lubiatowo were carried out during numerous field campaigns at a few locations on the cross-shore profile. In 2006, deep-water waves were registered by a directional wave buoy anchored offshore at a water depth of 15 m while the nearshore waves were measured using electronic string wave gauges. The latter devices were installed about 200 m and 100 m from the shoreline, at depths varying within the limits of 4.0–4.4 m and 1.2–2.4 m, respectively, as well as at two locations in a very shallow water zone, 20–30 m from the shoreline, at depths of about 0.5–0.7 m. Wave measurements at RB Shkorpilovtsi were carried out in the nearshore zone, with water depths ranging from 1.2 to 1.5 m. Exemplary results of the surveys at Lubiatowo and Shkorpilovtsi are described below.

During the field experiment at CRS Lubiatowo in 2006, the maximum wave height at a depth of 2.4 m attained 2.1 m while the mean wave heights at this point did not exceed 0.75 m, see Fig. 5a. In 2007, the maximum wave height at RB Shkorpilovtsi (water depth of 1.5 m) slightly exceeded 1.2 m while the mean wave height H_{mean} at this location amounted to not more than 0.45 m, see Fig 5b.

The results of wave measurements shown in Fig. 5 imply that the maximum wave height to water depth ratio (H/h) in the nearshore zone can amount to 1. Under such conditions, waves are very steep and close to breaking. Further, at those nearshore locations waves must have been broken before they reached the nearshore measuring points, but nevertheless they were still considerably high. Theoretically, the maximum

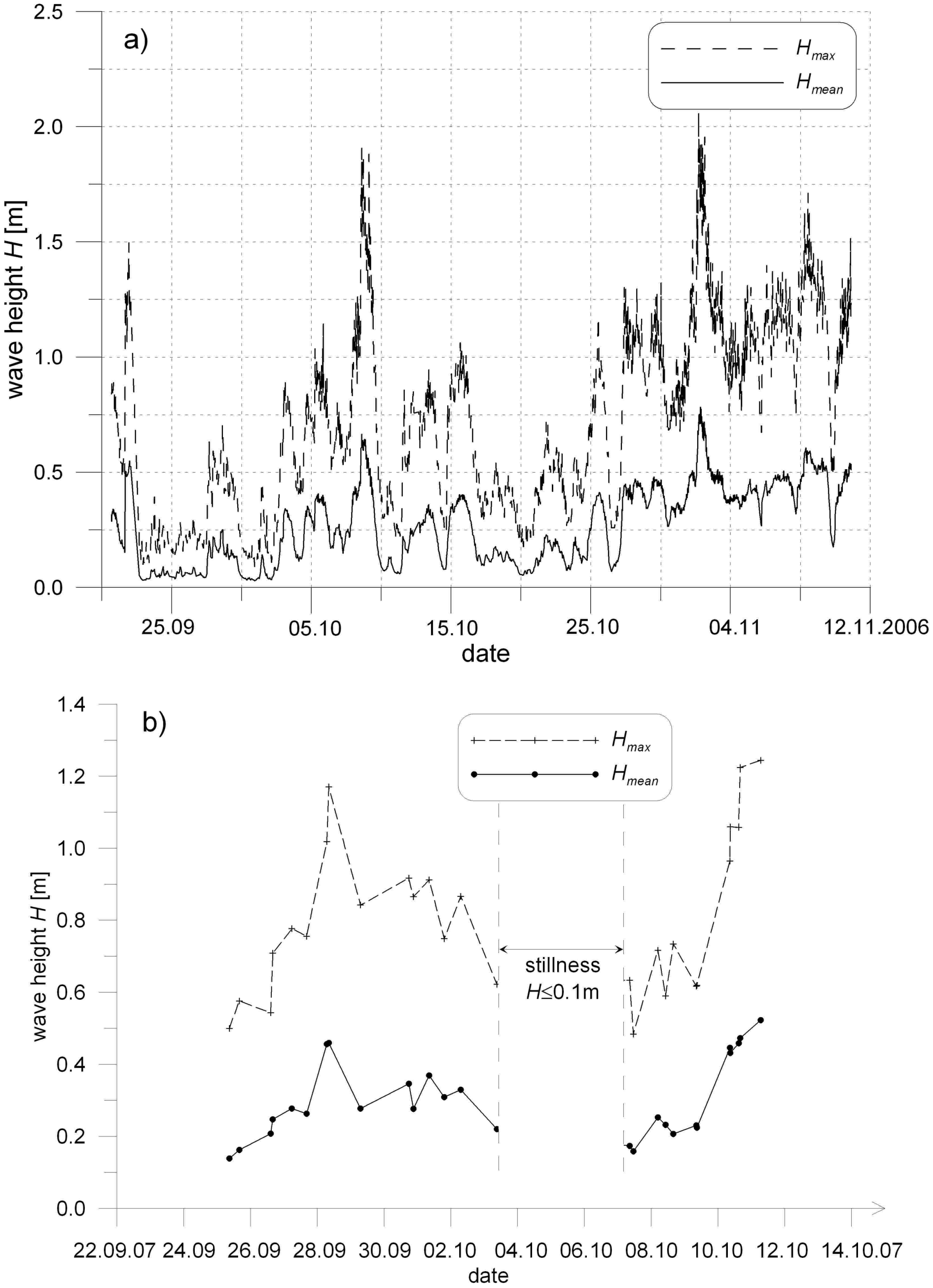

Fig. 5. Wave heights measured at depths $h = 1.2–2.4$ m at CRS Lubiatowo (a) and $h = 1.2–1.5$ m at RB Shkorpilovtsi (b)

H/h ratio for progressive waves can be 0.8. In the nearshore zone, one can expect a higher ratio because of the presence of standing waves that result from progressive waves interfering with the waves reflected from the shore. This effect is distinctly seen in Shkorpilovtsi records (the reflective shore). Surprisingly high shallow-water waves in Lubiatowo records (the dissipative shore) can be explained by storm surges (short-term sea level rise events) accompanying high waves in the Baltic Sea. Indeed, the extreme wave height value in Lubiatowo on 2 Nov. 2006 was associated with a storm surge of 1.6 m. Thus, the huge shallow-water waves in Lubiatowo were most probably registered when the water depth at the gauge was significantly greater than nominal.

The measurements of coastal currents at CRS Lubiatowo have been carried out since the early 1970s. In the 1980s and 1990s, a great progress was made in the accuracy of measurements by using electromagnetic current meters. During the experiment of 2002, the Acoustic Doppler Current Profiler (ADCP – Workhorse Monitor 1200 kHz) was used at CRS Lubiatowo for the first time. This device enables measurements of the entire vertical profile of velocity, distinguishing its components in two horizontal mutually perpendicular directions.

During the field experiment "Lubiatowo 2006", the measurements of current velocities were carried out at two locations on the cross-shore profile (see Fig. 2): about 200 m from the shoreline, at a water depth of 4.0–4.4 m (ADCP), and about 20–30 m from the shoreline, at a depth of 0.5–0.7 m (electromagnetic current meter) in the nearshore shallow-water zone. The time-averaged velocities of cross-shore and longshore currents measured in water columns at these locations are given in Fig. 6 and Fig. 7.

Figures 6 and 7 conform to the same sign convention of cross-shore velocities: the offshore velocities are positive and the onshore negative. Regarding longshore currents, velocities directed from W to E are positive, while westward currents have negative velocities. It can be seen from Fig. 6. that the maximum registered time-averaged longshore current velocity attains 1.2 m/s, while the maximum time-averaged velocity of the cross-shore flow (undertow) amounts to almost 0.4 m/s. It should be noted that mean cross-shore velocities higher than 0.4 m/s have never been observed at CRS Lubiatowo, while the maximum longshore current mean velocity was recorded in 2002 and amounted to 1.6 m/s.

Measurements of current velocities at RB Shkorpilovtsi in 2007 were carried out in the nearshore zone only, at the same location where waves were registered (see the "shallow-water measuring lift" in Fig. 3), namely at a water depth varying from 1.2 to 1.5 m. The measurements were conducted with a two-component electromagnetic current meter. Exemplary results of a series comprising water surface elevation as well as cross-shore and longshore instantaneous velocities at various levels above the sea bed on a stormy day (1 Oct. 2007) in Shkorpilovtsi are shown in Fig. 8.

In the case of Shkorpilovtsi, the sign convention for cross-shore velocities is opposite to the data from Lubiatowo, i.e. the offshore velocities are negative and the

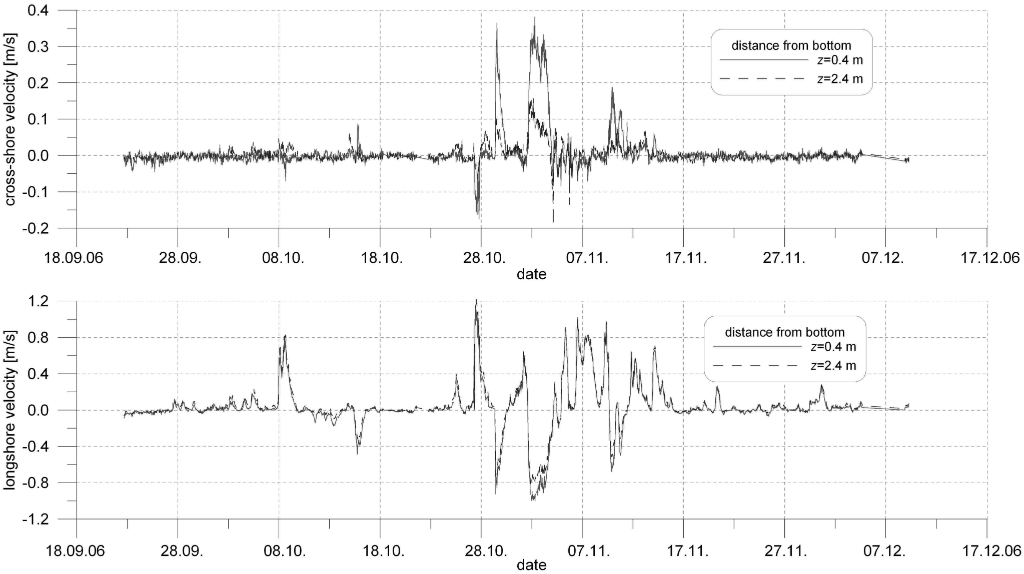

Fig. 6. Time-averaged velocities of cross-shore and longshore currents measured in the water column 200 m from the shoreline at CRS Lubiatowo in 2006

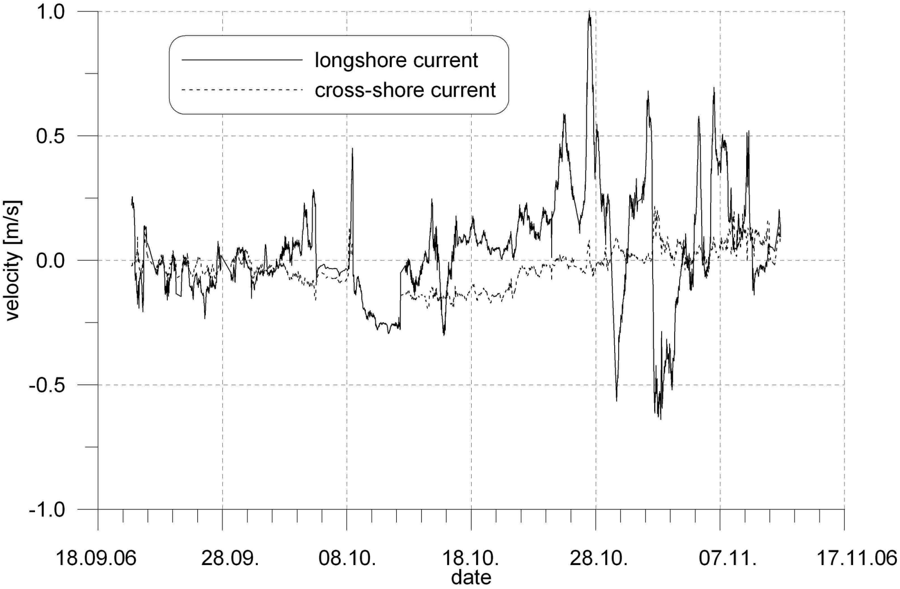

Fig. 7. Time-averaged nearshore shallow-water velocities of cross-shore and longshore currents measured at CRS Lubiatowo in 2006

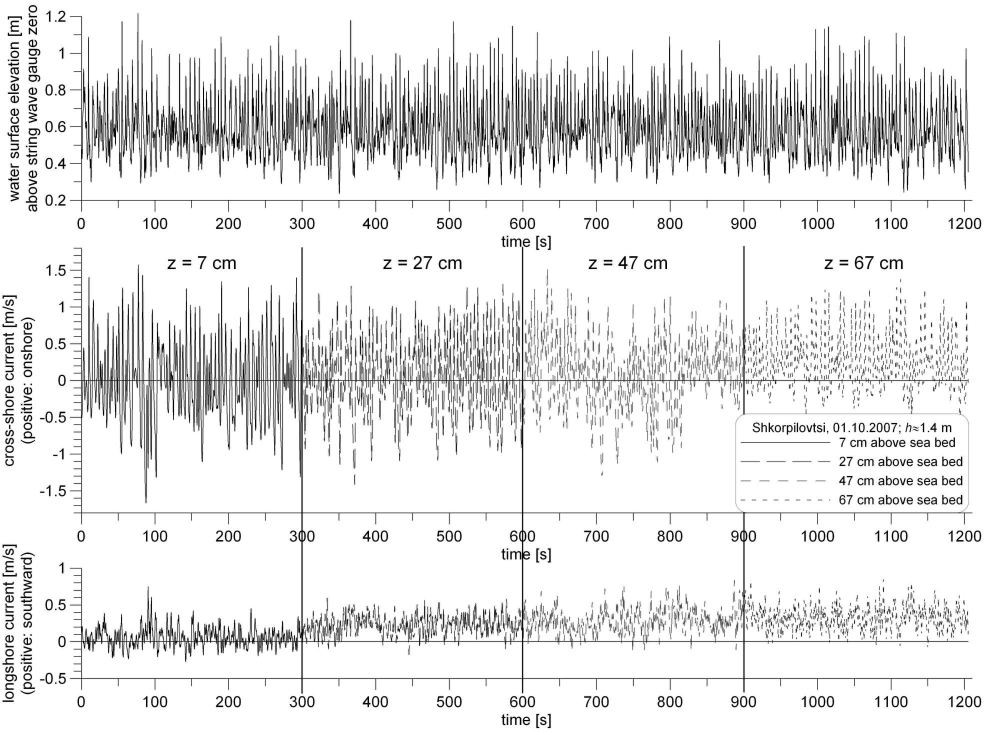

Fig. 8. Nearshore water surface elevation and instantaneous flow velocities registered at RB Shkorpilovtsi during a storm on 1 Oct. 2007

onshore positive. Regarding longshore currents, velocities directed from N to S are positive, while northward currents have negative velocities.

It can be seen from Fig. 8 that although instantaneous flow velocities are quite high (obviously related to wave-induced orbital velocities), mean values are relatively low. A detailed analysis of the parameters registered during the storm of 1 Oct. 2007 shows that the mean velocity at a level of 0.67 m above the bottom in the longshore and cross-shore directions amounted to 0.21 m/s and 0.32 m/s, respectively. Mean velocities closer to the sea bed were even lower. It is worth noting that wave parameters at the measuring location (water depth $h \approx 1.4$ m) were quite severe: $H_{\max} = 0.91$ m, $H_{mean} = 0.37$ m, $T_{mean} = 3.92$ s. One should point out that the extreme time-averaged cross-shore velocity recorded in Shkorpilovtsi was about half the value measured under similar stormy conditions at CRS Lubiatowo, while the extreme time-averaged longshore velocity in Shkorpilovtsi was a few times smaller than in Lubiatowo.

A better insight into the flow velocities measured at RB Shkorpilovtsi is provided by Fig. 9 and Fig. 10, which show the entire series of time-averaged extreme and mean cross-shore and longshore velocities measured in the nearbed layer, i.e. 0.07 m above the sea bottom.

It can be seen from Fig. 9 that although the extreme (maximum and minimum) nearbed cross-shore instantaneous velocities are quite high, reaching almost 2 m/s, the mean is close to zero (no resultant cross-shore current) except for the data of 8/9 Oct. and 11 Oct., when the resultant offshore velocity of about 0.5 m/s was registered. As regards the longshore current (Fig. 10), the only distinct resultant velocity was measured on 11 Oct. (0.41 m/s – northwards). On the same day, the extreme instantaneous velocity was also the highest during the entire survey (1.37 m/s – northwards).

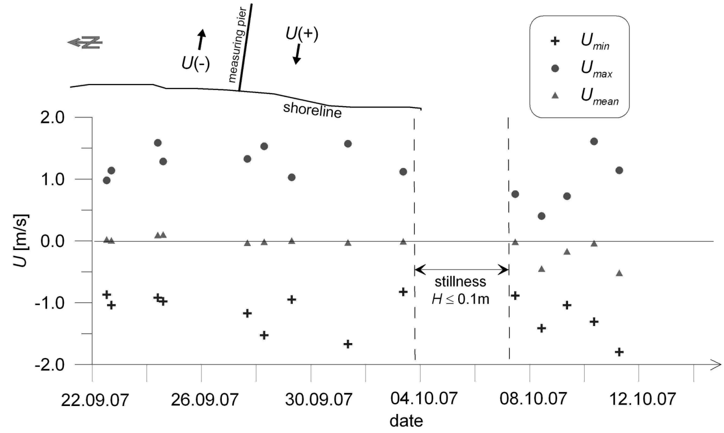

Fig. 9. Maximum, minimum and mean velocities of nearbed cross-shore currents (0.07 m above bottom) measured at RB Shkorpilovtsi in 2007

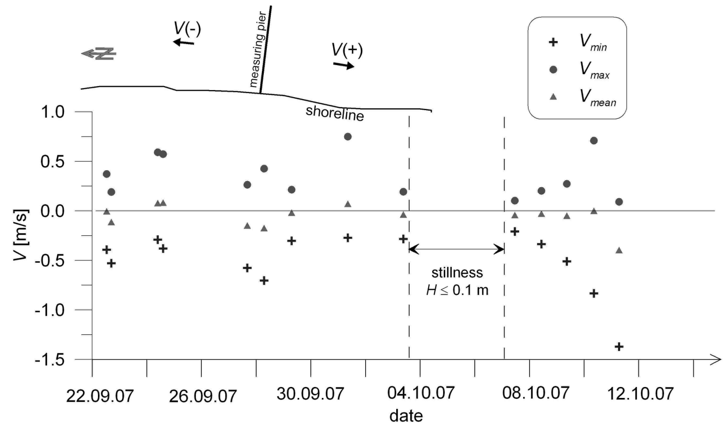

Fig. 10. Maximum, minimum and mean velocities of nearbed longshore currents (0.07 m above bottom) measured at RB Shkorpilovtsi in 2007

4.3. Grain Sizes and Motion of Sediment

Sandy sediments on the sea shore near CRS Lubiatowo can be regarded as representative of the multi-bar south Baltic Polish coast. The grain size distributions shown in Fig. 11 reveal a considerable variability across the shore profile. The median grain size diameter d_{50} lies in the range from 0.17 mm to 0.26 mm. The content of fine particles is higher (d_{50} is smaller) on the shoreface than on the emerged part of the beach. The coarsest sand particles are found at the shoreline. Occasionally, coarse sand has also been sampled around the second bar, at a depth of 3–5 m. The average grain size diameter, representative of the entire nearshore zone in Lubiatowo, can be assumed equal to about 0.22 mm.

The results of soil sampling confirm a general rule according to which fine particles, easily transported by wind, dominate on the beach near the dune toe and on the dune itself. Exceptionally, coarse sediment fractions can appear at the dune foot following intensive wave conditions and storm surges. After a storm the instantaneous shoreline position moves seawards and the coarser sandy material starts to accumulate at the mean long-term location of the shoreline. The concentration of coarse sand near the shoreline results from a highly asymmetric wave motion interacting with intensive return currents in the nearshore zone. This interaction causes the onshore movement of coarse sediment particles, predominantly as bedload, and the offshore transport of fine material (as suspended load). The presence of coarse sand grains at the shoreline itself is presumably an effect of asymmetric wave run-up and run-down phenomena (in the swash zone the latter is a counterpart of the return flow in the surf zone).

Similar mechanisms of sediment segregation take place on the morphologically different sea shore at RB Shkorpilovtsi (the Black Sea). As in Lubiatowo (the south Baltic Sea), the process of sand grain sorting in the nearshore zone results in the occurrence of a relatively fine material (d_{50} = 0.32 mm) at a depth of 1.5 m and much coarser sediment (d_{50} = 0.54 mm) at a depth of 0.5 m. As for the emerged part of the shore, grain diameters d_{50} at the dune toe and on the beach amount to 0.48 mm and 0.51 mm, respectively. Unlike in Lubiatowo, the soil at the shoreline is slightly finer (d_{50} = 0.53 mm) than in the nearshore shallow-water zone.

The complete grain size distributions of sediment sampled at 5 locations of the cross-shore profile in Shkorpilovtsi are given in Fig. 12.

As already mentioned, the variability of grain size distributions on the cross-shore profile results from specific features of wave-current hydrodynamics in the nearshore zone. Coastal hydrodynamics control the onshore-offshore sediment transport, the spatial variability of which is not only a driving force for sea bed changes but a reason for the segregation of sediment as well. Shoreline area is a very singular coastal boundary, at which wave energy is ultimately dissipated in the final breaking and run-up. This causes local erosion in the swash zone. Fine particles are more vulnerable to this erosion, which results in a lower content of fine sand and the predominance of coarse one about the shoreline. According to classical knowledge a classical state-of-the-art,

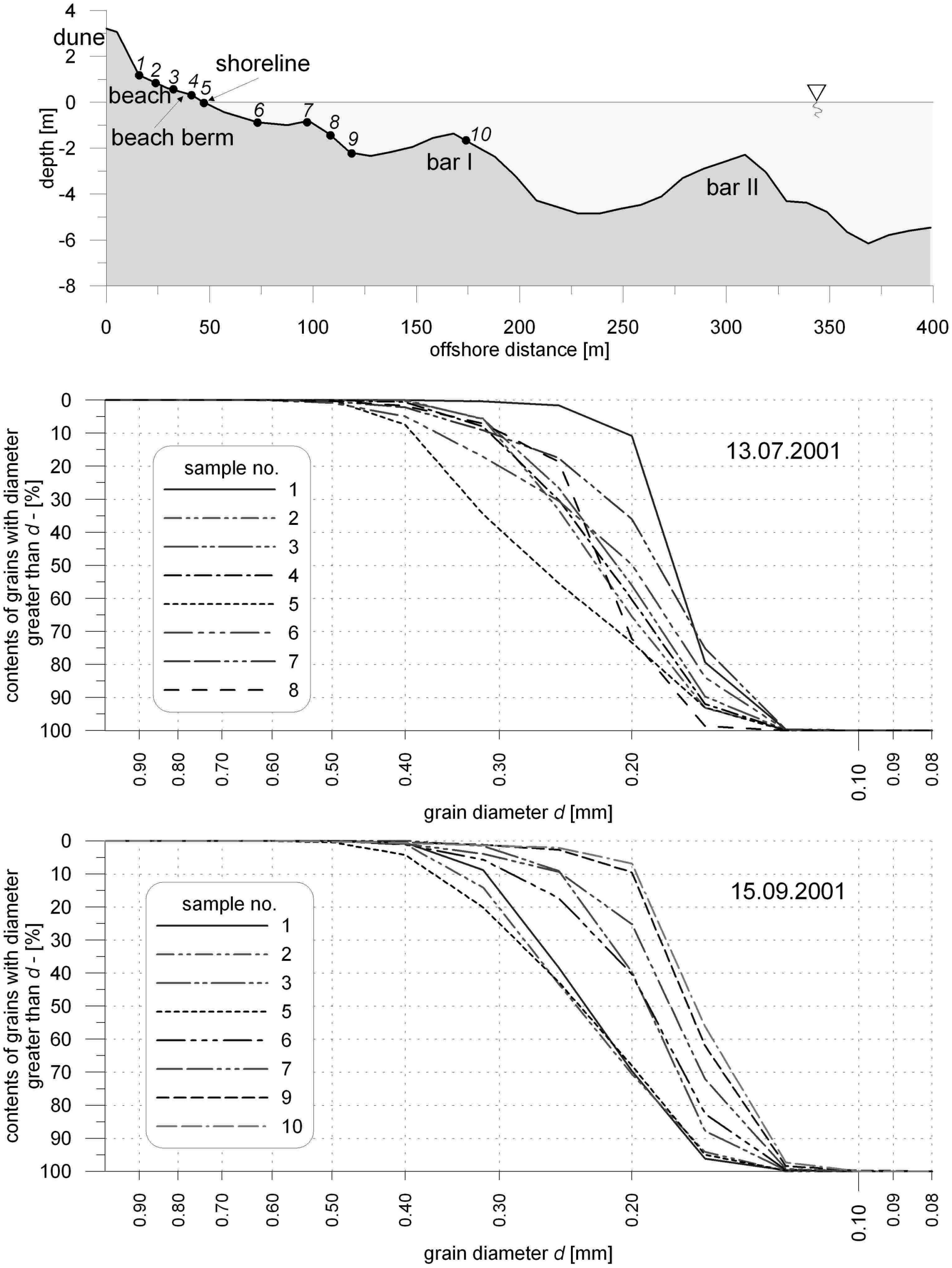

Fig. 11. Sea bed grain size distributions at various locations on the cross-shore profile at CRS Lubiatowo

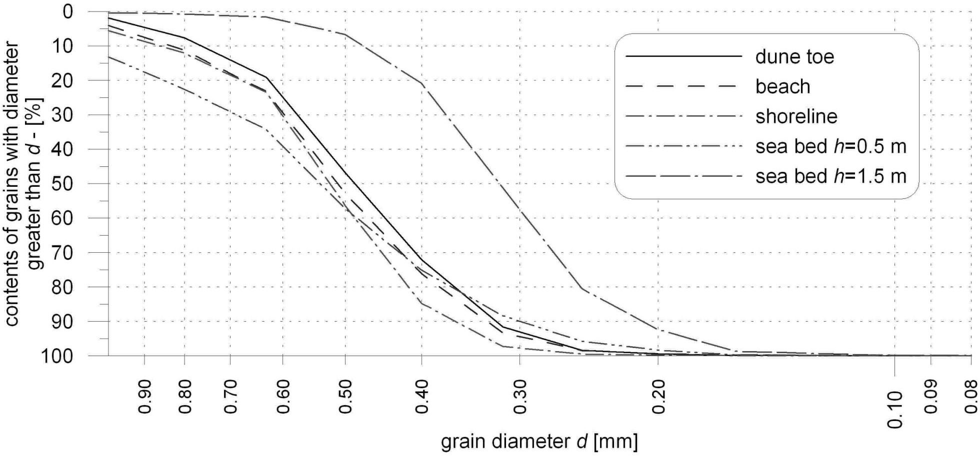

Fig. 12. Sea bed grain size distributions at various locations on the cross-shore profile at RB Shkorpilovtsi

fine particles are transported seawards by compensative currents and deposited at various locations depending on instantaneous hydrodynamics. Therefore, finer sediments are found offshore.

However, it should be pointed out that some surveys at CRS Lubiatowo have revealed the presence of sand grains much coarser than those found near the shoreline and considered as typical of Polish sandy shores. This fact is meaningful for the investigations on sediment transport and coastal dynamics because – as commonly known – a sea bed built of coarser grains is less vulnerable to erosion. Grain size field data collected at CRS Lubiatowo before and after a storm have been very helpful in the verification of theoretical findings on the horizontal sorting of graded sediments, and *vice versa*: computational simulations made it possible to explain the behaviour of size-graded sediment observed in the experimental data, see Kaczmarek et al (2004). That study revealed that changes in the sea bed level and grain sizes are driven by the vertical sorting of suspended sediment as well as by two-directional sediment fluxes (onshore: induced by asymmetric wave motion; and offshore: induced by undertow) and their spatial variability. Kaczmarek et al (2004) identified a few typical situations of increasing and decreasing rates of onshore and offshore sediment fluxes, resulting in various changes of bathymetry and local grain size distributions.

During the 2001 field survey at CRS Lubiatowo, laser technique was applied for the first time. A particle size analyser LISST-100 (Laser In-Situ Scattering and Transmissometry) by Sequoia Scientific Inc. was used to register the concentration of suspended sediment under storm conditions. The device is an optical instrument for *in situ* measurement of particle size spectra in waters with sediment loads exceeding 200 μl/l. Based on the principle of laser diffraction, the LISST-100 records the small-angle intensity distribution of light scattered by particles suspended in water. This distribution, which is proportional to the so-called volume scattering function, is inverted to obtain the particle concentration and size spectrum. In addition, the optical transmission is sensed for this inversion, so the instrument is also a transmissometer. By avoiding water sampling, particle aggregates remain undisturbed. Two supporting parameters are included in the measurement: pressure and temperature. The instrument measures concentrations of particles with diameters from 2.5 to 500 μm and is appropriate to operate at both Lubiatowo and Shkorpilovtsi sites.

The LISST-100 was installed at CRS Lubiatowo on a specially designed framework with a carriage driven by an electric motor. Motion of the carrier (with the attached instrument) was controlled on land from the laboratory building. The lowermost position of the carriage provided registrations 12 cm above the sea bed. The uppermost position of the carriage (about 2.5 m above the mean water level, see Fig. 13) enabled periodic maintenance of the device and data transfer from a built-in memory to a portable computer. The measurements were possible at an arbitrarily chosen location in the water column.

Fig. 13. Particle size analyser LISST-100 above water and while submerging at the measuring tower in Lubiatowo

The registrations of concentrations and grain size distributions were carried out a few times under various wave conditions. The measurements, with the sampling frequency of 3 Hz, were taken at 4–6 levels in the water column. At each level, the recording lasted about 2 minutes. The exemplary time series of nearbed size-graded concentration is shown in Fig. 14.

The results presented in Fig. 14 reveal that grain size distribution and concentrations of individual fractions are highly variable and depend on instantaneous pressure, related to wave motion. Furthermore, it can be seen that for high pressure values the concentrations of all fractions increase and that the most distinct increase concerns coarser grains (with diameters exceeding 0.15–0.2 mm).

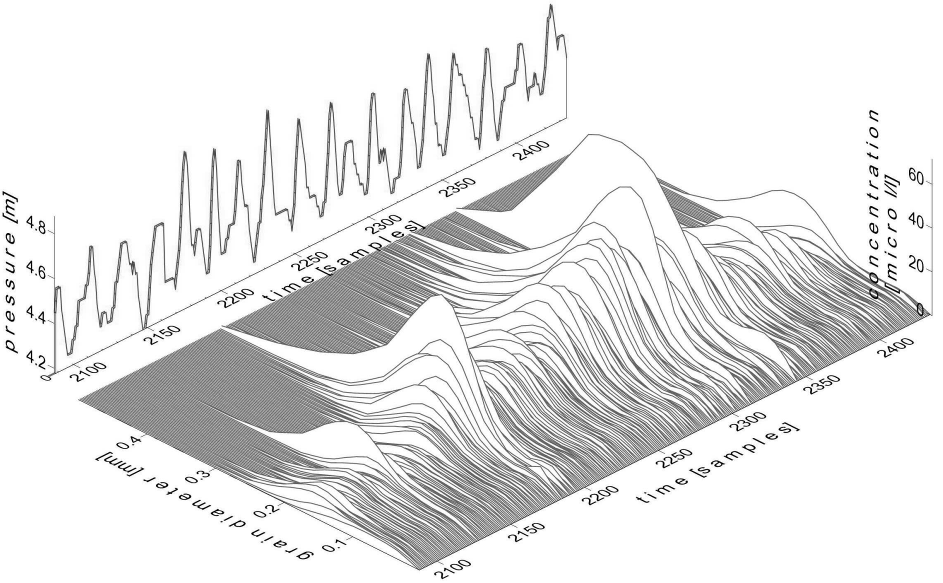

Fig. 14. Water pressure and the concentration of individual fractions of sediment suspended 12 cm above the sea bed at CRS Lubiatowo

Experimental data concerning concentrations of individual sand fractions and the vertical variability of grain size distributions (vertical sorting) are very important for fundamental investigations of size-graded sediment motion. For many research and engineering purposes, vertical distributions of total concentration for all fractions are very useful. Such distributions for the maximum and time-averaged (over 2 minutes) concentration are depicted in Fig. 15.

The field data shown in Fig. 15 imply significant vertical variability of the maximum concentration in the nearbed layer (20–30 cm thick). The maximum value slightly exceeded 2 g/l (corresponding to about 0.75 ml/l). It is known from theoretical models and large-scale laboratory data, see e.g. Kaczmarek, Ostrowski (2002), that for high shear stresses (corresponding to severe wave conditions) sediment concentration near the bed can be much higher, up to tens of grams per litre at ordinates of few millimetres above the bottom. Unfortunately, measurements *in situ* have not provided results for the layers so close to the bed. The concentration data collected in the water column beyond the nearbed layer are very cognitive as well. They seem to clarify questions concerning the possible presence of huge amounts of sand high above the sea bed in the entire surf zone. It can be seen from Fig. 15 that higher above the bed the concentration did not exceed 0.3 g/l (i.e. about 0.11 ml/l). Wave parameters, however, indicate that the wave was far from breaking at the measuring location. Therefore, it ought to be supposed that at other locations (at wave breaking points) sand grains could have been suspended high in the water column.

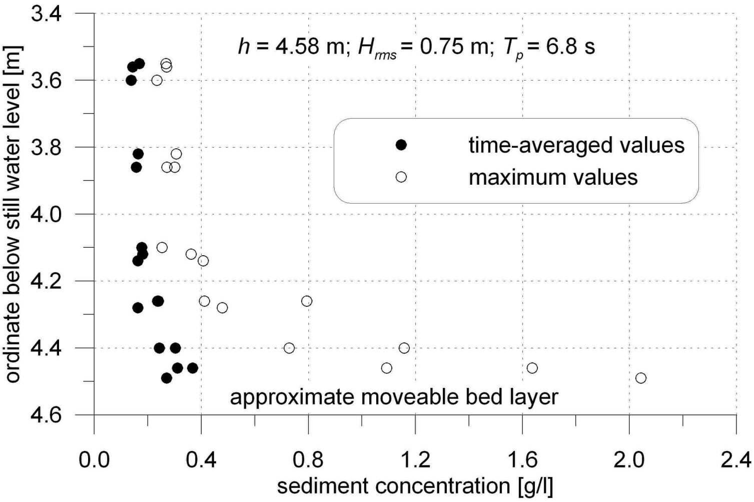

Fig. 15. Vertical distributions of sand concentration measured at CRS Lubiatowo

During the field experiment at RB Shkorpilovtsi, the device (LISST-100) was lowered from the pier on the "shallow-water measuring lift" (see Fig. 3), where broken or breaking waves were observed under storm conditions. However, as should be expected, air bubbles produced by the breaking waves disturbed laser measurements so much that the data collected under such circumstances were useless. Therefore, only the measurements carried out under weak and moderate wave conditions were subject to analysis. The exemplary series of sediment concentrations recorded at four levels above the sea bed (local water depth h = 1.2 m) under moderate wave conditions ($H_{\max}$ = 0.48 m) are shown in Fig. 16. It can be seen that the highest concentration of sand grains (with an instantaneous maximum of 2.5 ml/l) was detected close to the bed.

The respective vertical distributions of sediment concentration measured at RB Shkorpilovtsi in the nearbed layer, i.e. from 7 cm to 34 cm above the sea bottom, are presented in Fig. 17. It is visible that the mean concentration is very small at all levels under examination, amounting to 0.3 ml/l at z = 7 cm and decreasing to 0.25 ml/l ("background" concentration) at z = 24.5 cm. The maximum instantaneous nearbed concentration amounts to about 2.5 ml/l at z = 7 cm and drops rapidly to a background concentration of 0.25 ml/l at z = 34 cm.

Grain size implies the vertical distribution of suspended material under given hydrodynamic forcing. However, the results of field tests carried out under moderate wave conditions (the measuring lift beyond the surf zone – no breaking waves) at RB Shkorpilovtsi and CRS Lubiatowo show that at both sites the time-averaged concentration – although the highest at the measuring point nearest to the bottom (at z = 7–12 cm) – only slightly exceeds the background concentration to which it drops at a distance of 20–30 cm above the sea bed. The field data also show that the maximum

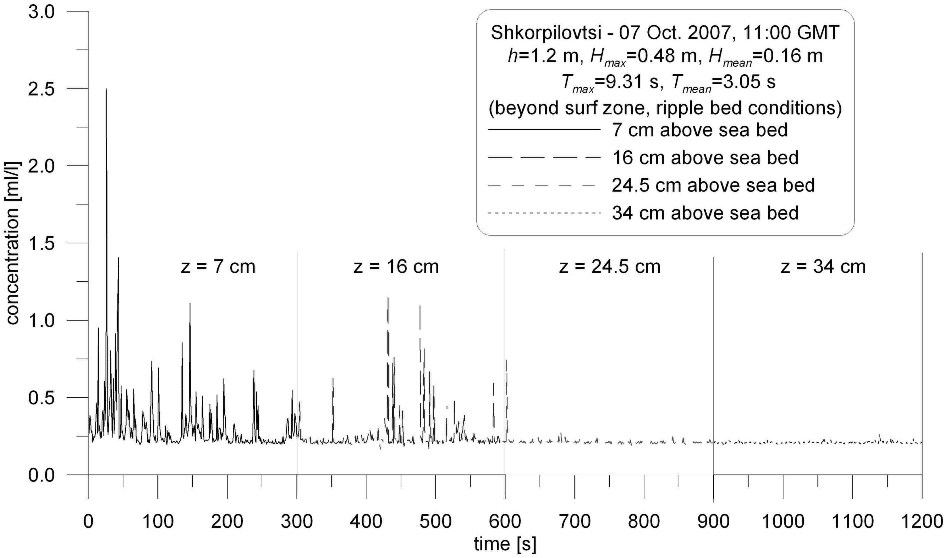

Fig. 16. Time series of sediment concentration measured at RB Shkorpilovtsi

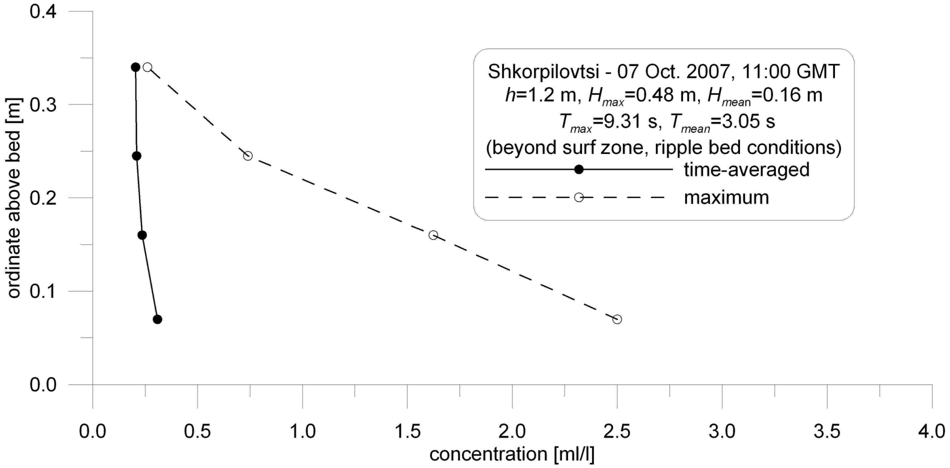

Fig. 17. Vertical distributions of sand concentration measured at RB Shkorpilovtsi

instantaneous nearbed concentrations amounted to 2.5 ml/l at $z = 7$ cm in Shkorpilovtsi and 0.75 ml/l at $z = 12$ cm in Lubiatowo. It follows from theoretical models and large-scale laboratory data that if it were possible to lower the instrument closer to the sea bed, the concentrations would certainly be many times higher, up to tens of millilitres per litre at a distance of few millimetres above the bed. Unfortunately, measurements so close to the sea bottom were unfeasible for technical reasons.

Very interesting information comes from the grain size distributions detected by LISST-100 at various levels above the sea bottom in Lubiatowo and Shkorpilovtsi. Generally, as should have been expected, finer sediments were found higher above the bed. In Shkorpilovtsi, however, a considerable contribution of coarser fractions were recorded at an ordinate of 34 cm from the theoretical bed level. On the basis of visual observations during the survey at RB Shkorpilovtsi, this effect can be justified by the domination of shell particles in suspended matter higher above the bed. This admixture (aragonite), constituting a few percent of the sea bed soil, despite its slightly greater density and grain diameter, has a much smaller fall velocity because of a flat shape of the particles – hence the presence of this material almost in the entire water column.

5. Final Remarks and Conclusions

Based on the results of field investigations, the comparison of coasts representative of two different European seas (the south Baltic and the west Black Sea) reveals some differences in the context of coastal morphology and wave-current patterns as well as grain sizes and sediment motion characteristics. The major qualitative and quantitative results of the comparison, collected from both recent field surveys and other archival data, are summarised in Table 1.

The results of field measurements of nearshore wave-driven currents show that the longshore flow velocities are higher at the dissipative shore than at the reflective shore and that the cross-shore velocities attain higher values at the reflective shore than at the dissipative shore. One cannot be sure whether this results from the coastal bottom slope or is caused just by the wave climate: the predominance of typically oblique wave impact in Lubiatowo versus a generally more perpendicular wave approach in Shkorpilovtsi.

As regards the grain sizes, it can be concluded for both the dissipative shore at CRS Lubiatowo and the reflective shore at RB Shkorpilovtsi that the coarsest sand grains are found at the shoreline or in the shallow water very close to the shoreline. At both sites, the content of fine particles is higher (d_{50} is smaller) on the shoreface than on the emerged part of the beach. The grain diameters, however, are much larger on the reflective shore in Shkorpilovtsi than on the dissipative shore in Lubiatowo. Further, the above difference is closely related to the configuration of the nearshore sea bed, which has a higher slope and smaller number of bars at the reflective shore than at the dissipative one.

Table 1. Summarised comparison of the sites at CRS Lubiatowo and RB Shkorpilovtsi

Feature	Lubiatowo	Shkorpilovtsi
mean annual air temperature [C]	7.5	12.5
mean nearshore water salinity [PSU]	7.5	19
maximum wind speed (averaged/ gusts) [m/s]	20/35–40	26/38*
maximum offshore wave height $H_{\max}$ [m]	7.6	4.95*
maximum significant offshore wave height $(H_s)_{\max}$ [m]	4.7	2.54*
maximum time-averaged longshore current velocity [m/s]	1.6	1.1*
maximum time-averaged cross-shore current velocity [m/s]	0.4 (directed offshore)	0.5 (directed offshore)
maximum storm surge [m]	1.6	0.5
sediment type	fine sand	fine and medium sand
mineralogical composition	quartz – about 100%	quartz – 96%/aragonite ($CaCO_3$) – 4%
sediment density [kg/m^3]	2650	2650/2720
typical median grain diameter d_{50} [mm]	0.17–0.26	0.32–0.54
maximum median grain diameter d_{50} [mm]	0.4	0.7
mean annual net longshore sediment transport rate [m^3]	70,000–100,000	about 26,000
mean bottom slope $\tan\beta$	0.01–0.02	0.02–0.05
surf scale parameter ϵ	about 342–684	about 72
no. of bars	4–5	0–2
emerged beach width [m]	15–60 (locally 100)	30–50
erosive/accumulative trends	no long-term trend	no long-term trend
ice phenomena on the shore	20 days/year at average, 2–3 months/year at maximum	not occurring
other site-specific features	dunes overgrown by grass, bushes and tress, dune toe protected by fascine fences	zone of grass-overgrown dunes, locally very wide

* Short-term data; higher values can occur in the long run

Finally, it should be mentioned that negative temperatures and the related ice phenomena play an important role at the Baltic site. Ice on the shoreline makes it less vulnerable to wave impact and erosion. The most frequent and severe storms usually take place in winter, and thus are often correlated with the nearshore ice phenomena. This natural increase in coastal resistance to erosion can never happen on the Black Sea shore.

Acknowledgements

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