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Sediment Grain Size Features versus Shoreline Changes in View of Field Investigations

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Abstract

The paper presents the results of analyses of relationships between variability of shoreline position, grain size distributions of sediments and the wave climate at the IBW PAN Coastal Research Station in Lubiatowo. The study reports the 2 year long field investigations, which have comprised registrations of shoreline evolution, grain size parameters of nearshore sea bed and wave motion in the nearshore zone. The analysis of the experimental data provides a realistic assessment of morphodynamic processes occurring and interacting in the investigated coastal region. In the study, the following sand characteristic parameters have been considered: the median diameter d50, the representative diameters d25 and d75, the sorting parameter S0 and the skewness parameter Sk. The values of these parameters are found to correlate with the features of the coastal forms, mainly the shoreline migration

1. Introduction

Complex investigations and modelling of coastal morphodynamic processes are associated with analysis and description of interactions of water and sediment motion, time-spatial evolution of main morphological elements of the coastal zone and variability of characteristics of sea bed sediments. The processes and physical relationships between water flow and sediment motion, or between sediment transport and sea bed changes have been the objectives of numerous investigations and analyses, while the studies on interactions and relationships between shore variability and sediment features have not been carried out so thoroughly and the relevant knowledge of this subject is still very limited. Some local relationships are known between flow velocities and various phases of sediment movement, as well as conditions for appearance of small bed forms such as ripples with respect to diameter of grains. However, there is very little information on relations between characteristics of coastal sediments and a main parameter of the coastal zone, namely the shoreline. The question arises whether the change in grain size distribution automatically results in change of the shoreline parameters, or whether this change influences the cross-shore profile shape only. An inverse question also exists whether the change of shoreline and beach due to a heavy storm, can noticeably modify the grain size features of coastal sediments. Such questions and uncertainties are closely associated not only with identification of mechanisms and morphodynamic processes of the coastal zone, but to a number of practical problems of shore protection. Within the latter aspect, the methodology and effectiveness of artificial beach nourishment is meant to a large extent.

The above questions referring to analysis of relationships between variability of shoreline with adjacent regions and grain size distributions of sediments have become the objectives of the present study. In the first stage, 2 year field investigations have been organised and carried out, comprising registrations of shoreline evolution, grain size parameters of nearshore sea bed and wave motion in the nearshore zone. The results of measurements then have been subject to thorough assessment and analysis.

2. Location of Survey and Methodology

The multitude of hydrological factors and morphological structures and coastal forms, as well as their most frequent non-linear and random interactions, ultimately constitute a complex physical system with a number of feedbacks, difficult for theoretical analysis and description. For the above reasons, direct *in situ* observations and field measurements can provide the most realistic assessment of morphodynamic processes occurring and interacting in an investigated coastal region.

The investigations were carried out on a multi-bar (3–5 bars) shore of the south Baltic Sea, near the IBW PAN Coastal Research Station (CRS) at Lubiatowo. The sea shore in this region is mildly sloped ($\beta \approx 0.015$) and built of fine quartz sand with a median grain size of $d_{50} \approx 0.022$ cm. Generally, aside from 3–4 stable bars, an additional bar is observed to appear and disappear frequently. This additional ephemeral bar, together with much more stable fist bar (bar No. I, close to the shoreline, see Fig. 1), have a distinct influence on the location and dynamics of the shoreline. As deducted in previous studies and analyses by Pruszak et al. (2000), both these bars store the sediment for some periods and behave in close correlation with shoreline migration. Beyond stormy periods, these two bars are the source of sediment restoring the shore, while during storms they (in particular bar I) mostly trap the sediment eroded at the shoreline and simultaneously protect the beach and dune from the impact of high storm waves.

Due to the existence of the bars, waves approaching the shore from a deep sea area are subject to significant transformation in the surf zone and most wave energy is dissipated due to multiple wave breaking. If the deep water wave height H_s exceeds 1.5–2 m, the mean wave energy dissipated at the cross-shore profile with three offshore bars (bars II, III and IV) amounts to about 80% of the input

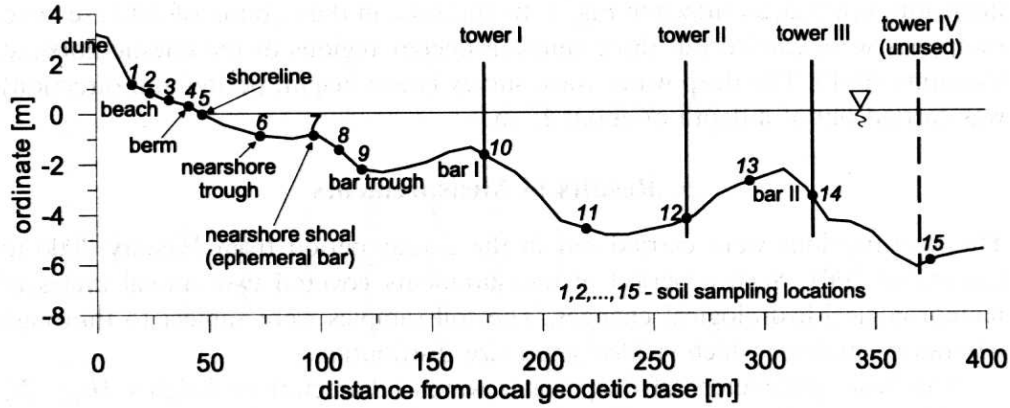

Fig. 1. Locations of sea bed soil samplings

deep water wave energy, see Pruszak et al. (1999). This denotes that in such cases not more than 20% of wave energy reaches bar I and even less reaches the shoreline proximity. For smaller height of deep water waves ($H_s < 0.5$–1.0 m), the amount of wave energy attaining 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 the total wave energy acts perpendicularly to the shoreline. Therefore, a small percentage of deep water wave energy attains the nearshore region and directly affects the shoreline and beach, causing their change. By assuming the generally known parameter:

$$\xi = \frac{H_b \omega^2}{g \cdot \tan^2 \beta}, \tag{1}$$

where:

- H_b – breaking wave height;
- ω – angular frequency of wave motion;
- β – mean bottom slope;

this can describe a scale of dissipative processes occurring in the surf zone. CRS Lubiatowo provides its variability in the range $1000 < \xi < 3000$, which distinctly classifies the considered shore as a dissipative one.

Simultaneous measurements of shoreline position, together with the topography of adjacent emerged beach, and sediment grain size distributions in the assumed cross-shore profile were started in January 2000. In 2001, the deep water wave registration was commenced using the "Directional Waverider Buoy". The wave measurements were taken continuously to late autumn 2001. Both the shoreline/beach variability measurements and the soil sampling were carried out monthly through the entire period considered. The monthly samplings of superficial sediment were carried out at the same locations of the beach and the nearshore sea bed, as shown in Fig. 1. In addition, in the autumn of 2001, sea bed samplings were carried out three times in deeper regions of the coastal zone, at locations 10–15. The deep water wave survey (wave height, period and direction) was carried out at a depth of about 17 m.

3. Results of Measurements

The investigations were carried out in the 2 year period from January 2000 to December 2001. Such a period of measurements covered two annual cycles of meteorological-hydrological changes. The soil samples were subject to thorough laboratory analysis, which yielded grain size distributions.

The basic parameters of deep water waves (characteristic heights $H_{\max}$, H_s and H_{mean}, as well as wave period T) were registered from February to October 2001. Water surface elevations were measured continuously and the resultant wave parameters came from the 20-minutes long periods of analysis, which were carried out every hour.

The wave parameters registered in the analysed period reflected typical hydrological-meteorological conditions for the analysed shore segment (region of CRS Lubiatowo). This has been found out by comparison of these parameters with the data for the same region in 1996–1998, reported by Pruszak et al. (2000). Thus the conditions of February–October 2001 have been assumed representative for longer periods of observations.

4. Analysis

On the basis of grain size distributions, the following characteristic parameters have been suggested for use in further analysis:

- median diameter d_{50},
- representative diameters d_{25} and d_{75},
- sorting parameter S_0, by P. D. Trask, as given by Racinowski et al. (2001)

$$S_0 = \left(\frac{d_{75}}{d_{25}}\right)^{1/2}, \tag{2}$$

- skewness parameter S_k, by P. D. Trask, as given by Racinowski et al. (2001)

$$S_k = \frac{d_{25}d_{75}}{d_{50}^2}. \tag{3}$$

Other parameters have not been considered, e.g. $C_d = (d_{90} \cdot d_{10})/d_{50}^2$, given by Kollis as a so-called domination feature, which is not recommended in lithology, as suggested by Racinowski et al. (2001). Similarly, the grain size inequality parameter, by A. S. Hazen of 1892, has not been taken into consideration.

Variabilities of parameters d_{50}, S_k and S_0 in the entire measuring profile (locations from 1 to 15) for the period 2000–2001 are shown.

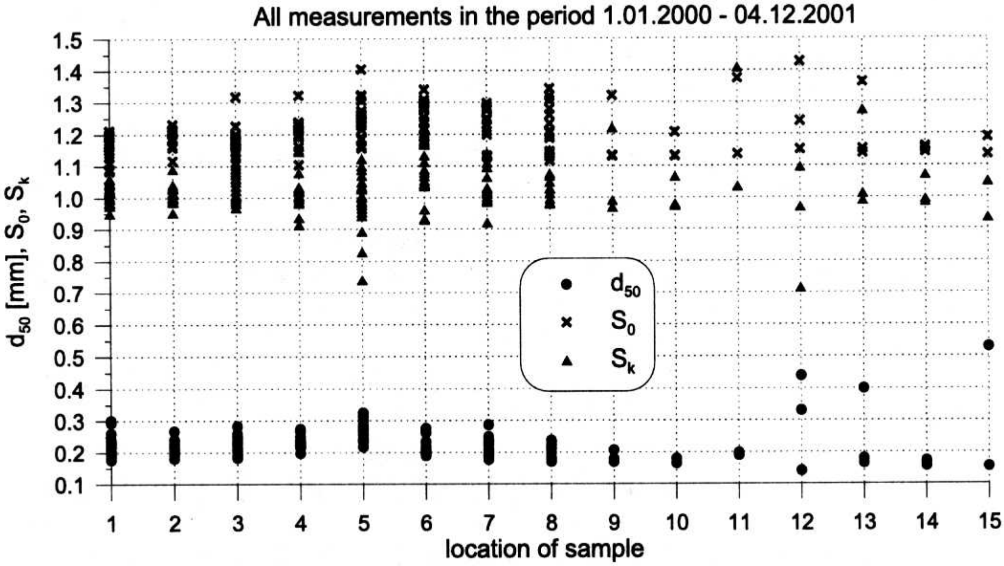

Fig. 2. Ranges of variability of grain size parameters for all measurements

Temporal variabilities of grain size parameters for 3 characteristic beach points (location 1 – dune toe, location 5 – shoreline and location 7 – nearshore shoal) are depicted in Fig. 3.

4.1. Lithodynamic Interpretation of Parameters

4.1.1. Median Diameter

The investigated sea shore, which can be assumed as representative for most of the Polish coast, has a median grain diameter d_{50}, varying in the range 0.13–0.35 mm. Most often the range is from 0.2 to 0.3 mm. The surveys presented confirm previous observations that finer sediments ($d_{50} \approx 0.2$ mm at average) can be found at the dune toe (location 1), apparently deposited by wind action. Exceptionally, at the end of a stormy period, coarser sediments can be found at the dune toe (see e.g. the measurement of 24.04.2001), at an instantaneous location of the shoreline. After a storm, the sea level goes down and the shoreline returns to its previous position, unless severe erosion has occurred. Here, coarser sand appears ($d_{50} \approx 0.3$ mm) in comparison to adjacent emerged and submerged beach; see Figures 2 and 3. This presumably results from distinctly asymmetric wave-induced nearbed flows in nearshore shallow waters. In such conditions, generally, coarse sand is transported onshore as a bedload in the phase of short and high wave crest, while fine particles are moved offshore during long lasting wave troughs.

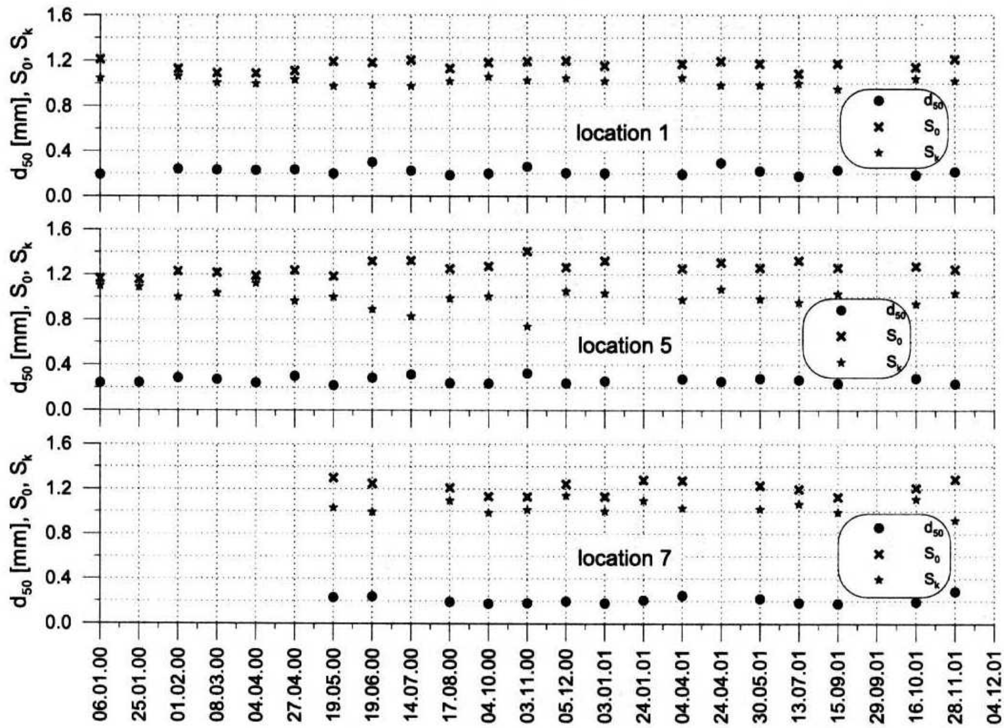

Fig. 3. Temporal variabilities of grain size parameters at locations 1, 5 and 7

The sediment accumulated at the shoreline is thus sorted by both wind and waves. Fine sand is transported landwards by wind or transported offshore in water as suspended load, while the less mobile coarse sand remains in the proximity of the shoreline. In general, no significant seasonal variability of d_{50} can be observed, as depicted in Fig. 3.

Further from the shoreline, in the location of bars, the range of d_{50} variability becomes distinctly larger, with the upper and lower limits of 0.53 mm and less than 0.2 mm, respectively. At locations 12–15, significant variability of d_{50} in time is observed, which can result from cross-shore profile changes and migration of bars. The smallest values of the median diameter ($d_{50} \leq 0.2$ mm) have been found at bar I (location 10), having the most stable position in comparison to the other bars. Also in bar troughs (locations 9, 11 and 14) the sediment grain size is relatively small, rather not exceeding 0.2 mm, see Fig. 2. Generally, the largest values of d_{50} are found close to the instantaneous shoreline. From this location, the median diameters decrease both landwards and seawards, due to asymmetric features of nearshore waves and wind action on the emerged part of the beach.

4.1.2. Sorting

The sorting parameter S_0 for all locations in the entire period of investigations lies in the range from 1.0 to about 1.4, most often varying within the limits 1.1 and 1.2; see Fig. 4. For fine and medium sand, the above values denote states from mean to very good sorting of beach sediment. Higher sorting has been observed on the beach, particularly at the dune toe, worse sorting – about the shoreline and at some locations of the nearshore sea bed, mainly at the bars. This can be the effect of varying of wave energy in the coastal zone. The record of sorting parameter S_0 has some fluctuations (Fig. 3), which can be associated with seasonal variability of wave energy reaching the nearshore zone and related intensity of changes of this zone. Generally, sediments are well or moderately well sorted within the limits of short-term shoreline migration. Their sorting parameters apparently depend on intensity of shoreline evolution.

Some correlation can be seen between S_0 and d_{50}, particularly for location 5 (shoreline), Fig. 4B. At the shoreline the empirical relationship $S_0 = f(d_{50})$ can be approximated, with the determination coefficient $R^2 = 0.35$, by the following linear formula:

$$S_0 = 1.23d_{50} + 0.94. \tag{4}$$

The relationships between S_0 and d_{50} become weaker while moving offshore and with increasing variability of d_{50}. While analysing all the results, one obtains very scattered measured data and it is hard to identify any distinct tendency in variability of S_0 as a function of d_{50}. Almost all measurements appear as a cloud of data in the ranges 0.15 mm $\leq d_{50} \leq$ 0.3 mm and $1.1 \leq S_0 < 1.35$, respectively. It is therefore difficult to interpret them physically.

In the literature concerning coastal zones, which is considered here, many studies can be found analysing more or less accurately, grain size features in the maritime environment. Except for manuals like those by Komar (1998), these publications refer to regional studies or laboratory experiments of specific scopes. Among the latter, one can distinguish the large scale laboratory investigations carried out in the wave flume of Hanover, reported e.g. by Dette et al. (1998a, b).

In the present study, a methodology slightly similar to the one of investigations by Katoh & Yanagishima (1995) has been applied. Those investigations have been carried out for natural conditions (hydrological and morphological) very similar to the ones occurring at the CRS Lubiatowo.

Katoh & Yanagishima (1995), analysing the mainly submerged part of the cross-shore profile with 0.15 mm $\leq d_{50} \leq$ 0.95 mm, noticed a quasi-parabolic relationship $S_0 = f(d_{50})$. It can be seen from the results of Katoh & Yanagishima (1995), that the left-hand side of the approximating curve (corresponding to the sediments analysed in the present study, with 0.15 mm $\leq d_{50} \leq$ 0.35 mm) reflects

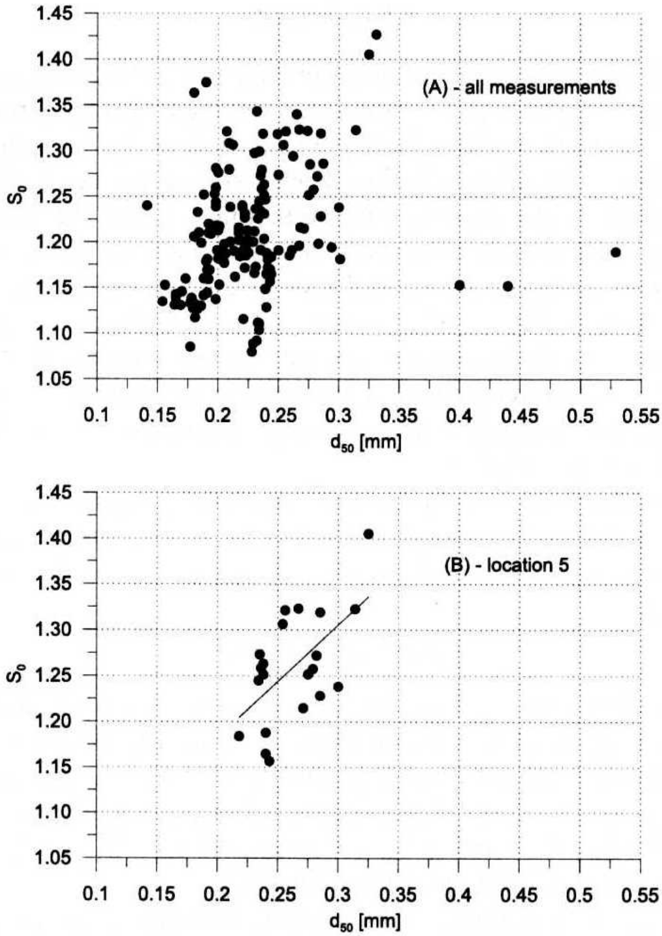

Fig. 4. Relationships between S_0 and d_{50}

a great number of concentrated data points; the right-hand side of the approximating curve (0.35 mm $\leq d_{50} \leq$ 0.95 mm) goes through much more scattered data. Further, the results obtained by Katoh & Yanagishima (1995) for 0.15 mm $\leq d_{50} \leq$ 0.35 mm show roughly linear relationship between S_0 and d_{50}, similar to the results for the location 5 of the present study. This can denote that for shores built of fine and medium sand, the linear relationship between S_0 and d_{50} exists on the beach and in the nearshore sea bed (where relatively smaller variability of d_{50} is observed, cf. Fig. 2). Further offshore, at the bars, this relationship disappears.

4.1.3. Skewness

Described by Eq. (3), the skewness parameter S_k at the emerged part of the beach lies within the limits 0.9–1.1, becoming much more variable (from 0.7 to more than 1.1) at the shoreline (location 5), see Fig. 5. For all measurements, the parameter

S_k varies from 0.7 to 1.4, as shown in Fig. 5A, most often amounting to about 1 and generally lying symmetrically with respect to $S_k = 1$. For the shoreline point (location 5) asymmetry of data appears with respect to $S_k = 1$, resulting in the variability range from $S_k \approx 0.74$ to $S_k \approx 1.2$. This reflects erosion of fine and accumulation of coarse sand at the shoreline. In contrast to the relationship between S_0 and d_{50}, there is a decrease in S_k for increasing d_{50} (and for increasing S_0 as well). This denotes that the coarser the sediment the better the sorting. Theoretically, one can expect the beach accumulation for increasing S_k (smaller water velocities and deposition of fine particles) versus erosion for decreasing S_k (more intensive flow and erosion of fines).

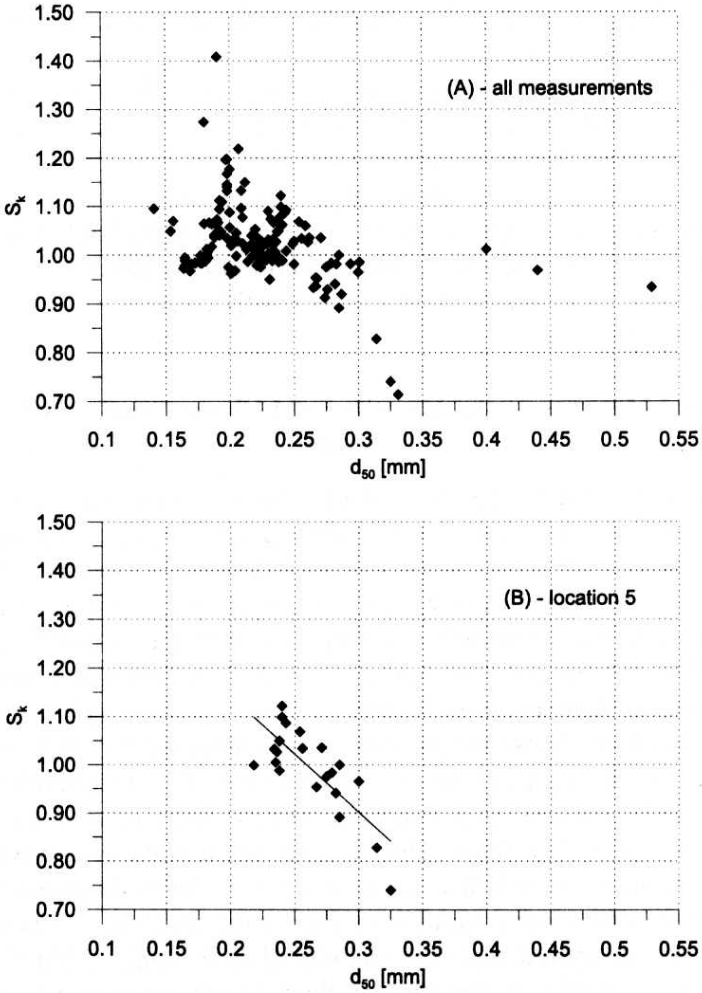

Fig. 5. Relationships between S_k and d_{50}

At the shoreline, for 0.15 mm $\leq d_{50} \leq$ 0.35 mm, the relationship between S_k and d_{50} can be described in the following linear form:

$$S_k = -2.4d_{50} + 1.62 \tag{5}$$

with a relatively large determination coefficient $R^2 = 0.62$.

For the entire data set, similar to the case of the sorting coefficient, a substantial scatter of results is obtained. It is not as significant as for $S_0 = f(d_{50})$ but still big enough for, again, no distinct relationship to be found. A slight tendency can only be seen, according to which S_k decreases with increasing d_{50}, as visible in Fig. 5A.

Hence, similar to the relationship between S_0 and d_{50}, also the relationship between S_k and d_{50} becomes much less distinct for the entire emerged and submerged beach than for the shoreline only. Secondly, no distinct seasonal variability of S_k in time has been found.

Katoh & Yanagishima (1995) suggest a so-called cubic relationship between S_k and d_{50} for 0.15 mm $\leq d_{50} \leq$ 0.95 mm. In the study cited the data points are significantly scattered for 0.15 mm $\leq d_{50} \leq$ 0.25 mm (the largest scatter is for $d_{50} \approx$ 0.2 mm). The difference between the empirical functions $S_k = f(d_{50})$ by Katoh & Yanagishima (1995) and by the present study probably results from the ranges of measurements. Katoh & Yanagishima (1995) considered a 400-m long cross-shore profile, while the present results mostly concern a narrow coastal strip near the shoreline.

4.2. Effect of Waves on the Shoreline and Characteristics of Nearshore Sediments

On the basis of the deep water wave data collected in the period from February to October 2001, the monthly averaged wave heights and periods have been determined. From this the wave energy has been calculated using Eq. (6). The wave energy depends on wave height which changes distinctly (locally rapidly) across the shore profile, due to wave transformation over the changing water depth. Therefore, the wave energy quantities at individual shallow water locations of the cross-shore profile, cannot be indicators of wave energy supplied to the coastal zone. It is difficult to choose the location at which the wave energy would be representative as the driving force for coastal processes. The deep water wave energy is unbiased in this context, as it concerns offshore wave conditions, undisturbed by the influence of sea bed shape. Hence, in the computations of wave energy, the significant offshore wave height $H_{0,s}$ (from the wave buoy data) has been used.

The absolute and relative variability of shoreline position L at two cross-shore transects of the considered region in the period from January 2000 to December 2001 is illustrated in Fig. 6. The biggest changes were observed in the first part of 2000. This presumably results from the hydrodynamic conditions, namely the wave energy affecting the shore. From mid 2000 to winter 2001/2002, the shoreline positions at profiles 5 and 6 oscillated within ±20% only, see Fig. 6.

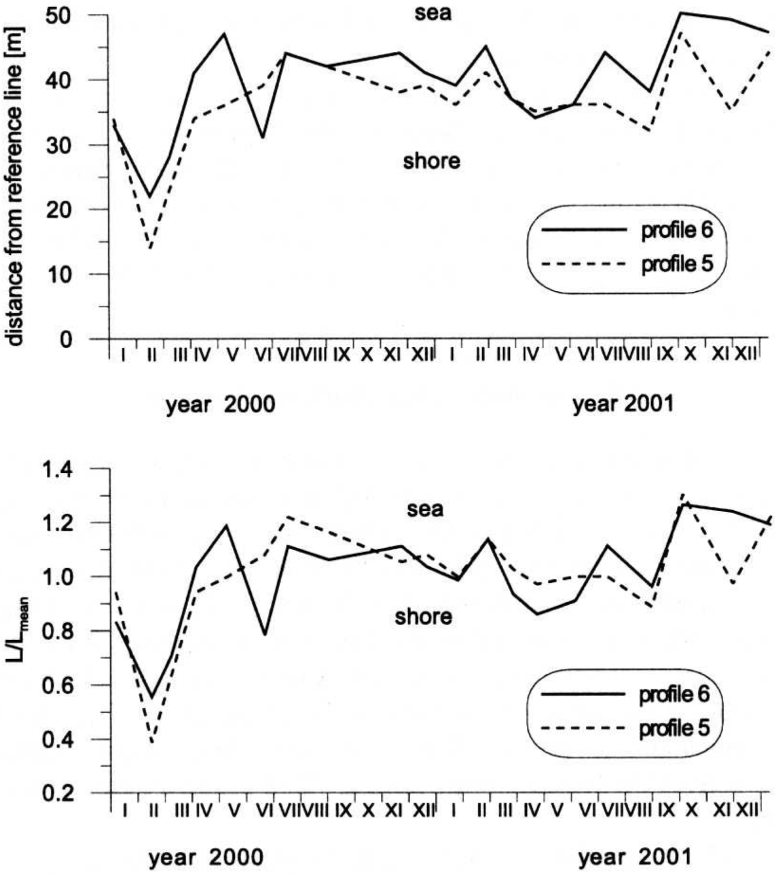

Fig. 6. Evolution of shoreline position at cross-shore profiles 5 and 6

From the analysis, unexpectedly, no clear correlation has been found between changes in the location of shoreline points and wave energy. Moreover, the shoreline moves slightly seawards when wave energy is high (February 2001). The monthly averaged wave energy is described by the following equation, see Pruszak et al. (2000):

$$E = \frac{1}{8}\rho g \overline{H}_{0,s}^{2} \quad \text{with} \quad \overline{H}_{0,s} = \frac{1}{N}\sum_{i=1}^{N} H_{0,s,i} \tag{6}$$

where N denotes the number of measurements in a month. In the period considered registrations were carried out for 20 min every hour. Each i-th registration yields the significant wave height $H_{0,s,i}$.

It should be supposed that the changes in deep water wave energy control the shoreline evolution on a long coastal segment, due to longshore migration of large coastal forms. Thus, there can be a logically justified response of the shoreline at some segments only and the lack of such a response at two chosen locations (profiles 5 and 6) is not so strange.

In the results, it is difficult to distinguish any scales of periodic shoreline variability at the analysed cross-shore transects. This is probably due to the relatively short period of observations and irregular occurrence of storms events, irrespective of the season. Therefore, the coastal evolution appears as a random phenomenon, without conventionally assumed seasonality of coastal behaviour. Hypothetically, this can result from the climatic changes and anomalies which have been observed in recent years.

4.3. Shoreline Versus Sediment Features

The variability of shoreline position does not cause any distinct change of sediment features such as d_{50}, S_0 and S_k (see Fig. 7). This conclusion concerns both phases of coastal erosion ($L/L_{mean} < 1$) and accretion ($L/L_{mean} > 1$). Because the features d_{50}, S_0 and S_k refer to the close vicinity of the shoreline, it can be concluded that, while moving landwards or seawards, it is "carrying" its systems of parameters. Thus, sediment features are bound to the shoreline irrespective of the character of the coastal process (erosion or accumulation). Considering this issue within a fixed system of coordinates, however, one should be aware of the fact that sediment features at individual geodetically fixed points are subject to continuous changes due to migration of the coastal forms "passing" their grain size parameters through these points.

Because of the relatively narrow range of grain size changes for the considered shore (only sandy sediments with the dominating fraction of 0.1–0.25 mm, at maximum 0.35 mm), the natural scale has been used in the analysis of frequency of occurrence of individual fractions. For more complex soils, comprising gravel, sand, clay and silt, the application of a logarithmic scale would be more appropriate, as recommended by Racinowski et al. (2001).

The frequency distribution curves shown in Fig. 8 reveal significant variability of shapes across the shore profile. The sand on the beach and at the shoreline is generally coarser, with wide grain size distribution and slightly greater asymmetry (skewness), with a shape tending to bimodality. Such features result from worse conditions for sorting, associated with very instable and turbulent forces, generated by wind, waves and currents, affecting the motion of grains in this region. At the adjacent submerged beach profile (down to bar I), grain size distributions become more symmetrical and narrow (better sorting). Besides, the content of fine particles increases (d_{50} decreases).

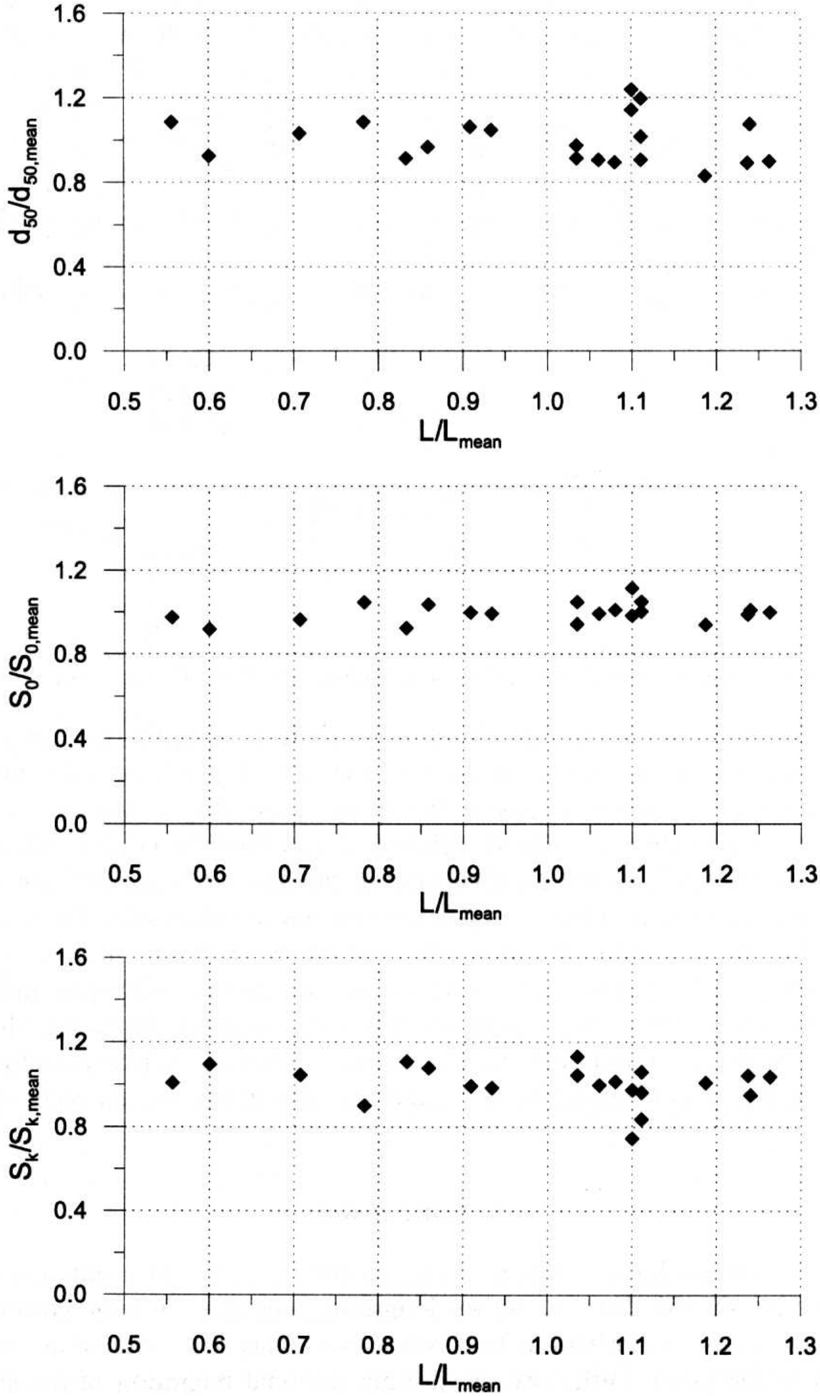

Fig. 7. Position of shoreline point versus sediment features

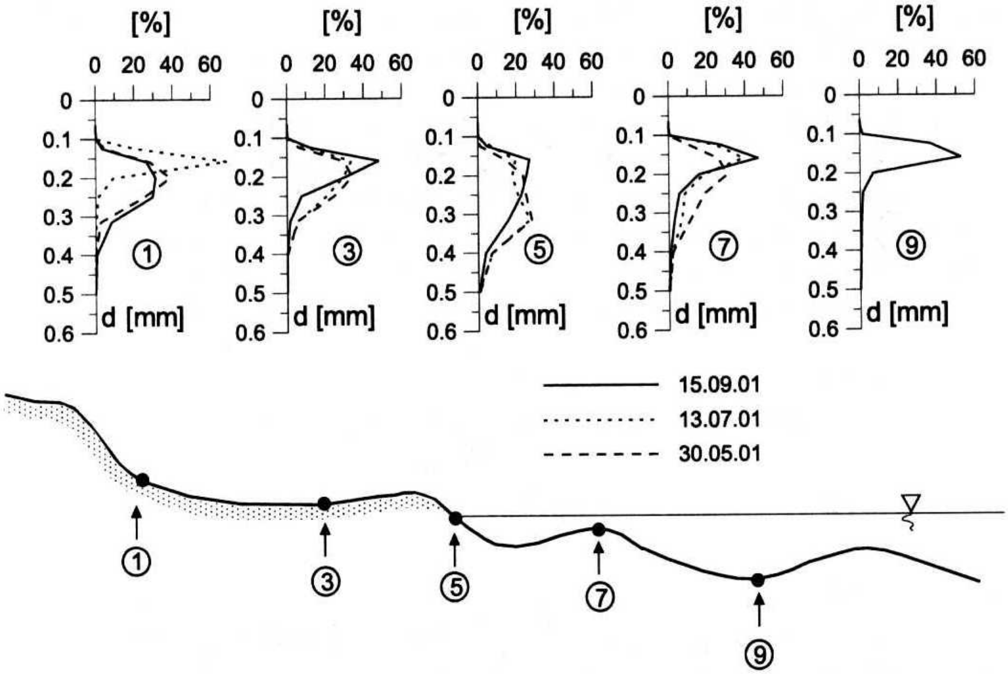

Fig. 8. Frequency distribution curves of the bed sediment on the cross-shore profile

All the above grain size distributions result from specific features of wave-current hydrodynamics in the nearshore zone. The hydrodynamics controls the net on-offshore sediment transport, the spatial variability of which is a driving force for sea bed changes. The shoreline is a very singular coastal boundary, at which wave energy is ultimately dissipated in the final breaking and run-up. This causes local erosion to which fine particles are more vulnerable. Thus, less content of fine and predominance of coarse sand on the shoreline. The fine particles are transported by compensative currents in the seaward direction and deposited at various locations depending on instantaneous hydrodynamics. Therefore, finer sediments are found offshore. Similar tendencies were discovered by Pawluk (1989) on the basis of extensive soil sampling, also in the coastal zone at Lubiatowo.

5. Conclusions

1. Shoreline evolution analysis, if carried out by means of a function of wave energy, should also account for longshore migration of large coastal forms which cause perturbations to classical (seasonal) behaviour of an individual shoreline point. Otherwise, no distinct seasonal migration of the shoreline point can be detected, neither can any clear relation to wave energy supplied to the shore.

2. Grain size features are strongly associated with specific coastal elements. For instance, migrating shoreline carries its system of grain size parameters to a new location immediately. Obviously, quite a different grain size distribution appears at its old location. In view of the fixed coordinates, the sea bed evolution process and migration of coastal forms is linked with simultaneous spatial change of grain size distributions.
3. In almost all states of coastal dynamics, the largest median grain diameters d_{50} are found at the shoreline. They decrease both landwards and seawards due to the action of wind and specific nearshore hydrodynamics, respectively.
4. Sediments near the shoreline are moderately or well sorted, their sorting parameter S_0 depending on shoreline change intensity. High sorting parameters are found on the beach, particularly at the dune toe. The value of sorting parameter fluctuates slightly with time which can be associated with seasonal variability of wave energy reaching the nearshore zone and related intensity of changes of this zone.
5. On the beach, at the shoreline and in the nearshore zone, the skewness parameter S_k decreases with increasing median grain diameter d_{50} and sorting parameter S_0. At the shoreline, the skewness parameter lies asymmetrically with respect to $S_k = 1$, yielding the variability range from $S_k \approx 0.74$ to $S_k \approx 1.2$. This shows erosion of fine particles and predomination of coarse sand about the shoreline.
6. A clear relationship exists between S_0 and d_{50}, particularly around the shoreline. This relationship, being almost linear for the emerged beach and the shoreline, becomes weaker while going seawards. Within the presented investigations, medium and fine sand occurred, with a relatively small spatial variability of d_{50}. Furthermore, no seasonal variability of S_k was observed.
7. On the emerged beach, particularly close to the shoreline, the grain size distributions are flat and wide (with a bimodal tendency), with greater skewness and grain size median. In the nearshore zone (submerged beach down to bar I), the grain size distributions become narrower and more symmetrical. This results from the specific characteristics of nearshore wave-current flows, including the effects of wave energy dissipation and asymmetry of wave shape, which implies the features of wave-induced cross-shore currents.

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