Depth of Closure and Seabed Variability Patterns

Grzegorz Różyński, Zbigniew Pruszak, Tomasz Okrój and Ryszard Zeidler[1]

Abstract

A method of analysis of depth of closure and bed variability is presented in the study. Statistical analysis of measurements showed standardized depths are gaussian random variables Repetitive measurements revealed peaked patterns of standard deviation of depth change and range between extreme measurements. They were approximated by a smooth functional type in form of a sum of exponential curves. The peaks were then associated with both the corresponding time scales and locations of bed features. The patterns can thus be used to identify segments of beach profiles controlled by events typical of given time scales The tail of the outermost peak was extrapolated to evaluate decadal depth of closure.

Introduction

Depth of closure (Dc) describes the seaward limit of significant depth change (Hallermeier, 1978, 1981), basing on repetitive records of beach profiles showing that their vertical variability declines with increasing depth. It is therefore a morphological boundary between an active and non-active part of the nearshore zone over the period determined by observations of the profile. For high-quality data Dc is assigned to a point where depth changes beyond that point become small. The position of Dc is a function of several factors. The closure criterion, and the associated time scale are usually regarded as the most important ones, because the former frequently depends on data accuracy, whilst the latter deeply affects Dc *per se;* a fixed closure criterion moves offshore for increasing time scales. Dc can be defined for (i) single events e.g. storms, where surveys before and after the event are examined (ii) time interval change, where bed evolution between two routinely done surveys is investigated, or (iii) time integrated (cumulative) change, where the history of bed evolution can be traced, providing very ample datasets are available. The processes controlling Dc in the current study are associated with quasi-seasonal, annual and decadal time scales, given 10 years of available observations. The site was usually sampled twice a year, which matched the concept of time interval Dc.

Nicholls et al. (1997) investigated Dc upon a high-quality dataset, consisting of 12 years of systematic surveys, taken twice a month and after extreme events, which were collected at Field Res. Facility at Duck, NC, USA. The variability of beach

[1] Snr Res Assoc., Assoc. Prof., Res Assoc. & Prof., resp., Polish Academy of Sciences' Institute of Hydro-Engng IBW PAN Gdańsk, Poland, ph: (+48) 58 552 2011, Fax: (+48) 58 552 4211, e-mail: grzegorz@ibwpan.gda.pl

profiles of that tidal shore (m = 1.5%, D_{50} = 0.2÷0.4 mm) revealed the existence of peaked bed variability patterns. The analysis of a steeper (m = 2%, D_{50}= 1 mm), non-tidal shore of Thyrrenian Sea at Cecina Mare I, cf. Różyński et al. (1998) also detected the existence of at least one peak. Too short records failed to undoubtedly establish the position of 2nd peak and Dc at that site. Since similar patterns were discovered for multibar, mildly sloping shore (m = 1÷1.5%, D_{50} = 0.22 mm) at Coastal Res. Facility (CRF) at Lubiatowo PL as well, the idea of generalized bed variability patterns is proposed in order to establish a universal concept of cross-shore variability.

The Lubiatowo Dataset

CRF Lubiatowo is a wave dominated, non-tidal sandy beach located on Polish coast of the Baltic Sea, some 80 km north-west of Gdańsk. It is a natural, mildly sloping, dune type unit, which usually exhibits 3÷4 longshore bars (Fig.1).

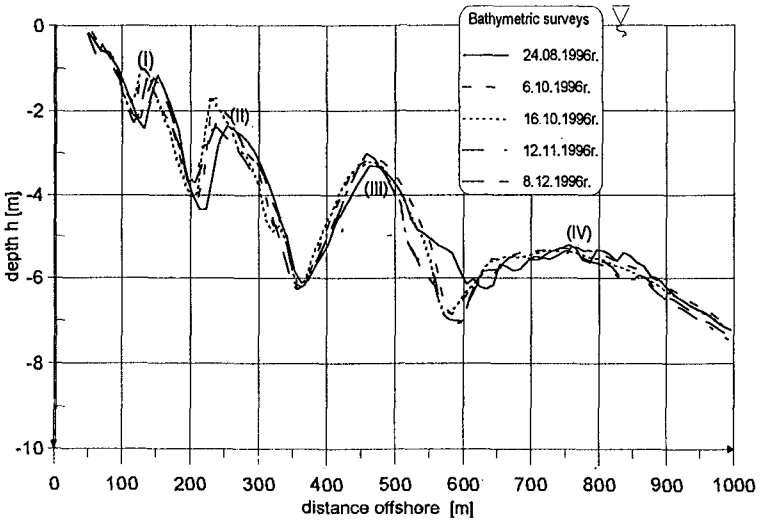

Fig.1 Typical beach profiles at CRF Lubiatowo

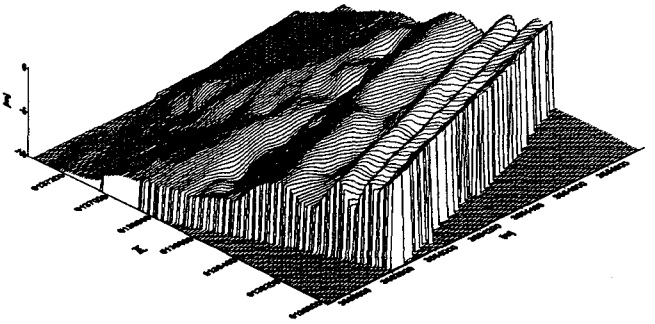

Fig.2 3-D picture of bar system at Lubiatowo in 1997

An ephemeral 5th innermost bar is sometimes observed, bars 1-3 are very stable, clear-cut features. They show little alongshore variability and perform some oscillations about their average positions (Pruszak et. al. 1997, Pruszak &Różyński 1998). The outermost bar is a transitional entity between a typical bar and deep water sediment deposit. It exhibits high alongshore irregularities on its offshore slope (Fig.2), so the determination of Dc needs long surveys, because the irregularities show unexpectedly large variations. For average storms the significant wave height outside the surf zone (h = 7 m) reaches Hs = 2÷2.5 m (3.5 m at the most) with the period T = 5÷7 s. During shoreward transformations the wave height is only 0.5÷1 m and T = 4÷5 s at depths 2÷3 m.

The bathymetric data applied in the analysis consists of surveys done along four neighbouring beach profiles between 1987 and 1996, spaced every 100 m and referred to as profile 4 (westernmost), 5, 6 and 7 (easternmost). All surveys are attached to a geodetic base in order to eliminate errors caused by a moving shoreline. The profiles were sampled with an echosounder, usually twice a year, more or less in the same time of spring and autumn, so quasi-seasonal and annual Dcs could be found. They all extend beyond the crest of the outermost bar, but few are long enough to capture the full, initially unexpected variability of its offshore slope. Only one survey was executed in 1991, 1994 and 1995, the 1991 records were too short for the Dc study and they were skipped. On the other hand, four surveys were done in 1987 and six in 1996, but only two of them for each of those years were selected for the Dc study (cf. Tab.1).

Table 1 Surveys employed in Dc investigations

Sampling date	remarks	Sampling date	remarks	Sampling date	remarks
16th May 1987	+	5th Jun. 1990	+	25th Oct.1995	++
14th Aug. 1987	not used	14th Aug. 1990	++	24th Aug.1996	+
22nd Sep. 1987	++	29th Oct. 1991	skipped	6th Oct.1996	++
15th Oct. 1987	not used	21st May 1992	+	16th Oct. 1996	not used
28th Apr. 1988	+	21st Oct. 1992	++	12th Nov. 1996	not used
5th Oct. 1988	++	20th Jul. 1993	+	26th Nov. 1996	not used
24th May 1989	+	30th Sep. 1993	++	8th Dec. 1996	not used
13th Sep. 1989	++	20th Jun. 1994	++		

(+) - quasi-seasonal time scale, (++) - annual time scale

Quasi-Seasonal and Annual DC

Various criteria yield various estimates of Dc. A standard deviation of depth change (*sddc*) is a widely used criterion, provided the number of surveys **n** sufficiently reduces the scatter of *sddc* value. Its value at closure is usually chosen between 0.06 and 0.15 m. However, equations (1) and (2) indicate the scatter of *sddc* declines very slowly, as the mean value is a random variable itself, and the *sddc* precision is proportional to squared number of observations:

$$\bar{h} = \frac{1}{n}\sum_{i=1}^{i=n} h_i \qquad (1)$$

$$\sigma_h = \sqrt{\frac{1}{n}\sum_{i=1}^{i=n}(h_i - \bar{h})^2} \quad (2)$$

Hence, it is better to apply a criterion which is less dependent on number of observations, such as the range of depth change (*rdc*), which quantifies the scatter between extreme measurements of given sample space. For Dc purposes this criterion was adapted in 'tight' and 'loose' variant i.e. 0.2 m and 0.3 m respectively. These values match well findings based on much more ample datasets (cf. Nicholls et al.,1997), where such *rdc* corresponded to *sddc* of 0.06 to 0.15 m.

Tab.2 presents quasi-seasonal Dcs between spring and autumn surveys (Fig.3). It shows that quasi-seasonal closures do not always occur, so even during summer period of a year the wave climate may be severe enough to produce quite substantial depth changes.

Table 2 Quasi-seasonal Dc [m.]

Year	profile 4		profile 5		profile 6		profile 7	
	0.2 m *rdc*	0.3 m *rdc*	0.2 m. *rdc*	0.3 m. *rdc*	0.2 m. *rdc*	0.3 m. *rdc*	0.2 m. *rdc*	0.3 m. *rdc*
1987	—	—	7.8	7.2	—	—	6.8	6.3
	5.8	5.7	4.7	4.6	5.7	5.7	—	5.5
1988								
1989	—	6.6	—	8.0	—	—	—	8.7
1990	—	8.0	6.3	6.3	5.0	5.0	5.0	5.0
1992	—	—	—	—	—	—	—	—
1993	—	5.7	—	7.3	5.2	5.2	—	—
1996	—	7.8	—	7.2	10.7	6.5	10.5	8.0

(—); non closing cases

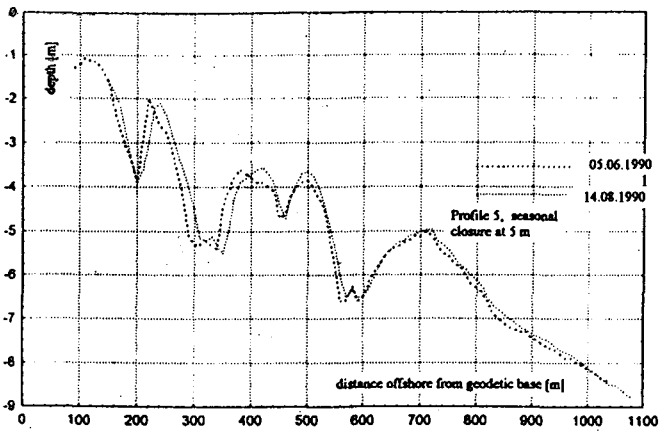

Fig.3 Exemplary quasi-seasonal closure

In most cases Dcs for loose criterion could be found on offshore slope of the outermost bar. However, their estimates for even neighbouring profiles vary to unexpected extent, e.g. profiles 4 and 5 in 1989 with Dc being equal to 6.6 m vs. 8.0 m respectively, or the same lines a year later, where Dc values are nearly ideally reversed (8.0 m vs. 6.3 m).

This indicates that local effects at offshore part of the outermost bar may play very important role in evolution of that part of the littoral zone even during apparently calm periods between late spring and early fall. This can be supported by routinely observed intermittent breaker patterns in the vicinity of 4th bar during stormy events, which profoundly influences local bed changes. For example the bed was so active in 1992 that no Dc could be found whatsoever. Consequently, high bed activity allowed for only few estimates of Dc for tight criterion. Tab.2 gives an overview of quasi-seasonal Dc as a random variable. It varies widely from 4.7 m to 10.7 m for tight, and from 4.6 m. to 8.7 m for loose criterion.

The only closing cases of annual Dc were obtained for autumn surveys of pairs 1989-90 (Fig.4) and 1995-96. These closures are rather shallow and valid for both tight and loose criteria, indicating rapid profile convergence. All this suggests a mild wave climate in winter seasons of those years.

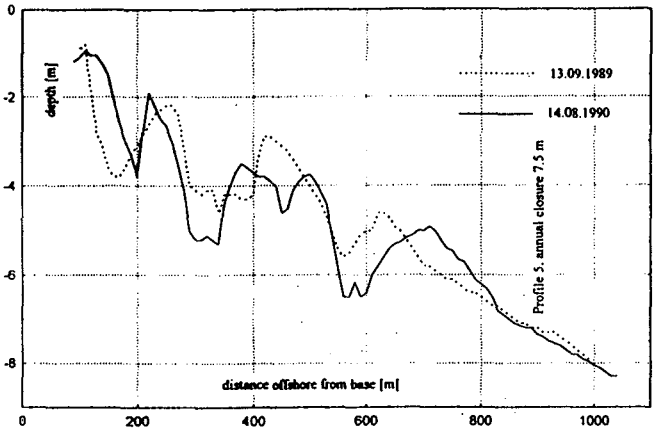

Fig.4 Exemplary annual closure

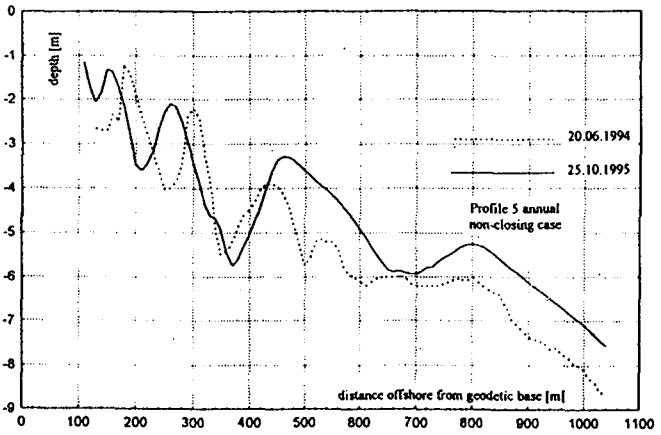

Fig.5 Exemplary annual non-closing case

By contrast, huge divergence of 1992-93, 1993-94 and 1994-95 (Fig.5) profiles over deeper portions of littoral zone proves high wave action intensity. The closing cases show much lower variability of Dc at various profiles i.e. for 1989-90 it is equal to **5.5 m** for profile 4 and **7 to 7.5 m** for the other three. The 1995-96 is even more stable and equals **6 m** for profiles 5,6,7 and **5.5 m** for profile 4. Such a result suggests that local effects, clearly visible in quasi-seasonal closures, were averaged to some extent over annual periods. The estimated values provide information on lower limit of annual Dc, which is greater than most annual Dcs Nicholls detected in Duck between 1982 and 1993. Therefore, greater average annual Dcs should be expected, which can be explained by extending further offshore, more complex multibar system at Lubiatowo, than basically 2 bar shore at Duck.

General Statistical Properties of Beach Profiles

The surveys employed in the study extend 1000 m offshore with some exceptions, where the depths were recorded up to 1400m. This prevents direct, empirical assessment of decadal Dc. However, it still can be evaluated, if the existing records of offshore slope of the outermost bar share the same general statistical properties. To verify this, depths corresponding to offshore distances of 800, 850, 900, 950, 1000, 1050 and 1100 m from geodetic base were lumped together ignoring individual profiles. This could be done, because the geodetic base forms a straight line and is parallel to the shoreline, so offshore distances are generally retained. A family of standardized probability distribution functions was then constructed and plotted together with a normal pdf, (Fig.6).

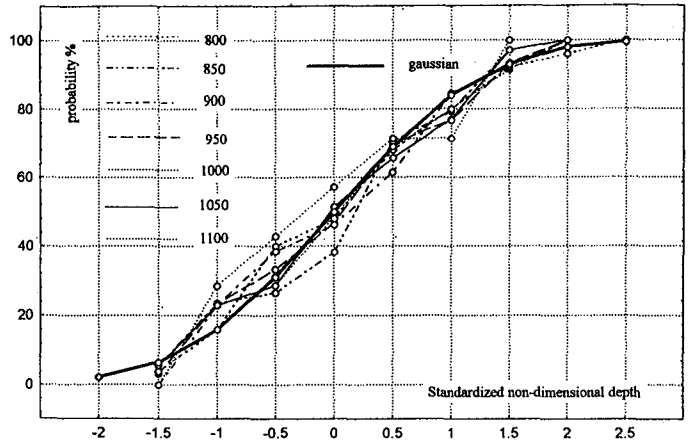

Fig. 6 Standardized empirical pdfs of depths 800-1100 m offshore vs gaussian

It can clearly be seen that the distributions do not depart much from normal pdf. What is more important those departures seem to be normal themselves, i.e. some of them are positive and other negative at a given point with respect to gaussian curve. Thus, no systematic behaviour of pdfs can be detected, so it may be assumed they are all gaussian and share the same general statistical properties, although mean depths and their standard deviations vary with distance offshore. This finding implies that depth changes are caused by independently acting factors, (wave height and direction, duration of a

given wave climate, storms, breaker locations, longshore and cross-shore currents, bed configuration at a given time, etc.) It may thus be inferred that similar general statistical characteristics are retained further offshore, so the seabed variability pattern(s) can be analytically extrapolated.

The same pdf analysis was carried out for less remote depths 300 - 600 m. offshore. It shows that also this part of beach profiles is generally gaussian (Fig.7). This finding is very interesting, because statistical normality of beach profiles allows for 2nd moment analysis with loss of no information. In other words mean depths and their covariance structure contain all probabilistic information on beach profile evolution.

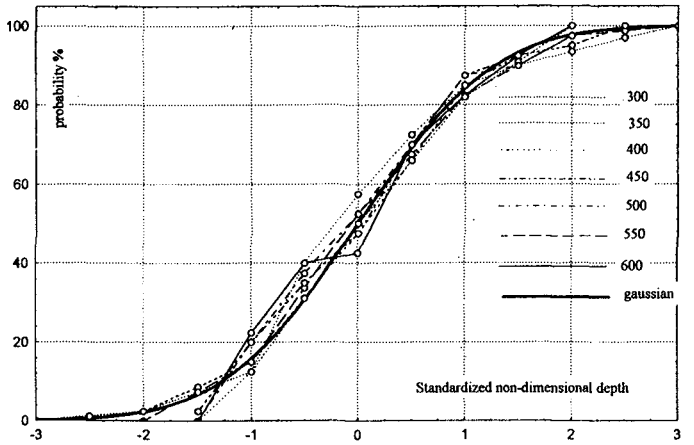

Fig.7 Standardized empirical pdfs of depths 300-600 m offshore vs. gaussian

Generalized Seabed Variability Patterns

As already mentioned, peaked patterns of cross-shore variability have been observed at several sites (Duck, Cecina Mare, Lubiatowo). Hence, a generalized bed variability pattern may be postulated, which can be adapted for different shores in analytical form of a smooth functional type to properly reproduce the peaks on the lines of standard deviations and/or ranges. Upon numerical experiments, the sum of exponentially decaying curves was selected, because this functional type fits best the line of standard deviations $\sigma(x)$ or ranges r(x):

$$\sigma(x) \text{ or } r(x) = \sum_i a_i \cdot \exp[-b_i((x-p_i)/p_i)^2] \qquad (3)$$

To illustrate the concept, the two peak *sddc* pattern for Lubiatowo was obtained for truncated surveys taken from 1964 until 1994. Even though these records are attached to a movable shoreline and lumped together, the pattern is still clearly visible (Fig.8).

In Eq.3 p_i denotes the position of *i*-th peak on the profile, read from the line of standard deviations or ranges, the coefficients a_i and b_i need to be least square fitted. The peak positions can be associated with phenomena that occur in different time scales, the greater p_i the longer the corresponding time scale. They may also be linked to characteristic profile features, such as bar crest, location of trough, etc. The bed

variability pattern can thus be used in order to identify segments of beach profiles controlled by events typical of given time scales, which can be done for each pair of a_i

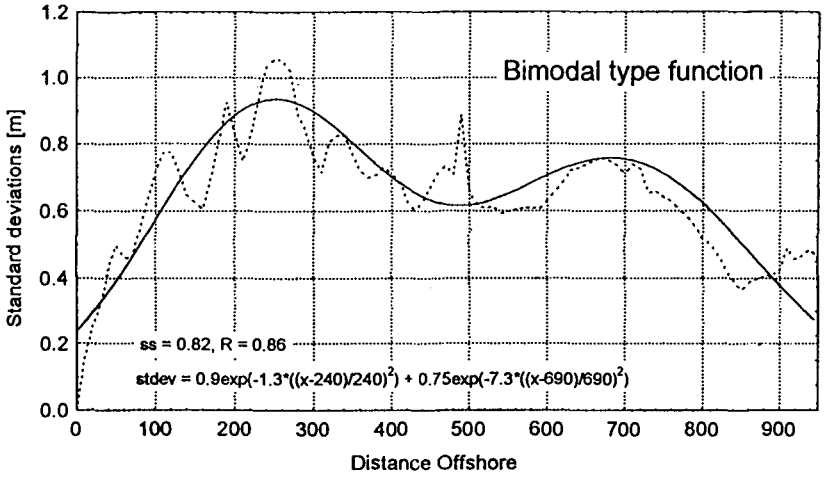

Fig.8 Peaked sddc pattern 1964-1994, lines attached to movable shoreline

and b_i. At locations sufficiently remote from the peak, the influence of that peak becomes negligible and it can be assumed the events associated with it no longer affect a beach profile at that location. Hence, such an analysis of the outermost available peak may determine the Dc associated with its time scale. In case when surveys do not reach the spot, where the tail of the outermost peak is sufficiently small, bearing in mind common general statistical properties of depths, the tail is extrapolated beyond the longest surveys and the bed equilibrium curve is employed:

$$h = A \cdot x^{2/3} \tag{4}$$

The average value of A for the 1987-1996 period is equal to 0.084. The peak line of *sddc* or *rdc* Eq.3 converges towards the bed equilibrium curve Eq.4 and Dc associated with the outermost peak can be evaluated. Fig.9 shows raw *rdc* lines of 4th, 5th, 6th and 7th profile together with the line of average *rdc*. Two clear-cut peaks, the greater one some 300 m and the smaller one at 580 m from geodetic base can be distinguished immediately. Interestingly, the inner one ideally corresponds to the position of 2nd bar crest, while the outer one perfectly matches the position of trough between 3rd and 4th bar (Figs.10a-d). They are both concentrated over small portions of beach profiles, which is a direct consequence of their link to very stable cross-shore locations of two morphological bed features. The 3rd peak is also visible, although it is very long and flat. It should not be surprising, because it matches the location of offshore slope of the outermost bar, which is very long and sometimes merges with sediment deposits further offshore. Since bed evolution of that part of the littoral zone is controlled by extreme storms, it should be expected that bed variability generating the outermost peak is spatially distributed. Its character is thus different from inner peaks, which are associated with firmly stable cross-shore bed features (crest of 2nd bar and trough between 3rd and 4th bar). Upon thorough scrutiny and the goodness of fit criterion, its

position was established at 1200 m from geodetic base, knowing that more long surveys will yield a better estimate.

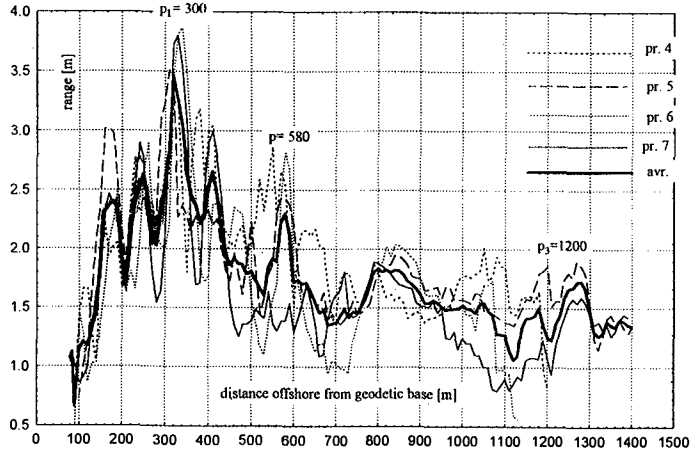

Fig.9 Rdc for profiles 4-7 with average rdc

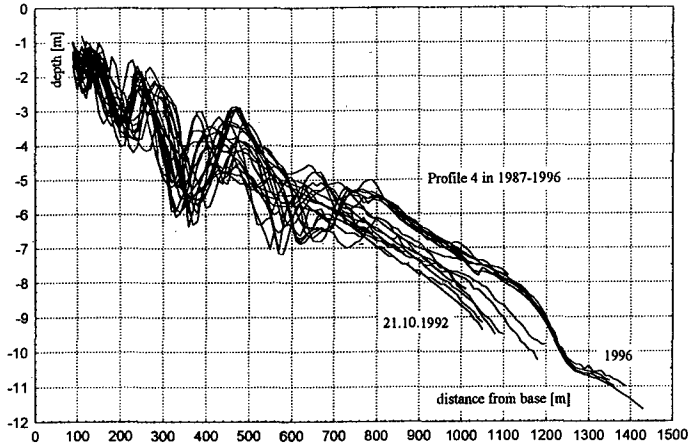

Fig.10a Collective chart of surveys for profile 4 between 1987-1996

The fit for mean ranges produced quite a peculiar result; a three peak model was assumed but the combination of 2nd and 3rd one resulted in a plateau between them (Fig.11). It slowly declines with distance offshore, so the decadal Dc can be evaluated by extrapolating the fitted line out of the existing surveys, cf. fitted functional type, Eq.5.

$$rdc(x) = 1.4 \cdot \exp[-1.8 \cdot (\tfrac{x-300}{300})^2] + 0.5 \cdot \exp[-1.4(\tfrac{x-580}{580})^2] + 1.3 \cdot \exp[-(\tfrac{x-1200}{1200})^2] \quad (5)$$

The fit of Eq.5 is very accurate, given $R = 0.85$ correlation between the model and data. Other attempts, aiming to retain the vivid 2nd peak produced results with worse goodness of fit, so they were skipped. Employing the bed equilibrium curve, a Dc could be found for both 'tight' and 'loose' *rdc* criteria. For a 'tight' variant it lies some **2800 m** offshore and equals **17 m** vs. **2600 m** offshore and **16 m** obtained for its 'loose' counterpart. This estimate appears to be realistic, given extreme ranges recorded 1300 m offshore for profile 7 and 1400 m for profile 5, where the greatest depth of **12.5 m** was recorded. By contrast, the longest survey, reaching 1500 m in 1988 for profile 7, revealed the depth of only **11m**. Knowing such high irregularities of offshore slope of 4th bar and the tendency to merge with sediment deposits further offshore, it can be believed that the decadal Dc should lie much further offshore, and be quite great itself, as the extrapolation of bed patterns indicates.

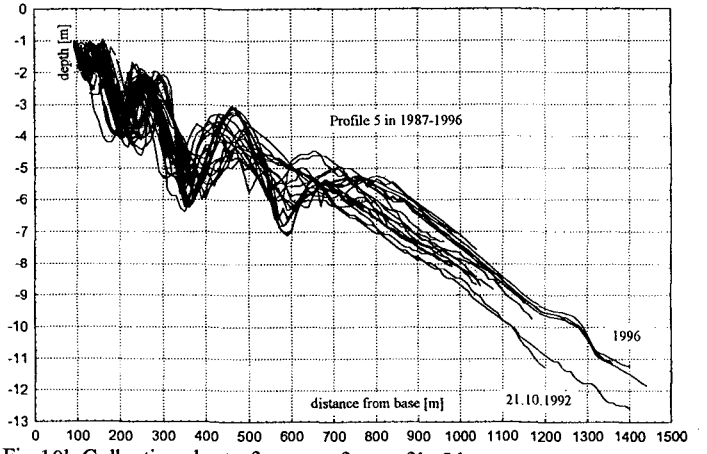

Fig.10b Collective chart of surveys for profile 5 between 1987-1996

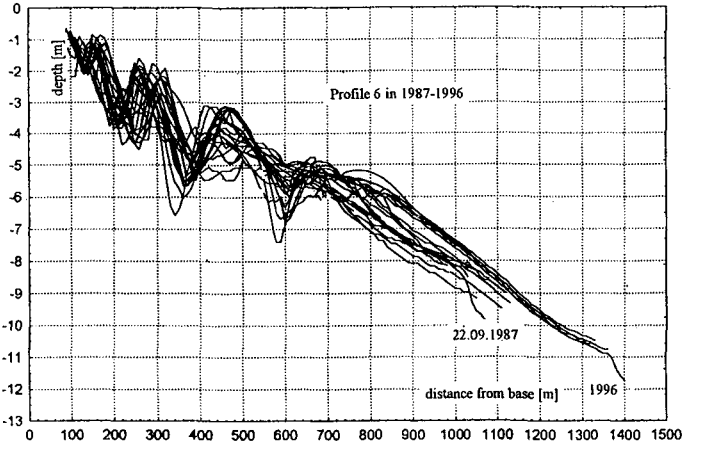

Fig.10c Collective chart of surveys for profile 6 between 1987-1996

evaluated, even though general statistical properties of depth between 300 and 600 m offshore are also gaussian. This however is not enough to assign a particular time scale to the innermost peak. The application of a tight *rdc* criterion shows that its tail practically disappears 600 m from geodetic base, corresponding to shallow Dc of 5.7 m. This value is equal to the most shallow quasi-seasonal Dc, which clearly indicates that the innermost peak is in general governed by a shorter time scale. It could only be detected if the bed was sampled more than twice a year.

Annual DC and Hallermeier Formula

Dc can also be calculated from extreme (deep water) wave conditions. Such computations can be done for different types of shores (tidal, non-tidal, one bar, multi-bar, etc.). In cases the Dc was established upon the analysis of bathymetric profiles, the approach basing on wave climate can be directly verified for a given shore type. Hallermeier, 1978, 1981 postulated that annual Dc can be assessed from the formula:

$$Dc = 2.28 \cdot H_s - 68.5 H_s^2 / g \cdot T^2 \qquad (6)$$

where H_s stands for significant, non-breaking wave height that is exceeded 12 hours in a year, T is the corresponding period and g is gravitational acceleration. The application of Hallermeier's formula needs long-term deep water wave measurements. In case they are not available, wave parameters can be hindcast from existing wind records. Wind measurements were carried out between 1960 and 1986 at Hel Harbour, situated some 50 km east of Lubiatowo and they are deemed representative for Lubiatowo. Only wave heights were hindcast, but knowing that the 2nd term in Eq.6 is usually close to unity, one may crudely assess annual Dc as $2.28 \cdot H_s - 1$. Wave height hindcasts were calculated upon wind samples, which were obtained every three hours as averages of 10 minutes time window, from 1st Jan. 1960 until 31st Dec. 1986. Bathymetric data and reconstructed wave heights do not overlap in time, so it is not possible to directly compare the results from the same years. Moreover, eight daily records appear to be too crude to extract wave heights lasting 12 hours a year. Therefore, annual Hallermeier Dc estimates could only be found for a small subset of years, cf. Tab.3.

Table 3 Hallermeier estimates of annual Dc

Year	H_12 [m.]	Dc [m.]
1960	3.88	8
1963	> 5.59	> 11.7
1968	< 5.59	< 11.7
1981	> 5.59	> 11.7
1984	3.5	7
1985	4.64	9.6

The value of 7 m for 1984 and equally shallow empirical annual Dcs for 1989-90 and 1995-96 show that shallow annual Dcs are not uncommon and may occur quite frequently. On the other hand, two cases where 12 hour wave could be identified (1963, 1968) indicate that more severe wave climate produces realistic, deeper Dc. Hence, Hallermeier's criterion seems to provide a reliable assessment of annual Dc for multibar shore at Lubiatowo, which a bit contradicts Nicholls'es view, based on Duck study, that it is biased towards conservative bound of annual closures. It may be justified by high

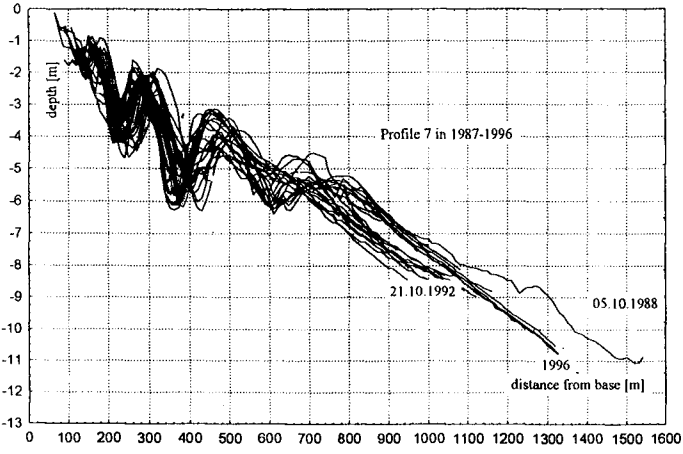

Fig.10d Collective chart of surveys for profile 7 between 1987-1996

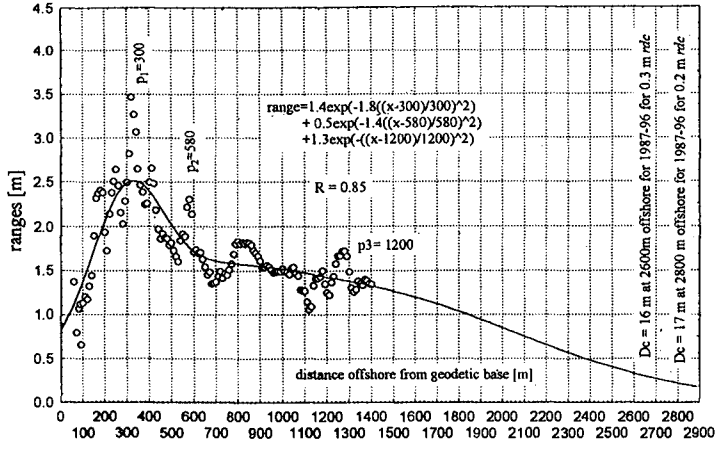

Fig.11 Generalized 3-peak seabed variability pattern for Lubiatowo

As mentioned before, each peak corresponds to a certain time scale and spatial distribution of the 3rd peak implies it accounts for longer periods, such as decades. The time scale of the 2nd peak can be found upon the following reasoning: if we skip the 3rd peak and apply either tight or loose *rdc* criterion, we arrive at h = 8.4 or 7.7 m respectively, calculated from Eq.4 for 1000 and 880 m offshore. General statistical properties of depths are the same, so it may be assumed that Dc associated with 2nd peak is equal to some **8 m**. This value defines a boundary for time scale, which in light of tab.2 corresponds to quasi-seasonal variability. Hence, the 2nd peak is generated by quasi-seasonal events. The time scale of the most conspicuous 1st peak cannot be

complexity of bar system at Lubiatowo with highly irregular offshore slope of the outermost bar vs. fairly regular, basically two bar shore at Duck.

Conclusions

1. The analysed beach profiles are gaussian all over their cross-shore range, so their covariance structure contains the whole statistical information. The profiles at other sites are likely to exhibit similar behaviour.
2. Repetitive measurements reveal the existence of peaked profiles of *rdc* and *sddc*. The peaks can be associated with relevant time scales generating them and can be analytically expressed by least square fitted sum of exponential functions. *Sddc* lines yield better description of profile variability, provided sufficient number of samples (50+) is available. *Rdc* lines need less samples to map profile variation, so they are handy in remote parts of beach profiles, where samples are usually scarce.
3. Statistical normality of beach profiles and their peak features permit to split beach profiles into segments associated with time scales of peaks.
4. Inner peaks correspond to locations of spatially concentrated bed features i.e. position of bar crest for the innermost peak and trough between two bars for the middle peak. The outermost peak corresponds to spatially distributed offshore slope of the outermost bar.
5. Temporal resolution of measurements prevents the evaluation of the time scale of the most conspicuous, innermost peak, so more frequent sampling would be needed to remedy this. The middle peak was identified as being driven by quasi-seasonal phenomena. The outermost peak is generated by much longer time scales of a decade or so, which is supported by its spatial distribution. Such distribution is characteristic for extreme events, where the whole profile, including its deeper parts, undergoes substantial evolution.
6. All detected Dcs that are situated outside the crest of the outermost bar, either on its offshore slope or on sediment deposits situated further offshore. Quasi-seasonal Dcs are equal to 5÷10 m and exhibit significant alongshore variation, which shows the importance of local effects in short time scales. Only few annual Dcs were found between 5.5 and 7 m, and they seem to represent upper bound of annual Dcs. Alongshore variation, although visible, is much less pronounced than for quasi-seasonal cases. It is not surprising, because longer time scales average local effects. Longer surveys up to 1500 m offshore are recommended to establish a set of empirically determined annual Dcs, if gentle nearshore slopes with multi-bar profiles, similar to CRF Lubiatowo are examined.
7. Very high bed irregularity outside the crest of the outermost bar results in high estimate of decadal Dc (16÷17 m), obtained from extrapolation of the outermost peak. The verification of this value would require very long surveys (3 km offshore) taken at least once a year over decades. Before this is done, an extrapolation based on the same general statistical profile properties, provides an unverified, yet based on realistic assumptions, assessment of decadal Dcs.
8. Hallermeier's formula for annual Dc seems to work well for the case of multibar shore with very irregular offshore slope of the most seaward bar.

References

Hallermeier R.J.,(1978) Uses for a calculated limit depth of beach erosion. *Proc. 16th Coastal Engineering Conference, ASCE, 1493-1512.*

Hallermeier R.J.,(1981) A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering, 4, 253-277.*

Nicholls R.J., Birkemeier W.A., Hallermeier R.J.,(1997) Application of the depth of closure concept. *Proc. 25th Coastal Engineering Conference, ASCE, 3874-3887.*

Pruszak Z., Różyński G., Zeidler R.B., (1997) Statistical properties of multiple bars, *Coastal Engineering 31, 263-280.*

Pruszak Z., Różyński G. (1998) *Variability of multibar profiles in terms of random sine functions. Journal of Waterway, Port, coastal and Ocean Engineering, ASCE, Vol.124, No.2, 48-56.*

Różyński G., Pruszak Z., Aminti P.,(1998) Dynamics of one bar and multibar beach profiles. *Proc 3rd Coastal Dynamics Conference, ASCE 325-336.*

Acknowledgements

This study has been based on work in the PACE project, in the framework of the EU-sponsored Marine Science and Technology Programme (MAST III), under contract MAS3-CT95-0002. The study was co-sponsored by the PAN Supported Programme IBW 2-1998