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ORIGINAL RESEARCH ARTICLE

Application of Dean's curve to investigation of a long-term evolution of the southern Baltic multi-bar shore profile

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Summary The paper presents the results of studies on the long-term evolution of the multi-bar cross-shore profiles. The analysis is focused on time-dependent variability of shoreline position, a modified parameter *A* of the conventional Dean's equation and a parameter *F* describing the amount of nearshore sediment resources in the multi-bar cross-shore profile. The study also deals with interrelationships between these quantities. The analysis is carried out using field data collected at Lubiatowo, Poland, on the dissipative shore, representative for the south Baltic. The considered coastal segment is found to be stable in the long-term scale. The results of analysis show that the parameter *A* can either increase or decrease together with the shoreline advance. It is concluded that the shoreline position change is a parameter unsatisfactorily representative for behaviour of the seashore. The use of the Dean's approximation for estimation of the sediment resources *F* on the multi-bar seashore profiles is found reasonable to eliminate the effects of peculiarities of such shores.

1. Introduction

A typical sandy multi-bar coastal zone constitutes a complex morphological system described by a characteristic cross-shore profile with large bed forms (bars) and a shoreline, as well as a beach and dunes. While behaviour of the shoreline and beach forms is the key indicator of coastal dynamics in the longshore direction, the spatial-temporal evolution of the subaqueous cross-shore profile is driven mostly by processes

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occurring in the direction perpendicular to the shoreline. Variety and intensity of coastal morphological changes depend on impact of waves and currents. This impact has a random character and is variable in time and space. Recently, the severity of extreme marine hydrological and hydrodynamic events is said to increase due to climate change (see e.g. Shaltout et al., 2015; Tsoukala et al., 2016). The morphological changes are observed across the entire coastal zones built of sandy sediments, even at the depths of 15—17 m (see e.g. Uścinowicz et al., 2014). On the other hand, in some cases, extensive technical interventions in the shallow water coastal regions have minor influence on nearshore morphodynamics (see e.g. Kubowicz-Grajewska, 2015).

Loss of wave energy due to breaking in the surf zone is strictly related to the presence of underwater bars. A well-developed bar system causes multiple wave breaking and as a result smaller part of deep-water wave energy reaches the shoreline vicinity and the beach than in a case of shore profile without bars (see e.g. Komar, 1998; Pruszak et al., 2008). The cross-shore profile shape can be therefore assumed as a key factor ruling the wave breaking and energy dissipation process. The layout and number of seabed forms (bars) on the cross-shore profile is an indicator of the wave breaking pattern. The number of bars is frequently said to depend on seabed inclination and sediment grain sizes, as well as on the offshore wave climate (see Dolan, 1983; Katoh and Yanagishima, 1993; Moore et al., 2003; Pruszak et al., 1999).

The precise quantitative assessment of evolution of a coast is very difficult, particularly in a case of the multi-bar sandy sea shore. Many coastal parameters are subject to changes which can be of various quality. For instance, retreat of the dune toe can be accompanied by the shoreline advance but in some circumstances both the shoreline and dune toe can move either landwards or seawards. Erosion observed simultaneously at the dune, emerged part of the beach and the shoreline can be compensated by accumulation of huge amounts of sand in the nearshore region, e.g. by volumetric expansion of the bar system. The situation becomes even more complicated if the coastal morphodynamics is considered in multi-scale time domains. Thus, there has been a need to elaborate a reliable method of accurate estimation of coastal evolution trends. Such a method, proposed herein, seems to yield reasonable results independently of peculiarities of an analysed seashore segment.

Analysis of selected parameters of the multi-bar shore profile is a fundamental aim of the present study. The study concentrates on interrelationship between the parameter A of the modified Dean's curve approximating each cross-shore profile, shoreline position with respect to the long-term mean and the parameter F describing the amount of sediment resources in the nearshore part of the coastal zone. In the present analysis, the temporal scale of decades has been considered (period from 1987 to 2008) and the coastal zone with 2—5 bars. The parameter F, expressing nearshore sand resources and resistance of seashore to erosion, has been defined in accordance with the Dutch approach, adapted by Cieślak (2001).

2. Study site and field data

The analysis was carried out by use of data collected on the typical south Baltic shore, namely at the Coastal Research Station (CRS) in Lubiatowo. The station was established in 1968 and has been operated by the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN). Since 1970s, numerous field surveys have been carried out at CRS Lubiatowo during which a lot of data have been collected. Some of these data have been used in studies published in scientific papers. The present article contains the Lubiatowo data unused till now, as well as the data already utilised but within a new interpretation.

The mean nearshore slope is $\beta = 0.015$ (0.04 at maximum very close to the shoreline) and the seabed is built of fine quartz sand having the median grain diameter equal to $d_{50} = 0.22$ mm. The Baltic can be assumed as the non-tidal or micro-tidal sea and water motion is therefore generated only by wind-driven waves and currents. The underwater bar system consists of 3—5 bars. The first stable bar occurs about 100—120 m from the shoreline, the second one ca. 250 m, the third one 400—450 m while the fourth one often overlaps with the fifth one constituting a large form 650—750 m from the shoreline. Aside from these stable bars, there is also an ephemeral bar in the form of a flat shoal located near the shoreline. The view of the considered coastal segment, its location in the south Baltic Sea and the layout of exemplary analysed cross-shore profiles are shown in Fig. 1.

The presence and layout of bars, together with instantaneous wave conditions, imply numbers and locations of wave breakings. In mild and moderate wave conditions, waves break over the first bar and sometimes also in the region of the second bar, that means 100—250 m from the shoreline. During storms, waves are subject to multiple breaking and constitute a few breaker lines over the bars located farther seawards. If the waves are very small, they reach the nearshore zone unaffected by the seabed and break in close shoreline vicinity. A typical storm of average intensity generates waves having a significant height of $H_s = 2.5$ m at water depth of $h \approx 15$ m. The maximum significant wave height can reach H_s equal to 3.5—4.5 m. In such conditions, wave period is equal to 5—8 s (while it does not exceed ca. 4.5 s in mild conditions). Due to wave transformation and breaking on the cross-shore profile, a part of wave energy E dissipates which qualitatively depends on the incipient (deep-water) wave height. For instance, as calculated by Pruszak et al. (2008), the deep-water waves higher than 1.5 m loose at least 60% of their energy in the nearshore zone of CRS Lubiatowo site (which implies that not more than 40% of wave energy reaches the shoreline vicinity).

Within the present study, cross-shore transects stretching several hundred metres seawards (most often about 900—1000 m) and shoreline positions along 2.6 km coastal segment have been analysed. The bathymetric profiles spaced by 100 m from each other have been measured since 1987 while the shoreline position data have been collected since 1983. The analysis has been focused on three selected profiles, numbered 6, 11 and 21 (see Fig. 1). The variability of cross-shore transect no. 21 in the period from 1987 to 2008 is shown in Fig. 2a while the shoreline evolution in the same time is presented in Fig. 2b. Locations of the selected profiles 6, 11 and 21 are also shown in Fig. 2a.

It can be seen in Fig. 2a that the changes in bottom ordinates attain 4 m while Fig. 2b implies that the scope of variability of shoreline position at some locations is almost 100 m.

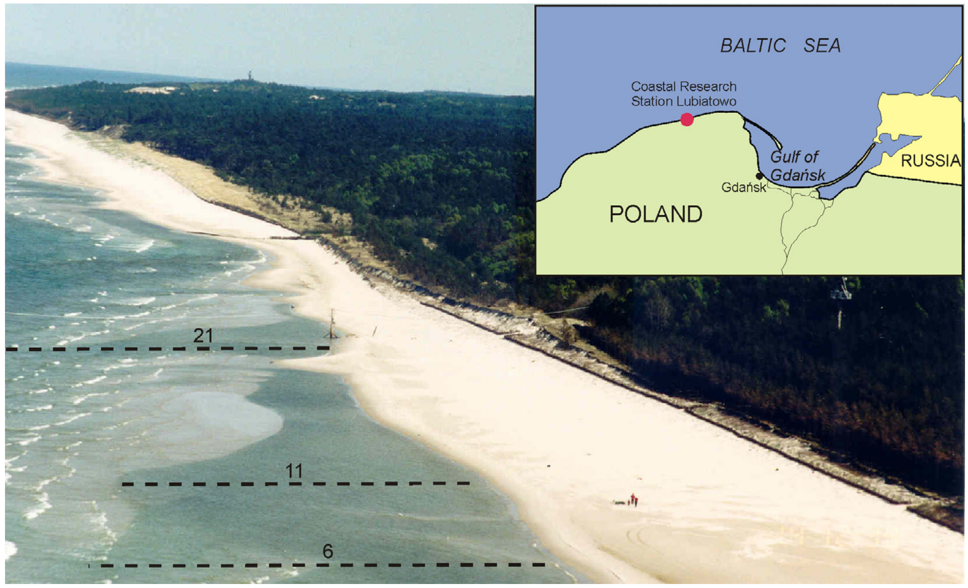

Figure 1 Location of the study site, its view and layout of exemplary cross-shore profiles.

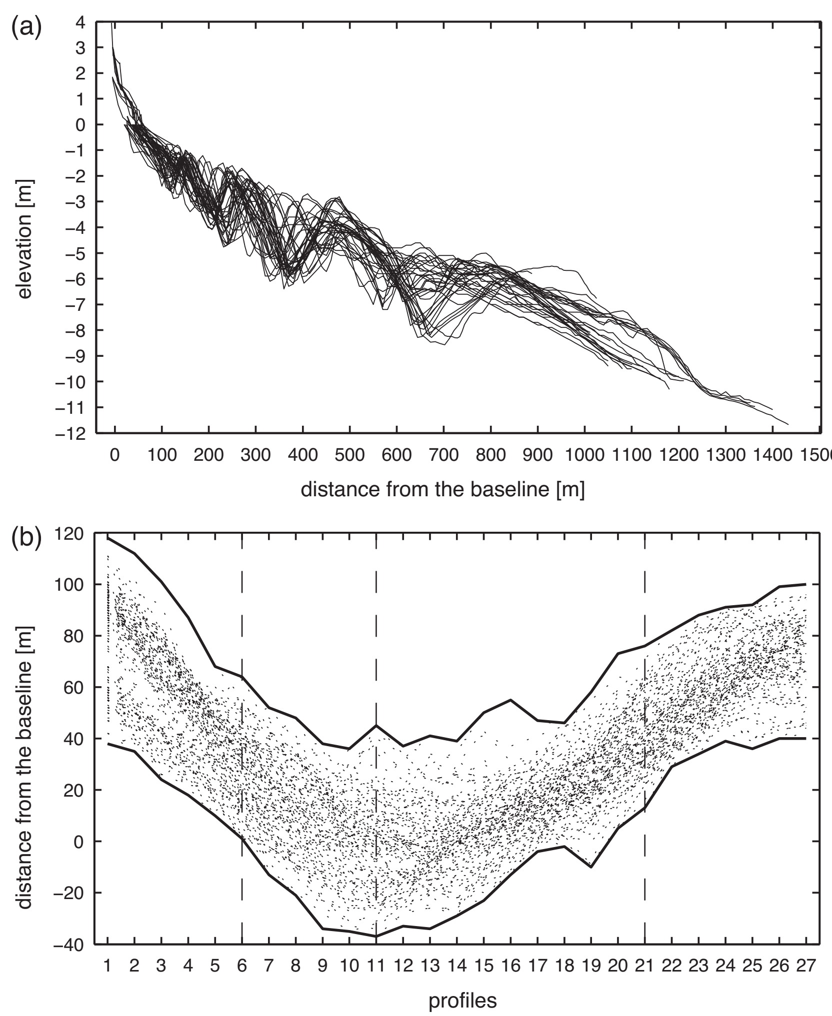

Figure 2 Long-term variability of the cross-shore profile (a) and shoreline position (b) at CRS Lubiatowo in the period from 1987 to 2008.

3. Analysis

3.1. Approximated equilibrium seabed profile

The measured cross-shore profile can be approximated by the classical curve proposed by Dean (1976, 1985):

$$y' = A \cdot x'^{2/3}, \tag{1}$$

in which x' and y' are the cross-shore distance and the water depth in the coordinate system shown in Fig. 3. The parameter A is a so-called "profile scale parameter" with dimensions of length to the 1/3 power. Basing on the linear wave theory, Dean (1977, 2002) has shown that Eq. (1) is consistent with uniform wave energy dissipation per unit volume within the surf zone and the shape described by Eq. (1) defines the "equilibrium beach profile".

In this system, however, the approximating function is vertical at the shoreline which is unreal. To get rid of this inconvenience, Pruszak et al. (1997) modified Dean's approximation by application of displacement of the shoreline point to location where the line of the nearshore mean seabed inclination ($\tan\alpha$) is tangent to Dean's curve, as shown in Fig. 3. The modified Dean's function reads as follows:

$$\begin{aligned} y &= A \cdot (x + x_o)^{2/3} - A \cdot x_o^{2/3} \\ &= A \cdot \left\{ \left[x + \frac{8}{27} \left(\frac{A}{\tan\alpha} \right)^3 \right]^{2/3} - \left(\frac{2A}{3\tan\alpha} \right)^2 \right\}. \end{aligned} \tag{2}$$

The measured cross-shore transects have been approximated by Eq. (2) using the least-square method. This ensured determination of Dean's parameter A for each measurement of the analysed shore profiles. The time-dependent values of the parameter A for profiles 6, 11 and 21 are shown in Fig. 4.

It can be seen in Fig. 4 that the parameter A value oscillates in the range from 0.075 to 0.107. Further, no distinct periodicity is visible. There is a decreasing trend for all three analysed profiles which can suggest that the nearshore zone has become shallower during the considered period.

The parameter A quantitatively represents the shore stability. Small values of A are typical for accumulative shores while high A values indicate steep shores, vulnerable to wave impact and erosion. Coastal erosion is basically identified as the shoreline retreat which most often corresponds to retreat of the entire cross-shore profile. In some cases, however, regression of the shoreline is compensated by accumulation of sediment in the nearshore zone, e.g. in the form of underwater bars. Evolution of the shoreline δ at the considered cross-shore transects with respect to the time-averaged shoreline position is drawn in Fig. 5, in which the positive and negative values stand for the shoreline advance and retreat, respectively.

The linear trends presented in Fig. 5 indicate the long-term shore accretion at profiles 6 and 21. The scatter around the approximating line is distinctly less for the profile no. 6 than for the profile no. 21 which implies that the profile no. 21 is more dynamic than the profile no. 6. It can be seen in Fig. 5 that the profile no. 11 has also been very dynamic. In this case, however, the approximating line reveals a significant trend of the shoreline retreat.

More detailed insight into shore profile change is obtained by analysis of the parameter A as a function of shoreline position δ. The results of such calculations are shown in Fig. 6.

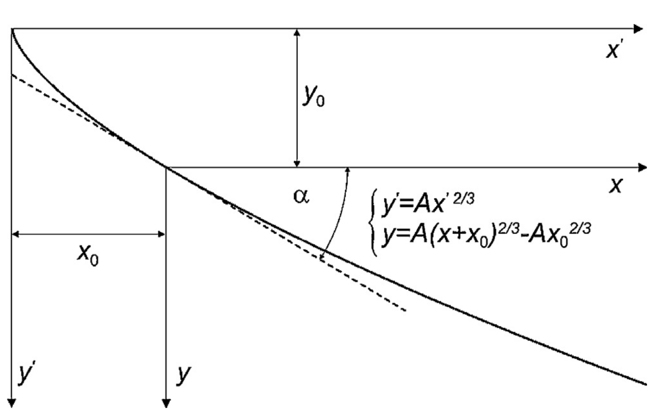

Figure 3 Modified Dean's curve.

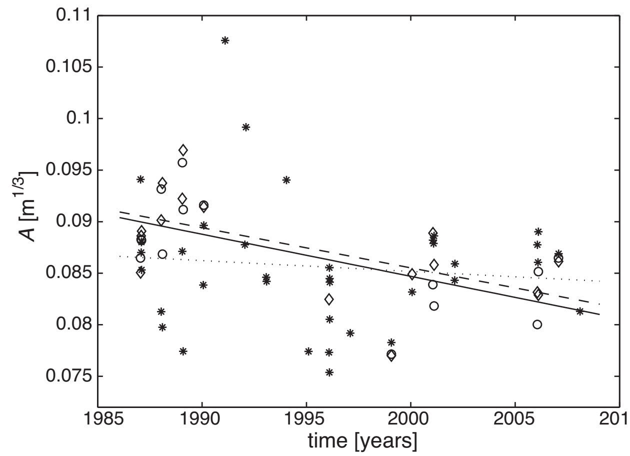

Figure 4 Variability of parameter A in time with trend lines for profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

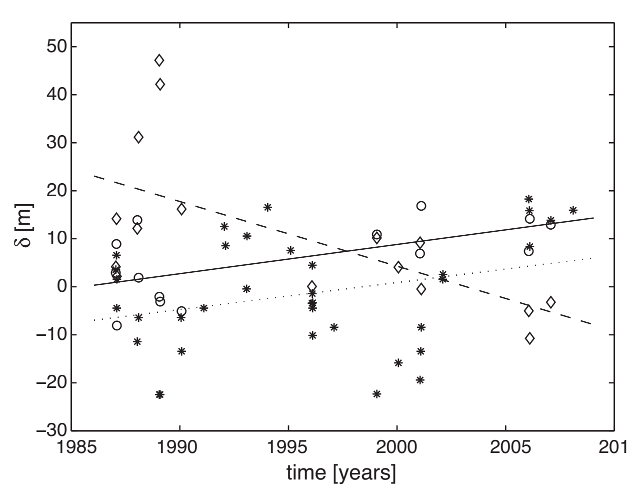

Figure 5 Shoreline evolution $\delta(t)$ with trend lines at profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

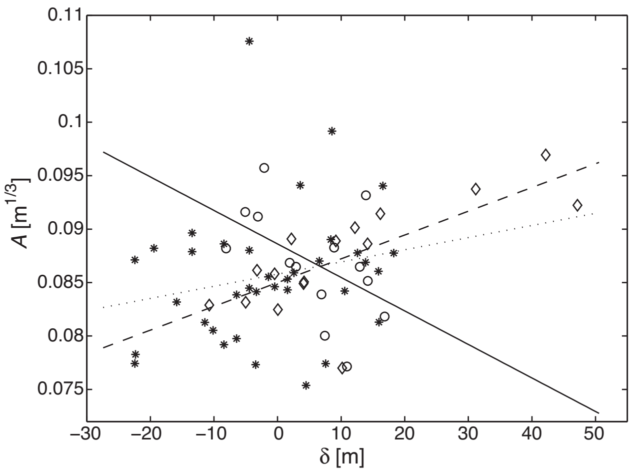

Figure 6 Parameter A as a function of shoreline position δ with trend line for profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

The results of analysis plotted in Fig. 6 show the increasing parameter A together with the shoreline advance at profiles 11 (small deviations from the approximation) and 21 (very large scatter from the approximating line). Simultaneous increase of A and δ denotes steepening of the cross-shore profile together with the seaward shoreline displacement. As regards the profile no. 21, the most considerable scatter is visible. For the profile no. 6, the increase of A is accompanied by decrease of δ. This denotes a case in which the shoreline advance occurs on the cross-shore profile becoming shallower (accumulation of sediment on the entire profile). In general, it can be concluded from Fig. 6 that the considered sea shore can behave variously and the shoreline position δ is a parameter the evolution of which does not reflect behaviour of the entire cross-shore shape.

It should be pointed out that similar values of the parameter A of Dean's function (Eq. (1)) and the modified Dean's function (Eq. (2)) can be obtained for various shapes of the multi-bar cross-shore transects. This is illustrated in Fig. 7 where the exemplary approximations of the profile no. 11 by use of the modified Dean's curve (Eq. (2)) for 1989, 2001 and 2007 are shown. The caption of Fig. 7 indicates that the parameter A is almost the same for 2001 and 2007 (with relatively exact approximations in both cases) while the cross-shore reliefs differ considerably. For 1989 (with a satisfactorily good approximation), the parameter A is only slightly bigger than for 2001 and 2007 while the cross-shore shape for this year is totally different than observed in 2001 and 2007.

As depicted in Fig. 7, the actual cross-shore transects were subject to conversion from the 5-bar profile in 1989 to 2-bar profiles in 2001 and 2007. As mentioned before, the approximation goodness is better for the profile displaying smaller number of bars. In particular, it can be seen in Fig. 7 that the offshore part of the profile (350 m from the shoreline and farther) is perfectly well approximated by the modified Dean's function. It could have been expected as the approach of Dean was originally proposed for sea shores having no bars or small numbers (no more than 1—2) of bars.

3.2. Nearshore sediment resources

In view of the previous considerations, evolution of shoreline position does not reflect actual erosion or accretion of the sea shore. For a sandy coast, the amount of non-cohesive sediments constituting the nearshore seabed indicates the shore character, namely whether it is erosive or accumulative. According to Cieślak (2001), on the south Baltic coast, including the Polish seashore, the above feature is represented by sediments deposited in the zone between the dune foot (landward edge of the emerged part of the beach, located about 2.0 m above the mean sea level) and the depth of 6—7 m. This part of the cross-shore transect, namely beyond the ordinates +2 m and −6 m (or −7 m) ought to be taken into account while determining the sediment resources in the sandy coastal zone, see Fig. 8.

The nearshore sediment resources volume per one metre along the shoreline [$m^3\ m^{-1}$], i.e. the area of the cross-shore profile denoted as F in Fig. 8, depends on the boundary ordinate y_2 which delineates the seaward limit of analysis (x_2). This boundary can be assumed identical to the classical coastal engineering parameter: the depth of closure, at which the nearbed lithodynamic processes become distinctly less intensive than in the nearshore zone. In the present study, the value $y_2 = -6$ m has been assumed.

The time series of the actual variable F and of the variable F determined from the Dean's approximation are shown in Fig. 9a and b, respectively.

Fig. 9a and b reveal increasing linear trends for almost all profiles, both with respect to the variable F determined for the actual cross-shore transects and for F determined using the Dean's-approximated profiles, which implies that the sediment resources at the analysed coastal segment have grown in the long run (since 1987). The amount of nearshore sediments represented by F mostly lies in the range of 1600—2000 $m^3\ m^{-1}$ and 1750—2100 $m^3\ m^{-1}$ for the actual and Dean's-approximated profiles, respectively. In view of the study published by Dubrawski and Zawadzka (2006), in which the quantity F determined in the same way for the erosive shore segments in Kołobrzeg (west part of the Polish coast) has been reported to be equal to 1000—1200 $m^3\ m^{-1}$ only, the considered seashore at CRS Lubiatowo can be assumed as stable or even accumulative. This finding can be supported by analysis of Hel Peninsula (ca. 40—70 km eastwards of CRS Lubiatowo) seashore stability carried out by Ostrowski and Skaja (2011). Analysed in that study, the root part of Hel Peninsula is subject to regular intensive artificial beach nourishment which is necessary to provide accumulative features of this shore segment (wide beach and high ordinate of the dune toe). The respective values of F calculated analogously (with $y_1 = +2$ m and $y_2 = -6$ m) for the root part of Hel Peninsula in 2003—2008 range from 1200 $m^3\ m^{-1}$ to 2000 $m^3\ m^{-1}$. The above considerations suggest that the parameter F is an indicator of the coastal resistance (or vulnerability) to erosion. For individual south Baltic shore segments this value is different. Since this criterion is site-specific, depending on local conditions (e.g. wave climate and grain size), it ought to be determined for each considered site separately.

By intuition, variability of the parameter F ought to be distinctly correlated with the shoreline position changes which means e.g. that the bigger shoreline advance is

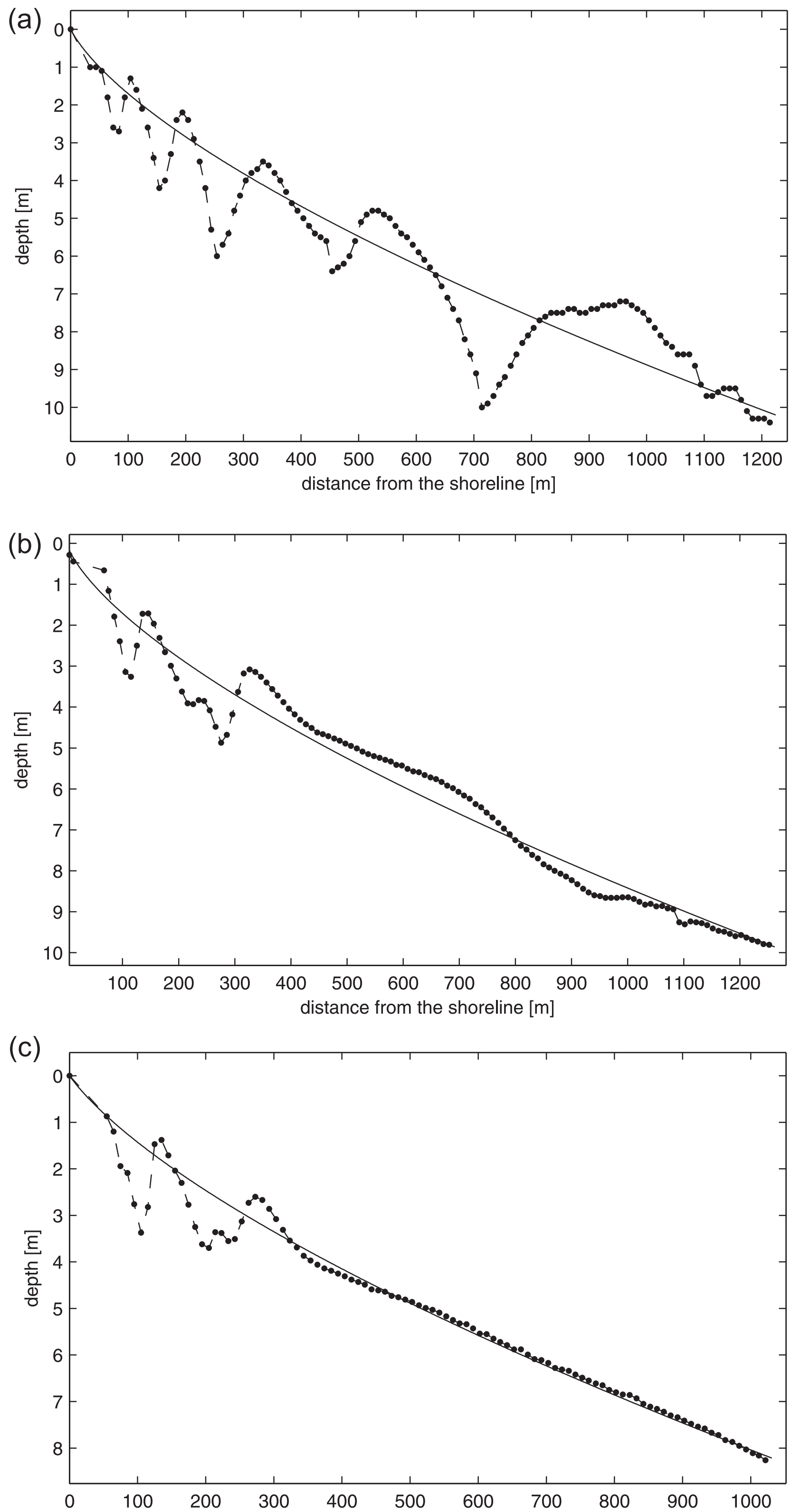

Figure 7 Results of approximation of profile no. 11 by modified Dean's function: for 1989 with $A = 0.0922$ and $R^2 = 0.847$ (a), for 2001 with $A = 0.0858$ and $R^2 = 0.963$ (b) and for 2007 with $A = 0.0861$ and $R^2 = 0.957$ (c).

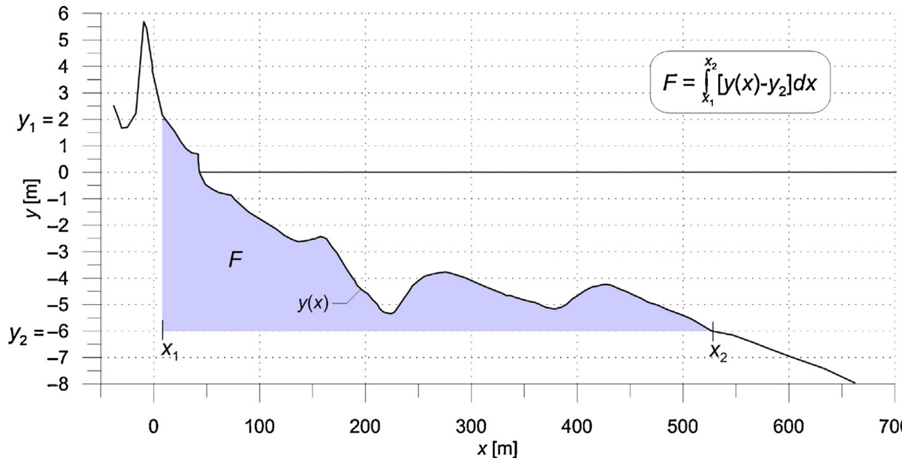

Figure 8 Definition of nearshore sediment resources F, after Cieślak (2001).

observed the higher value of F is obtained from the calculations. This is not entirely confirmed by results of analysis shown in Fig. 10a and b for the actual and Dean's-approximated shore profiles.

The trend lines plotted in Fig. 10a and b clearly show that in some cases the shoreline evolution can take place independently of the nearshore seabed profile change. This is particularly visible for the profile no. 11 where the shoreline advance δ is not related with the increase of the sediment resources F in the nearshore zone. For the profile no. 21 the considerable seaward movement of shoreline position is accompanied by merely a slight growth of sediment resources while for the profile no. 6 the beach accretion at the shoreline corresponds to distinct sediment accumulation in the

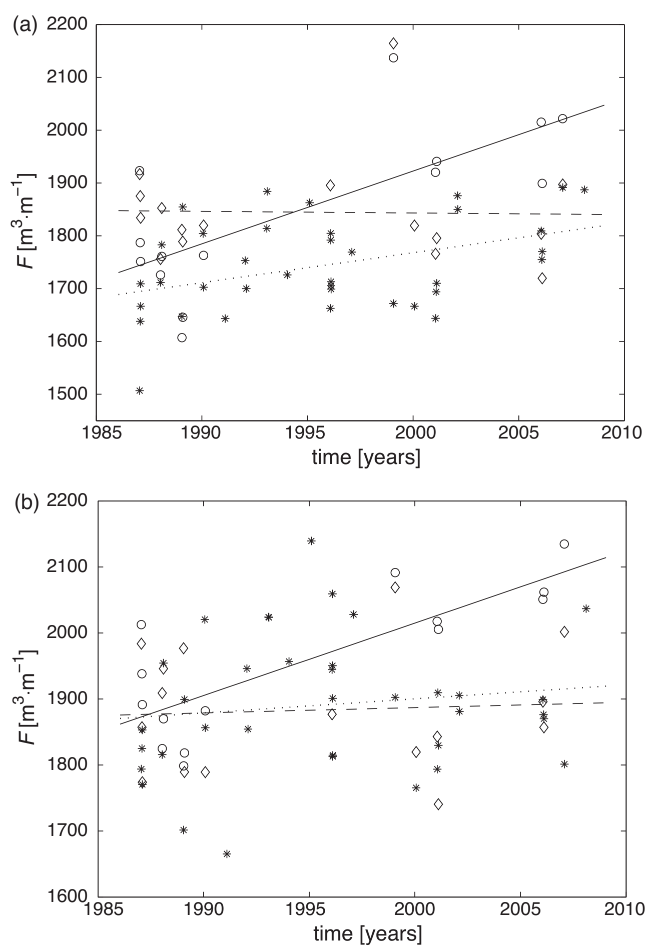

Figure 9 Variability of sediment resources F (a) and sediment resources F calculated for Dean's curve (b) in time with trend lines for profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

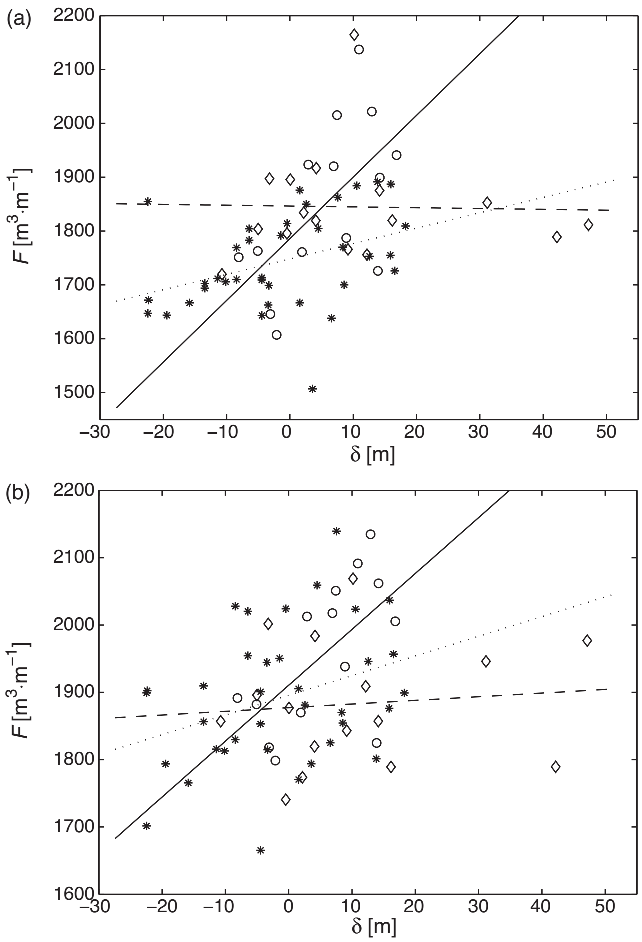

Figure 10 Sediment resources F (a) and sediment resources F calculated for Dean's curve (b) as a function of shoreline position δ with trend lines for profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

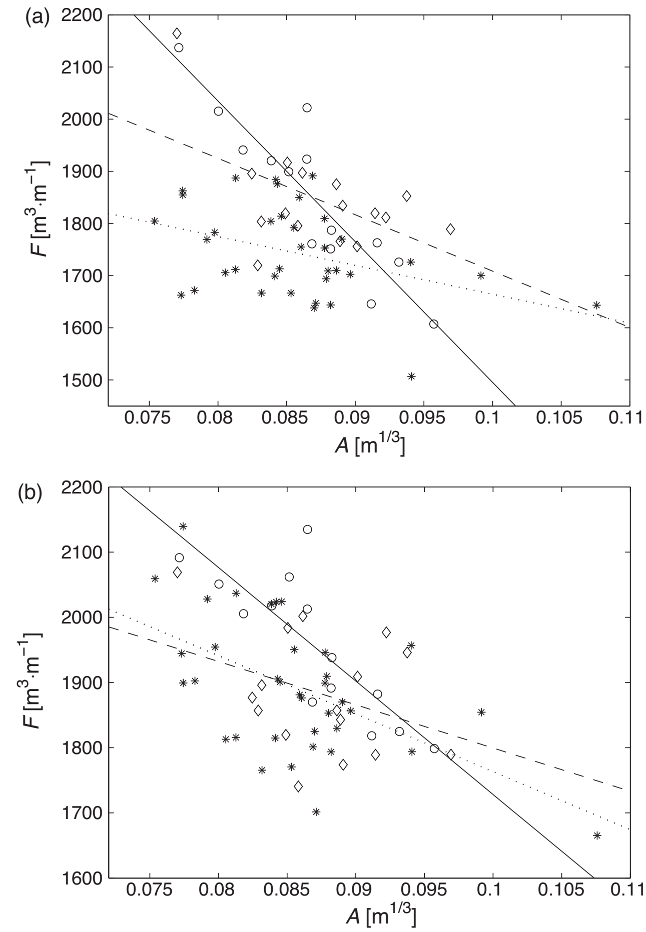

Figure 11 Sediment resources F (a) and sediment resources F calculated for Dean's curve (b) as a function of parameter A with trend line for profiles 6 (circle, solid line), 11 (diamond, dashed line) and 21 (asterisk, dotted line).

entire nearshore zone (F significantly proportional to δ). Such various dependencies of F on δ result from the fact that the shoreline position is sensitive to any (even very weak) hydrodynamic conditions while the sea bottom at bigger depths (5—7 m) is subject to changes during more severe conditions. Secondly, in some circumstances the emerged part of the shore profile can quickly evolve due to aeolian processes and influence the parameter F while the shoreline position and the nearshore seabed can remain unchanged at the same time.

In contrast to the ambiguity of the relationship between the nearshore sediment resources F and the shoreline position δ, a more clear mutual association between the parameter F and Dean's coefficient A can be expected. Typically, volumetric increase of the nearshore sand resources is accompanied by flattening of the non-bar profile which results in decrease of the parameter A in Dean's curve. For the multi-bar shore, the bars may be located closer or further to each other, can be more or less steep, higher or lower. These features can distinctly imply the value of F, even if the coefficient A remains similar. Yielded by the present analysis, the parameter A decreases with growing F for all cases presented in Fig. 11a and b. It is worthwhile noting, however, that the inclinations of the approximating lines differ significantly from each other, particularly in Fig. 11a (the actual value of F versus the parameter A). This results from the bottom relief of the analysed coastal segment at which, as mentioned before, the multi-bar characteristics can yield the same or similar values of A for variety of cross-shore profile shapes. It should be noted again that the wind-induced evolution of the emerged beach influences the parameter F while it has no meaning to the parameter A.

For the multi-bar shore, identification of x_2 (see Fig. 8) in the calculation of F can be problematic since the depth y_2 (−6 m) may occur at a few locations (Fig. 7a). Secondly, bars are very dynamic forms and can migrate, evolve, disappear, appear, bifurcate and join with each other, even in short time scales. For instance, the outer bar can in fact contribute to sediment resource defined by the approach of Cieślak (2001), although being formally not taken into account due to the depths exceeding y_2. A question arises whether the commonly used approximation of the real cross-shore profile by the Dean's curve is reliable enough to calculate the sediment resources F on the basis of such approximation. The positive answer to this question would eliminate doubts which can appear when the quantity F does not comprise huge amounts

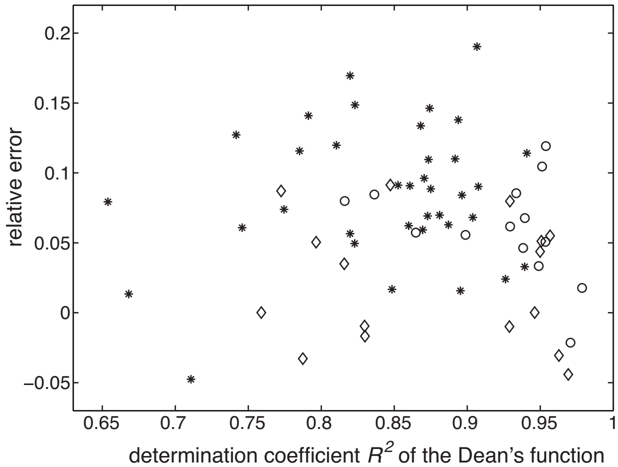

Figure 12 Relative error between sediment resources F calculated for the real profile and approximated by the Dean's curve as a function of determination coefficient R^2 of the Dean's approximation for profiles 6 (circle), 11 (diamond) and 21 (asterisk).

of sand accumulated in the outer bar, as illustrated in Fig. 7a and Fig. 8. In such a case, the sediment resources are underestimated. One can also imagine the contrary situation, when the sea bed inclination becomes significantly steeper just beyond the outer boundary of the calculation domain (corresponding to the ordinate $y_2 = -6$ m). In the latter case, the nearshore sediment resources can be underestimated. Calculation of the parameter F for the Dean's approximation of the entire cross-shore transect seems to be a reasonable solution which can dispel the above uncertainty.

The answer to the respective query is provided by the results of computations presented in Fig. 12 which shows the relative error in determination of F for the real and Dean's-approximated nearshore sea bottom shape.

It can be seen in Fig. 12 that the accuracy in calculation of the quantity F for the Dean's-approximated seabed profile with respect to the actual F value is quite good, having the relative error (vertical axis) not exceeding 0.2. This takes place independently of goodness of the Dean's approximation, expressed by the determination coefficient R^2 (horizontal axis). This finding constitutes a good basis to use of the Dean's approximation for estimation of the sediment resources on the multi-bar seashore profiles in order to eliminate the effects of peculiarities of such shores.

4. Conclusions

The analysis of variability of the parameter A characterising the Dean's curve show that this parameter can behave independently of the shoreline migration. In contrast to the classical knowledge on no-bar or single-bar seashore, according to which coastal erosion is inevitably represented either by increase of the parameter A (deepening of the nearshore profile) or by maintenance of the same value of A (retreat of the entire profile), the multi-bar shore erosion can be accompanied by decrease of A (shoreline retreat with simultaneous accumulation of sediment within the bar system). The parameter A has thus been found not to be a fully representative indicator of the multi-bar cross-shore profile evolution.

It has also been definitely confirmed that the changes of shoreline position (especially in the short-term time scales) are not always correlated with changes of the coastal sediments amount. Hence, features of the entire nearshore sea bottom relief ought to be considered in analysis of coastal morphodynamics. For the multi-bar dissipative sandy coast, typical in the south Baltic, the seashore zone stretching from the dune toe (ordinates of about +2 m) to the depth of ca. −6 m has been found representative for estimation of the sediment resources F. In order to get rid of the effects of peculiarities of the multi-bar cross-shore profiles and related possible underestimations or overestimations, the parameter F is proposed to be calculated for the seabed shape approximated by the Dean's curve. It has been proved that such approach eliminates the bias caused by the profile peculiarities and, at the same time, does not produce significant inaccuracies in comparison to analysis of actual cross-shore transects. The proposed method can be applied in a variety of time scales: from short-term coastal changes (hours and days) to long-term evolution (decades).

Finally, the nearshore sediment resources F can be treated as an indicator of the shore stability. For individual south Baltic shore segments this value is different. Since this criterion is site-specific, depending on local conditions (e.g. wave climate and grain size), it ought to be determined for each considered site separately.

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