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MORPHOMETRIC ANALYSIS IN INVESTIGATIONS OF THE COASTAL ZONE

Part I

SEPARATION OF MORPHOLOGICAL ELEMENTS AND SCOPE OF MORPHOMETRIC MEASUREMENTS

Abstract

Hypsometric and bathymetric measurements of the Polish coastal zone, which were carried out since the early 50ties of the last century, provided a very large amount of empirical material. Standardisation of profile recordings in the Coastal Zone Databank provided a basis for the determination of the multi-temporal changes of the coast. Comparative analysis of coastal zone profiles is of basic importance in planning coastal protection and in designing coastal defence methods. For this aim morphological elements of the shore (beach and dune) and the nearshore (from waterline seawards) zones were separated, and measurements were made on profiles drawn in identical scale. In the present paper, methods of separating morphological elements and the scope of morphometric measurements on cross-shore profiles are presented. The next parts shall discuss: the methods of analysing morphometric parameters (part II), the methods of determining the erosion/accretion systems (part III), and the use of morphometric analysis in the protection of selected regions of the Polish coast (part IV).

Introduction

The coastal zone is a contact area of the sea, land and atmosphere, in which intense interaction of various forms of energy takes place. This generates a specific morphological system, in which the basic, first order forms are the shore and the nearshore areas. Within these forms exist sub-forms, on which morphometric measurements are carried out. Most often, two are distinguished on the shore – the beach and the foredune, in accordance with the principles proposed by Rudowski [11, 12]. At first, separation of forms in the nearshore was carried out in accordance with Rudowski's methodology [11, 12], but later it was modified [5, 2] to allow assessment of the influence of artificial nourishment. Separation of new sub-forms was gradually introduced as the knowledge of coastal dynamics developed [6, 8, 9, 10].

Work on classification of the coastal zone is carried out both to improve knowledge [14, 7] and for practical reasons [1]. The value of morphometric (cartometric) measurements of the change of the waterline and dune foot line is illustrated in the works on trends of development of the Polish coastal zone [13, 15, 16]. At present, material which would allow an elaboration of a morphologic-morphometric characteristic of the nearshore zone at a similar level, is not available. It is hoped, that due to the continuing recording of historical information for the needs, and in accordance with the standards, of the Coastal Zone Databank and hypsometric and bathymetric field measurements, carried out for that Databank, elaboration of such characteristic also for the nearshore zone will soon become possible. This becomes increasingly important for coastal protection in view of the developing process of sea level rise. The inclusion of new elements in the morphologic and morphometric analyses was especially important for evaluations of the effectiveness of artificial nourishment.

In relation to earlier separations, which discerned the deeper nearshore zone, including the outer bar system, and the shallow nearshore zone with the inner bar system [12], at present the following are separated at first approach: the shore slope with shore (beach) terrace located between the waterline and the trough before the inner bar; the bar zone (including the inner and outer bars) and the slope seawards of the bar zone. The width of these forms changes within limits dependent on the amount of accumulated sediments and the slope of the nearshore zone. When sand from a nourished shore is supplied to the nearshore zone, at first the waterline shifts seawards, shore terraces develop and the volume of the shore slope increases. Next, the material from the shore and shore slope feeds the bar zone, rebuilding or developing the bar zone. There is a constant exchange of sediments between the bar zone and the shore slope, and the intensity of this exchange depends on the force and duration of storms and on the height of storm surges.

The sets of data from morphometric measurements of forms on the shore and nearshore allow to determine the activeness of the morpho-lithodynamic processes, thus providing information of basic importance to forecasts of erosion/accretion processes and to the design of coastal protection along given stretches of the coast.

Material

The separation of morphological elements and morphometric measurements were carried out on 1:100/500 hypsometric profiles (shore), and on 1:200/5000 bathymetric profiles (the nearshore down to 10 m water depth) along the Polish coast. The Coastal Zone Databank contains an especially large number of data from the Hel Peninsula (km 0.0-23.5-36.0), where massive nourishment was carried out in the period 1989-2000. For the stretch km H 0.0-23.5 data from 470 cross-shore profiles, crossing the coastal zone from the back of the dune on the shore to the 10 m water depth in the nearshore.

Separation of the forms and their parameterisation was carried out for many other regions, mainly in order to determine the amounts of sand reserves and the rates of change of the coastal zone during the past 40-50 years.

Sets of morphometric parameters formed a separate block of the Coastal Zone Databank. They allow carrying out comparative analyses for various time spans and also the determination of the durability of erosion/accretion systems in the coastal zone. It should be pointed out that the parameterisation was carried out on natural morphological sections, i.e. without relating them to the equilibrium profile [4], as is normally done in other engineering methods of nearshore zone assessment. In result of the measurements on the profiles, sets of linear (m), surface (m^2) and volumetric (m^3, m^3/m) parameters are obtained, as well as a number of other calculated measures and proportions, are obtained. Basic types of the nearshore are shown in Fig. 1, and of the shore – in Fig. 2.

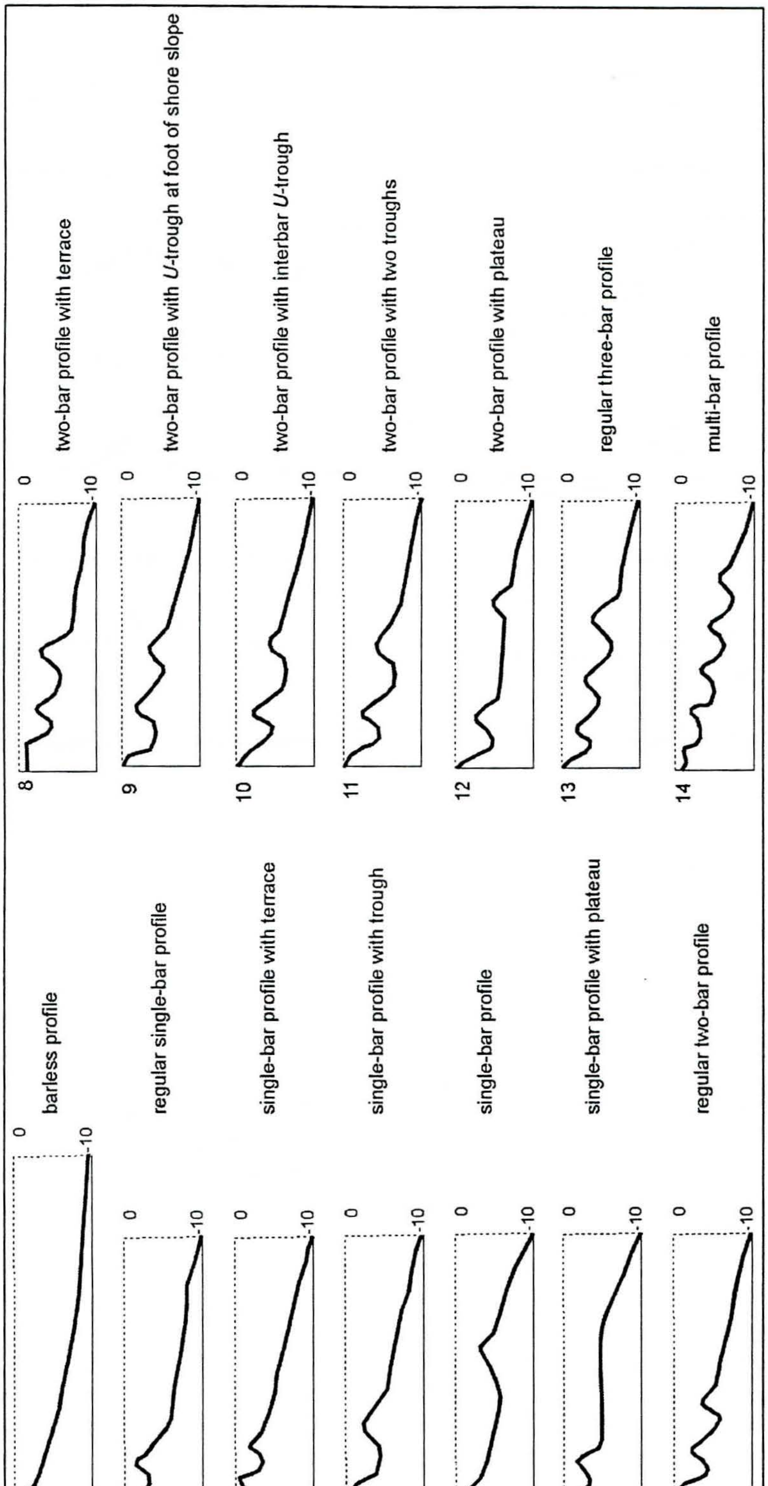


Fig. 1. *Basic types of the nearshore along the Polish coast*

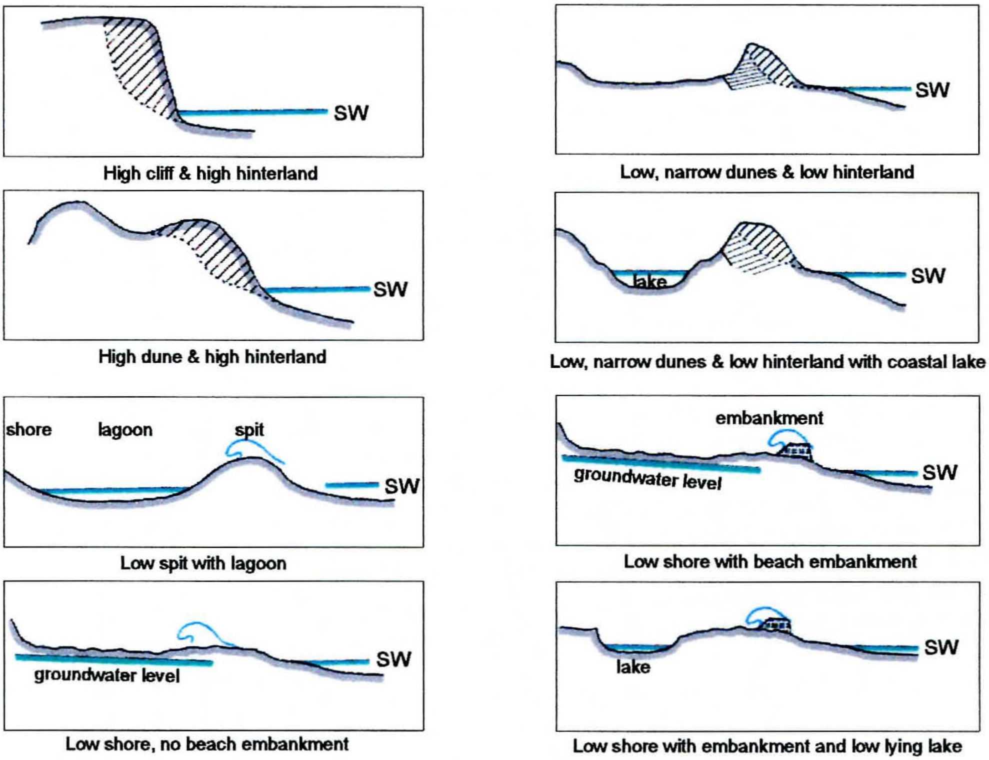


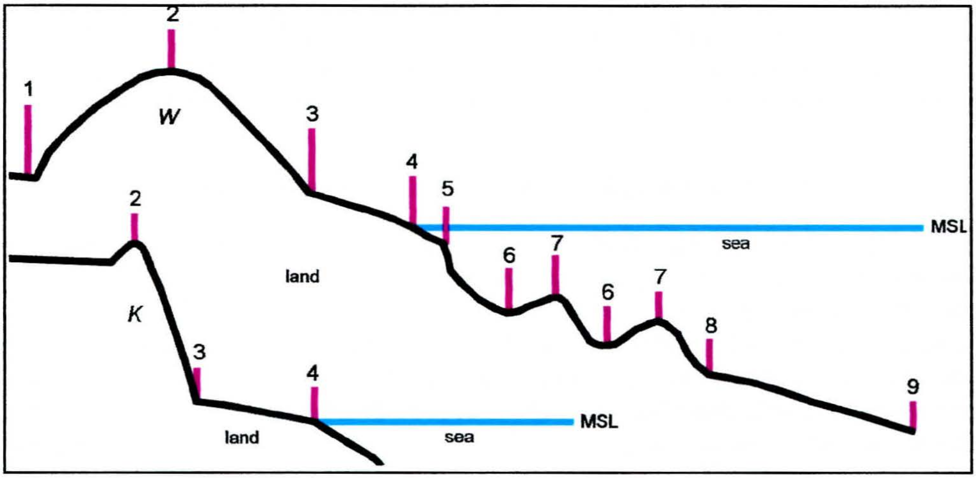
Fig. 2. *Types of shore along the Polish coast (modified in acc. with [1])*

Morphological and morphometric analysis of the coastal zone

General principles of separation of morphological forms

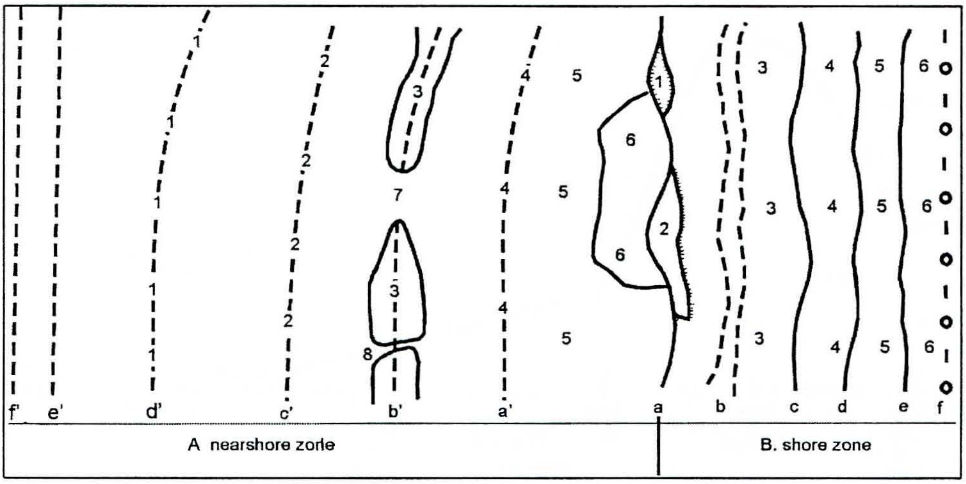
Along the hypsometric-bathymetric profile of the coastal zone, i.e from the back of the dune or top of cliff to the 10 m depth contour, were marked points, dividing the forms on the profile. This allowed to determine the boundary morphological lines. Changes in time and space of the position of these points, and in effect of the lines, illustrate the intensity of transformation of the coastal zone's forms, the rates of change, the danger to the hinterland and the need for technical protection of the coast, the boundaries of the zone of safe investment, the minimum width of the zone of special spatial planning etc. Maintaining one of the morphological lines – most often the waterline or the dune foot line - in a constant position is the main objective of coastal protection in conditions of the present and predicted transgression of the sea.

The distribution of the points, separating the coastal zone's morphological forms (Fig. 3) and corresponding morphological lines (Fig. 4), describes the structure of the analysed area. Proper and accurate locating of the points separating forms on profiles is a basic precondition of morphometric measurements. Lines, obtained by connecting appropriate points on neighbouring profiles, enable carrying out measurements of surfaces, volumes and other parameters. Through the determination of the range of forms parallel and perpendicular to the shore, single or multiple erosion/accretion systems become apparent in the shore and nearshore zones. The cross-section of the coastal zone shown in Fig. 4 includes all the elements subjected to morphometric parameterisation.



1 – dune hinterland
2 – top of dune
3 – foot of dune/cliff
4 – contact of land and water
5 – end of shore terrace
6 – axis of trough at foot of shore slope and between the bars
7 – tops of bars
8 – end of bar zone
9 – 10 m depth contour

Fig. 3. *Location of points marking the range of the main sub-forms of the coastal zone (W – dune coast, K – cliff coast)*



FORMS
1 – outer bar,
2 – interbar trough,
3 – inner bar,
4 – trough at foot of shore slope
5 – shore slope,
6 – shore (beach) terrace,
7 – area of accretion,
8 – break in bar

MORPHOLOGICAL LINES
a' – trough at foot of shore slope,
c' – interbar trough,
e' – range of bar zone,
b' – top of inner bar,
d' – top of outer bar,
f' – range of nearshore slope (to -10 m),

FORMS
1 – lagoon,
2 – beach embankment,
3 – beach,
4–5 dune,
4 – seaward slope of dune,
5 – landward slope of dune,
6 – hinterland,

MORPHOLOGICAL LINES
a – waterline – 500 cm,
b – storm surge line 570/650 cm,
c – dune foot line,
d – dune top line,
e – range of dune slope,
f – reference line

Fig. 4. *Diagram showing basic morphological lines and forms in the coastal zone*

Specially important for the morphological and morphometric analysis are three lines: the reference line, which is linked to the national survey grid, the waterline at mean sea level (i.e. sea level 500 cm), and the line of the 10 m water depth contour, which closes the nearshore slope and is located outside the zone of most intense hydrodynamic influence on the seabed.

Morphometric forms and parameters of the shore

A number of morphological forms was distinguished and corresponding morphometric parameters were measured along the hypsometric (shore) profile between the waterline at mean sea level and the located at the back of the dune reference line (Fig. 5 and Table 1). Measures of the following elements of the shore were mainly used in the analyses: beach width, dune width (or width of its seaward part), height of beach, height of dune, area of cross-section of beach, area of cross-section of dune (seaward and landward parts), reach of 570 cm sea level (alarm sea level) and of 100-year and 500-year sea level, and corresponding to such storm surges cross-section areas of eroded dune. Coefficients of beach and dune (seaward part) inclination, and of beach and dune profile filling were calculated. Also morphometric measures for the whole shore, i.e the beach and dune belt were determined both for natural and nourished stretches of coast.

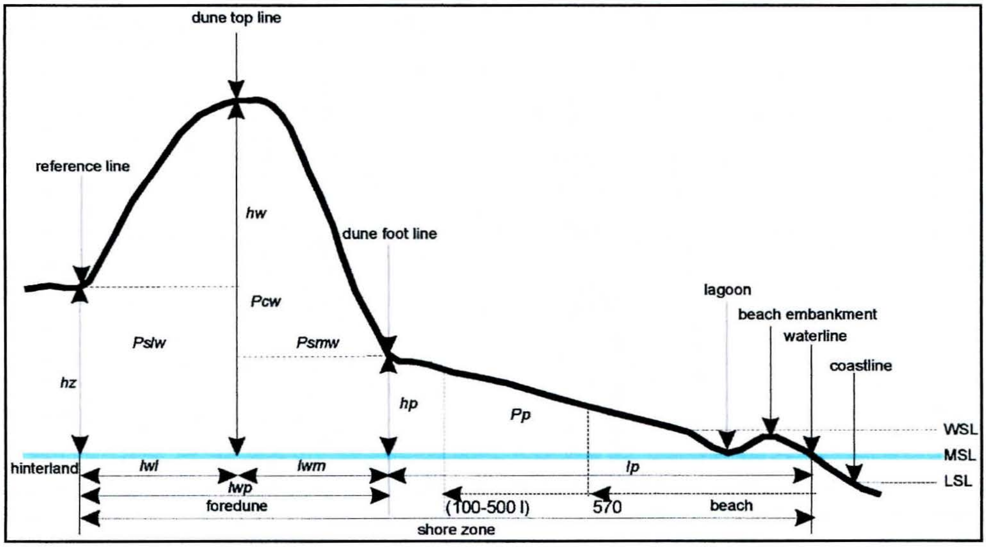


Fig. 5. *Morphological elements and morphometric parameters of the shore*

Because the hypsometric profiles are linked to the national geodetic grid, shifting of the shore seawards or landwards can be determined, and changes in the coastal system, in that the rates of erosion, become visible. The coefficient of filling of the morphological forms on the shore and in the nearshore zone is used both for calculations of the rates of erosion and of the magnitudes of sediment loss, and for evaluating the amount of material needed to balance the loss. Coastal protection by artificial nourishment is in essence an attempt at maintaining a permanent position of the coastline and such a level of beach and dune filling that required resistance of the shore to storm incidents of given return period (e.g. 100 years) is ensured.

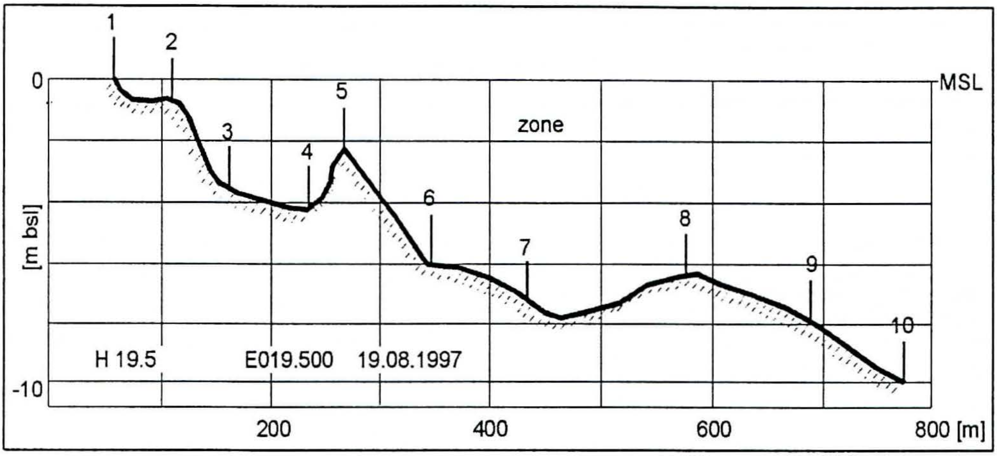
Table 1. Morphological elements and morphometric parameters of the shore (Fig. 5)

Morphological elementse (lines and forms)	Morphometric parameters	Symbols	Units
– coastline – waterline (500 cm) – dune foot line – dune top line – reference line			
– beach, beach embankment and beach lagoon	– beach width – beach height – beach inclination – beach cross-section – beach filling	*lp* *hp* - *Pp* *wp*	m m - m^2 m^3/m
– foredune and: seaward part and landward part of dune	– dune width – dune height – width of seaward part of dune – width of lanward part of dune – inclination of slopes – cross-section of slopes: – seaward – landward – area of dune cross-section – filling of slopes: – seaward – landward – filling of dune profile	*lwp* *hw* *lwm* *lwl* - *Psmw* *Pslw* *Pcw* *wmw* *wlw* *ww*	m m m m - m^2 m^2 m^2 m^3/m m^3/m m^3/m
– beach and dune belt (shore)	– shore width – area of shore cross-section – shore cross-section filling – reach of 570 cm sea level oraz 100- i 500-letniej wody – active area of shore ($Pan = Pp + Psmw$) - ordinate of hinterland	- - - - - -	m m^2 m^3/m m m^2 m

Morphometric forms and parameters of the nearshore zone

Morphometric measurements of the nearshore zone are preceded by a determination of the cardinal points and boundary lines of the morphological forms on a bathymetric profile (Fig. 6).

This procedure allows to determine the position of lines separating the morphological forms in the nearshore zone, and to carry out morphometric measurements. Linear, surface (of active and non-active parts) and volumetric parameters are measured. The basic linear parameters in the shallow part of the nearshore zone (Fig. 7) determine its development, and therefore its resistance and wave energy dissipation potential. Such procedure was used



1. contact of land and sea (MSL 500 cm),
2. end of shore terrace, 1-2 shore terrace
3. beginning of *U*-trough at foot of shore terrace, 1-4 shore slope,
4. end of *U*-trough – foot of landward slope of the inner bar,
3-4. *U*-trough at foot of shore slope,
5 & 8. tops of inner and outer bars,
6-7. interbar *U*-trough,
6. foot of seaward slope of inner bar,
7. foot of shoreward slope of outer bar,
4-5-6. inner bar,
7-8-9 outer bar,
9. beginning of "deep-water" slope,
4-9. bar zone,
10. 10 m depth contour,
1-10. nearshore slope

Fig. 6. *Location of cardinal points, determining the range of main morphological forms on nearshore profile*

at the beginning, when morphometric analysis was introduced. With transformation of the nearshore profile, caused by supply of nourished material, the scope of morphometric analysis, and therefore the number of indicators, had to be increased. The new morphometric parameters had to be introduced especially in order to enable observation of changes in the active part of the nearshore zone, i.e. the shore slope and the trough and bar system (Figs. 7-9).

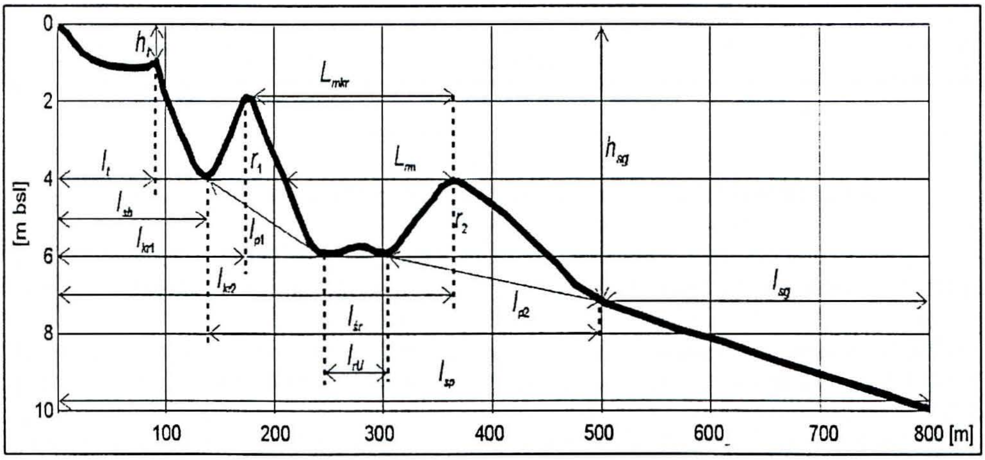
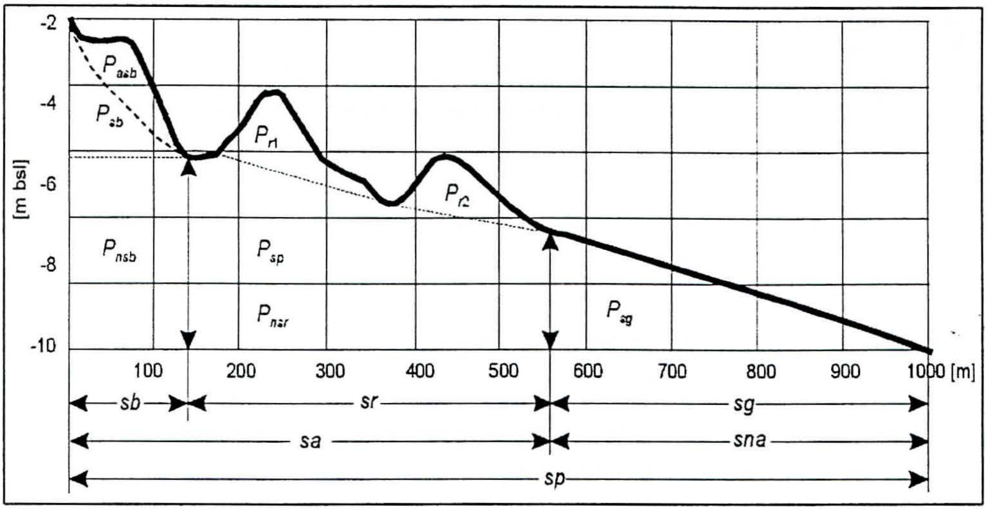
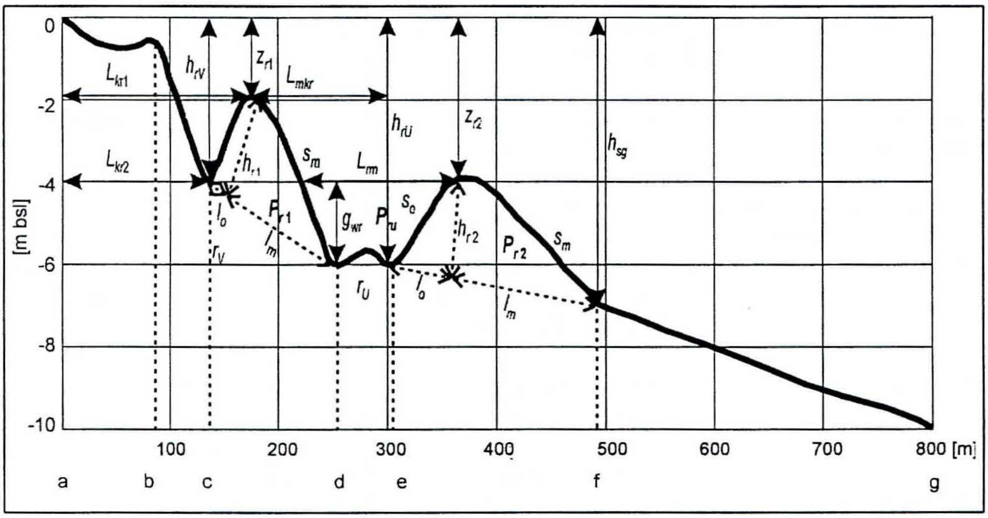


Fig. 7. *Linear parameters of the nearshore zone*



Rys. 8. *Areas of cross-section of forms in the nearshore zone*



Rys. 9. *Parameterisation of the trough and bar system*

The general parameterisation of the nearshore zone (Figs. 7 and 8), and the detailed parameterisation of the bar and trough zone (Fig. 9), determine the resistance of the nearshore zone and its potential ability to attenuate wave energy. Basing on selected morphometric parameters, a so-called morphological resistance coefficient was worked out, on which the rate of shore erosion depends. In total, over 40 morphometric parameters can be used for characterising the nearshore zone (Table 2). This set of parameters is not closed, e.g. it does not include the centre of gravity of a bar, as well as other parameters used in modelling nearshore profile changes.

Table 2. Morphological elements and morphometric parameters of the nearshore zone (Figs. 7-9)

Morphological elements (lines and forms)	Morphometric parameters	Symbols	Units
– coastline (*lb*)	–	–	–
– end of shore (beach) terrace	–	–	–
– troughs	–	–	–
– tops of bars	–	–	–
– bar zone	–	–	–
– 10 m depth contour	–	–	–
– shore terrace (*t*)	– width of terrace	l_t	m
	– depth at end of terrace	h_t	m bsl
– shore slope (*sb*)	– width of shore slope	l_{sb}	m
	– area of cross-section of shore slope	P_{sb}	m^2
	– active area of shore slope	P_{asb}	m^2
	– non-active area of shore slope	P_{nsb}	m^2
	– total area under shore slope ($P_{nsb} + P_{sb}$)	P_{csb}	m^2
	– inclination of shore slope	-	-
	– filling of shore slope	*wsb*	m^3/m
– *V*-trough at foot of shore slope (*rV*)	– trough depth	*hrV*	m bsl
– *U*-trough at foot of shore slope (*rU*) or interbar trough	– depth of trough	*hrU*	m bsl
	– width of trough	*LrU*	m
	– relative depth of *U*-trough	*gwr*	m
	– area of *U*-trough cross-section (for relative depth)	*PrU*	m^2
– bars (*r*)	– length of bar base	*lp* (1*o*+1*m*)	m
	– length of base of shoreward slope of bar	1*o*	m
	– length of base of seaward slope of bar	*lm*	m
	– height of bar	*hr*	m
	– inundation of bar	*zr*	m bsl
	– inclination of slopes	*so* and *sm*	
	– area of bar cross-section	*Pr*	m^2
	– bar filling	*wr*	m^3/m
	– distance between tops of bars	L_{mkr}	m
	– distance from bar tops to waterline	L_{kr}	m
	– total area of bars ($P_{r1} + P_{r2} + ...$)	P_{sr}	m^2

Table 2 (contd.)

Morphologic elements (lines and forms)	Morphometric parameters	Symbols	Units
– bar zone (*sr*)	– width of bar zone – active area of bar zone ($P_{r1} + P_{r2} + ...$) – non-active area of bar zone – total area of bar zone ($P_{nsr} + P_{sr}$) – inclination of bar zone – filling of active part of bar zone	l_{sr} P_{sr} P_{nsr} P_{csr} w_{sr}	m m^2 m^2 m^2 m^3/m
– slope seawards of bar zone (*sg*) to 10 m water depth	– width of slope – water depth at top of slope – slope inclination – slope filling – area of slope cross-section	l_{sg} h_{sg} w_{sg} P_{sg}	m m bsl m^3/m m^2
– nearshore slope (*sp*) to the 10 m depth contour	– nearshore slope width – cross-section area of *sp* – filling of *sp* – inclination of *sp* – area of active part of shore-slope ($P_{sb} + P_{sr}$) – area of non-active part of shore slope ($P_{nsb} + P_{nsr} + P_{sg}$)	l_{sp} P_{sp} w_{sp} P_{asp} P_{nsp}	m m^2 m^3/m m^2 m^2
– active zone (*sa*)	– width of active zone ($l_{sb} + l_{sr}$) – inclination of active zone (at h_{sg})	l_{sa} -	m -
– non-active zone (*sna*), i.e the deepwater slope below the bar zone	see (*sg*)	–	–

Parameterisation of the bar and trough zone

The bar and trough zone along the Polish coast is formed in the specific conditions of a non-tidal sea, at local and periodical deficiency of sediment and variable hydrodynamic conditions. This special part of the nearshore slope is formed by bars (though some profiles have no bars) and troughs (*V*- and *U*-shaped). The larger is the sediment deficit, the smaller is the number of bars in the nearshore zone, the narrower is the nearshore slope, and shore terraces tend to disappear. Two or more bar rows are present only along accumulative stretches; however, this concerns at most only 20% of the Polish coast. Accumulation in the nearshore zone is observed along the Vistula Spit and Amber Coast (Jantarowe Wybrzeże), and stretches of coast between Lubiatowo and Rowy, and between Międzywodzie and Świnoujście. Along the rest of the coast the bar zone is not well developed, and its dissipative potential is low, with small ability to protect the shore against erosion.

Rebuilding of the bar zone is a process proceeding at various rates, dependent on the intensity of feeding by sediments transported along the coast or supplied to the coast in result of hydrodynamic activity. Natural or artificial alimentation of the nearshore zone can significantly change the topography of the active part of the nearshore zone, i.e the shore slope and the bar zone. The development of bars is always accompanied by a parallel development of troughs, in that a passage from *V*- to *U*-shaped troughs. This is an adaptive transformation (durable or passing) of an accumulative nearshore zone, allowing outflow of water supplied to the swash zone by incoming waves at constant hydrodynamic conditions. Parameterisation of the bar and trough zone (Fig. 9) includes over a dozen morphological elements, which are used to evaluate the resistance of the nearshore zone and to determine the reach of 'longshore erosion/accretion systems. Measurements of the bar zone are carried out on profiles with undisturbed morphology. This allows to gain knowledge about the real – natural parameters and about the significance of relationships between all the measures of the nearshore zone.

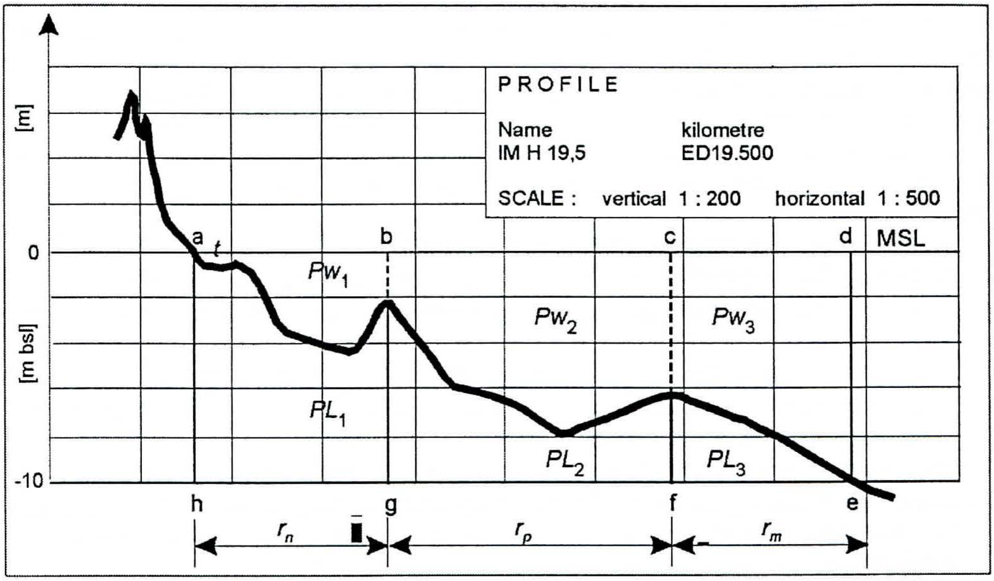
The adaptive rebuilding of the nearshore zone under the influence of sediment transport is a continuous process. On the other hand, rebuilding of that zone in effect of storms is of a "jump" character, though it occurs within boundaries determined by the resources of sediments (sand). The nearshore profile finally reaches an equilibrium state appropriate to the volume of water exchange (inflow and outflow) in the active part of the nearshore. In nature, the nearshore is always in equilibrium. However, due to the differences in "saturation" (amount of sand in the dynamic layer in relation to the actual hydrodynamic conditions), the adaptive capacity of the profiles to the wave and current conditions is limited. The adaptive processes proceed mainly in the dynamic layer, in the active zone of the nearshore, and are represented by an increase of the waviness of the seafloor.

Up to this time it was impossible to prove that a catastrophic (super-critical) deformation of the nearshore zone has occurred, which could result in a coastal disaster. Nevertheless, observed sudden shifting of the nearshore profile (eg. Kołobrzeg 1994), resulting in progressing damaging of the beach and dune, does initiate coastal emergency situations, such as breaking of the dune belt. This in turn can result in flooding of the hinterland in areas located below, or close to, the momentary sea level.

It was found that when sand from beach nourishment flows into the active zone in the nearshore, then an intensive reconstruction of the trough and bar system takes place. Inner bars, located nearest to the waterline, increased their volume only slightly. But in the outer bars (middle and seaward), the accumulated material increased their volume up to 10 times the initial volume. At the same time a type *U* trough system developed both in the belt below the shore slope and between the inner and outer bars. These observations showed that a quantitative assessment of the adaptive processes in the bar zone is needed, and in effect a number of new morphometric parameters was introduced. These parameters describe the volumetric changes of this part of the nearshore (this especially concerns the troughs). Also measurements of the cross-section areas of the solid and water parts of the profile from the waterline to the 10 m depth, and separated by the tops of the bars, were introduced.

Three zones are distinguished in the nearshore: the zone of wave run-up on the shore slope and shore, the wave breaking zone, and the outer zone. The width of these zones depends on the number of bars, the tops of which separate various sized hydrodynamic cells (transformation-circulation-dissipation cells) – Fig. 10. On coasts with no bars there is only one cell, in a single-bar profile there are two cells, for a two-bar profile there are three cells, etc.

Measurements of the solid part of cross-shore profiles, of the various belts within the profile, and of the water areas above the distinguished zones, allow a precise assessment of the resistance of the nearshore zone and of the coastal protection potential at the site of the profile.



PL_1	- cross-section area of solid part of wave run-up zone (*rn*)
PL_2	- cross-section area of solid part of wave breaking zone (*rp*)
PL_3	- cross-section area of solid part of outer zone (*rm*)
PL_{sp}	- ($PL_1+PL_2+PL_3$) – cross-section area of solid part of profile under the nearshore slope (*sp*)
P_{w1}	- cross-section area of water part of wave run-up zone (*rn*)
P_{w2}	- cross-section area of water part of wave breaking zone (*rp*)
P_{w3}	- cross-section area of water part of outer zone (*rm*)
P_{wsp}	- ($P_{w1}+P_{w2}+P_{w3}$) – cross-section area of water part of profile above the nearshore slope (*sp*)

Fig. 10. *Diagram showing the separation of areas of zones in the nearshore*

Summary

On shores of Polish dune coasts, morphological and morphometric analysis includes the beach, foredune and the beach and dune belt to the reference line (reference point). The waterline determines the reach of the mean sea level (500 cm). In the boundaries between the waterline and the reference line were distinguished morphological forms of the shore, and morphometric measurements were carried out (Table 2). After statistical processing (Part II), the sets of morphometric results form a reference database for consecutive hypsometric measurements, realised along strictly determined profiles of the shore. Volumetric parameters are of special comparative value, since the resistance of the shore to hydrodynamic influences and the rates of shore retreat depend on the reserves of sediments collected in the shore.

Separation of the morphological forms of the shore is a relatively easy and quick process, but the morphometric measurements are very labour consuming. A part of the measurements, mainly the measurements of cross-section area of the forms, has been computerised. Linear measurements, due to the large differences between profiles, are still made

manually. The morphometric characteristic of the shore is obtained through the measurement (calculation) of 23 parameters. A change of only one of these parameters results in a rebuilding of the whole shore. This may be the effect of natural or anthropogenic causes. The deficit of coastal sediments is the main cause of weakening of adaptive processes on the shore, resulting in shore erosion. The maintenance of a constant volume of the shore, for which artificial nourishment is used, is practically the only method of stabilising the coastline and protecting the coast. Morphometric parameterisation of the coastal zone is especially important in planning and design of coastal protection by nourishment.

In the nearshore zone, built of three forms: the shore slope, bar zone and the deepwater slope seaward of the bar zone (reaching to 10 m water depth), over 40 morphometric measurements were made.

The basic objectives of these works were:

- to obtain a full morphological and morphometric characteristic of the nearshore,
- to determine the relationships between measures of the morphological forms in the nearshore,
- to assess the resistance of the nearshore to action of hydrodynamic factors,
- to determine the erosion/accretion systems in the nearshore and to compare them with similar systems in the shore zone,
- to determine the durability of erosional predisposition of the analysed forms,
- to obtain information necessary for designing artificial nourishment in order to reduce the sand deficit and to increase the resistance of the coastal zone to action of hydrodynamic factors.

Information already gathered in the Coastal Zone Databank, and the continued measurements, allow to prepare and analyse a vast number of morphometric data. This is an extremely important comparative material, only thanks to which changes of the coast in conditions of rising sea level can be evaluated.

The methods of analysis and the use of separate parameters and of sets of morphometric parameters in coastal protection practice will be presented in the further parts of the paper.

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