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State of shore and backshore on the basis of monitoring results for selected polish seashores

Stan brzegu i nadbrzeża na podstawie wybranych wyników monitoringu polskich brzegów morskich

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Abstract: Aim of works on morphology and morphometry of the coastal zone is identification of qualitative and quantitative changes in the beach-dune strip and in the shoreface in conditions of their natural and anthropogenic transformations. As shore and backshore are essential elements reducing risks from the sea to the adjacent hinterland, this article focuses on evaluation of their parameters. Moreover, elements of the coast are described herein in detail. The research material used for the purposes of this article were records of bathymetric-tacheometric measurements of the Polish coast, made at consistent profiles evenly spaced every 500 m. The measurements did not cover the areas adjacent to the Bay of Gdańsk or the Lagoons. This article presents an analysis of the measurements of components of the coastal zone, which covered four morphodynamical areas (the Hel Peninsula, Jastrzębia Góra – Jarosławiec, Jarosławiec – Sarbinowo, and Sarbinowo – Międzyzdroje), twelve sandbar stretches (the Helska, Karniewska, Sarbska, Łebska, Długie, Gardno, Wicko, Kopań, Bukowo, Jamno, Resko, and Dziwnowska Spits) and thirteen cliff stretches (the cliffs in Chłapowo, Jastrzębia Góra, Rowy, Dębina, Ustka, Jarosławiec, Wicie, Sarbinowo, Ustronie Morskie, Śliwin, Trzęsacz, Pobierowo, and on Wolin Island). The basic linear parameters of the beach-dune and beach-cliff belt were read from 678 printouts of tacheometric profiles. A detailed analysis carried out in this manner made it possible for the endangered sections of the coast to manifest themselves. The obtained data are a basis for further comparative analyses, and assessment of the shore under conditions of implementation of the Act on the Protection of Sea Coasts.

Keywords: beach, backshore, dune, cliff, sandbar, spit, morphodynamic area, morphometric parameters, hydrodynamics

Streszczenie: Celem prac nad morfologią i morfometrią strefy brzegowej jest poznanie jakościowych i ilościowych zmian zachodzących w pasie plażowo-wydmowym i na podbrzeżu w warunkach ich naturalnych i antropogenicznych przekształceń. W artykule skupiono się na ocenie parametrów brzegu i nadbrzeża, jako znaczących elementów redukujących zagrożenie przyległego zaplecza od strony morza. Ponadto opisano szczegółową charakterystykę elementów wybrzeża. Materiałem badawczym były zapisy pomiarów batymetryczno-tachimetrycznych polskiego wybrzeża, w stałych profilach rozmieszczonych co 500 m. Pomiary nie objęły swoim zasięgiem obszarów przylegających do Zatoki Gdańskiej czy zalewów. W artykule przedstawiono analizę pomiarów elementów strefy brzegowej, które objęły cztery rejony morfodynamiczne (Półwysep Hel, Jastrzębia Góra--Jarosławiec, Jarosławiec-Sarbinowo oraz Sarbinowo-Międzyzdroje), dwanaście odcinków mierzejowych (Helska, Karniewska Sarbska, Łebska, Długie, Gardno, Wicko, Kopań, Bukowo, Jamno, Resko i Dziwnowska) i trzynaście odcinków klifowych (chłapowski, jastrzębski, rowski, dębski, ustecki, jarosławiecki, wicki, sarbinowski, ustroniomorski, śliwiński, trzęsacki, pobierowski i woliński). Na wydrukach 678 profili tachimetrycznych odczytano podstawowe parametry liniowe pasa plażowo-wydmowego i plażowo-klifowego. Tak przeprowadzona szczegółowa analiza wybrzeża pozwoliła na uwidocznienie zagrożonych odcinków. Uzyskane dane stanowią podstawę do dalszych analiz porównawczych i oceny stanu brzegu w warunkach wdrażania zapisów ustawy o ochronie brzegów morskich.

Słowa kluczowe: plaża, nadbrzeże, wydma, klif, mierzeja, rejony morfodynamiczne, parametry morfometryczne, hydrodynamika

Introduction

Sea coast constantly undergoes changes, both seasonal and the ones that take years. The coasts of the Baltic Sea are quite exceptional, what with them not being affected by tidal excursions, contrary to the coasts of other seas.

Monitoring is a basic element of executing the strategy for protection of the sea coasts, as it enables a proper control over its implementation, and forming action programs in a reasonable fashion. The gathered measurement data also make it possible to perform analyses and assess the condition of the coastal zone, and the backshore as a part of the scientific and research works.

In the years 2004 – 2006, the maritime administration conducted monitoring measurements throughout the entire length of the sea coast, and the shores of the Vistula Lagoon for the first time. Despite a differentiated approach to the scope of the monitoring, and the way it should be carried out, it was possible to obtain a rather homogenous material from the water level-bathymetric profiling, which covered the technical zone (50 m from the highest point of a dune's crest) and the shoreface down to the depth of 15 m. Span between the profiles equal 500 m was determined by the scale of spatial-temporal changes occurring on the coasts of the Southern Baltic Sea [12]. Over 1200 profiles of the coastal zone were acquired, which in turn gave a basis for creation of a monitoring bank functioning as a part of the BRZEG databank dedicated to the coastal zone.

In the years 2012 – 2013, another monitoring of the coastal zone and the shoreface was conducted. It covered shores of the high seas, excluding the Gdańsk Bay, combining the traditional water level–bathymetric measurements with the Light Detection and Ranging (LiDAR) laser scanning. 678 profiles were obtained this way, covering a total of 339 km of the coast, an analysis of which is presented herein.

On the Polish coast there were distinguished six morphodynamic regions: the Vistula Lagoon – Sopot, the Gdańsk Bay, the Hel Peninsula, Jastrzębia Góra – Jarosławiec, Jarosławiec – Sarbinowo, and Sarbinowo – Międzyzdroje. The surveyed area covered four of them. Apart from that, the survey targeted also twelve sandbars (the Helska, Karniewska Sarbska, Łebska, Długie, Gardno, Wicko, Kopań, Bukowo, Jamno, Resko, and Dziwnowska Spit), and thirteen cliff stretches (the cliffs in Chłapowo, Jastrzębia Góra, Rowy, Dębina, Ustka, Jarosławiec, Wicie, Sarbinowo, Ustronie Morskie, Śliwin, Trzęsacz, Pobierowo, and on Wolin Island).

Materials and methods

Source of data for the analysis were the data gathered in 2012/2013 in the BRZEG databank containing information on the coastal zone and maintained by the Department of Maritime Hydrotechnics of the Maritime Institute in Gdańsk.

The processed data had been obtained from tacheometric measurements made at consistent cross-sections evenly spaced every 500 m, as well as from the LiDAR scanning, which is characterized by a fast rate of data acquisition, a very high spatial resolution, and accuracy of the obtained measurement. The registered parameters enable determination of coordinates of the measured objects in the XYZ three-dimensional space.

The method outranks the former research methods that used to be employed while surveying the coast. They only allowed for acquisition of detailed data on the beach and seabed ordinate's location in single measurement profiles (which used to take much more time), or alternatively, obtaining much less detailed data.

The method, however, has its limitations. The desire to make use of the data obtained via LiDAR in creating tacheometric profiles consistent with the BRZEG databank's standards forces us to find solutions to a series of problems, and to activate appropriate operational procedures.

The results of the bathymetric measurements and geodetic profiles of the coast are stored in the elementary files of the bank. An elementary file is a file in text format. Every elementary file contains data on only one intended measurement profile.

Saving the file allows for making printouts of the profiles – cross-sections of the shore at a range of scales. For the purposes of parametrical analysis of the beach-dune strip, there were used mainly the 1:500 (horizontal) and 1:100 (vertical) scales.

From the printouts of the tacheometric profiles the following linear parameters of the beach-dune /cliff strip (see Figure 1/ *Rys. 1*) were read:

- beach – width measured from the shoreline to the dune's basis (l_p), height of the beach (h_p), and the range of sea-level rises 570 cm, 600 cm;
- dune/cliff – width measured from the dune's basis (the foot of the cliff) to its highest point (l_{wp}), the maximum height (h_{wmax}), and the range of sea-level rises 650 cm.

Moreover, the areas of the beach and the dune were measured via the digitalization method up to the maximum height, and the filling and gradient of the beach and of the seaward slope of the dune/cliff were calculated.

The remaining part of the assessment was conducted in accordance with the objectives pursued. The obtained data were saved in the Microsoft Excel® program. Calculations of other parameters were also made in this program. The results were presented in descriptive, statistical and graphical form.

The method of morphometric analysis of the water level–bathymetric profiles, which had been already used in the Depart-

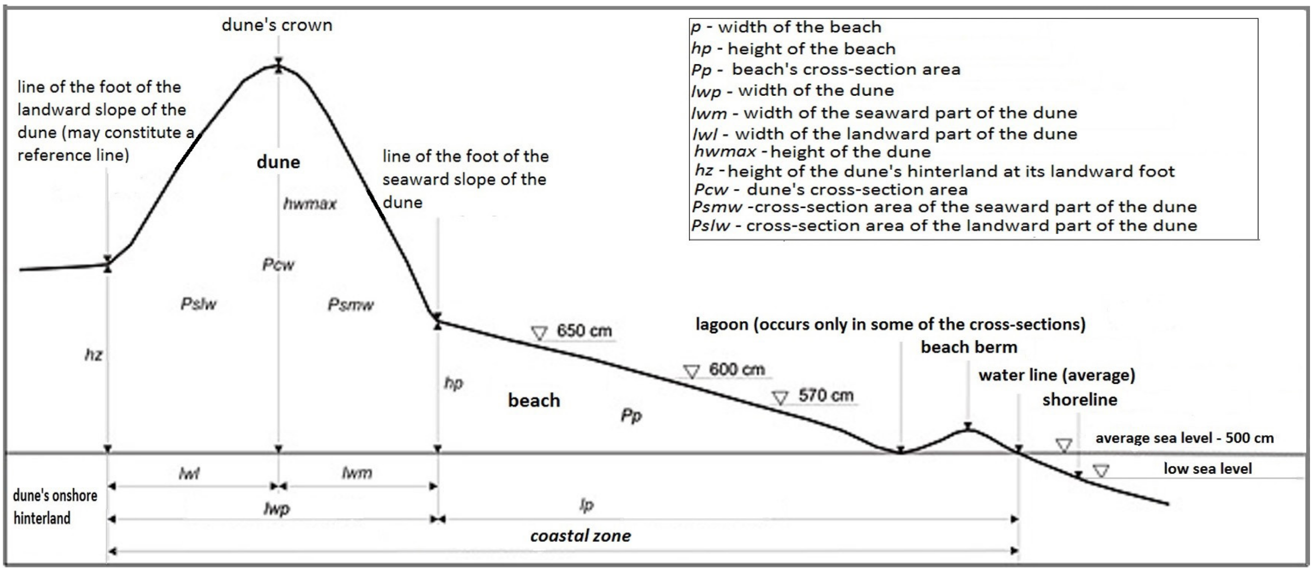

Fig. 1. Morphological elements and morphometric parameters of the coastal zone used in the analysis

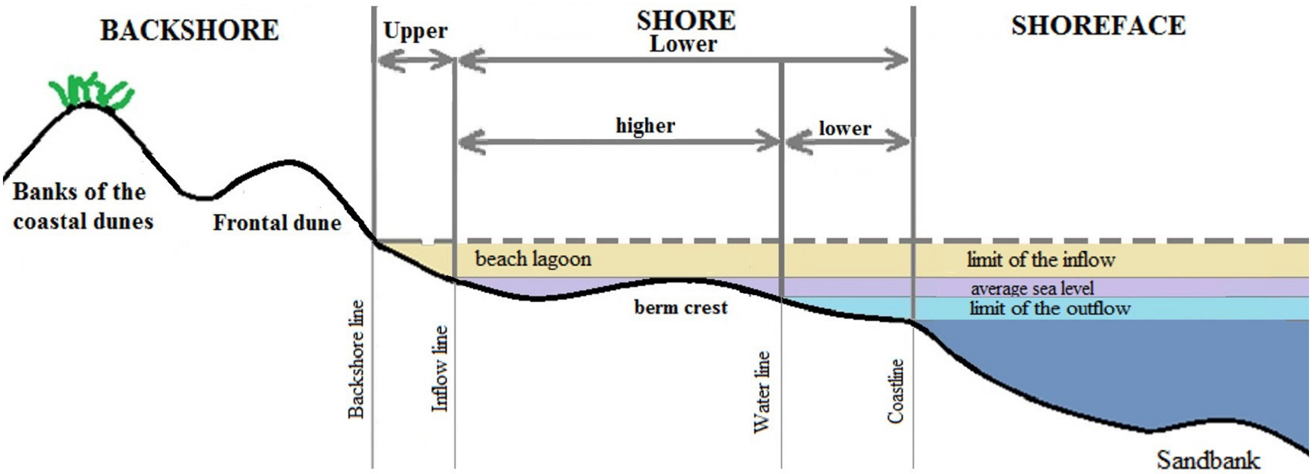

Fig. 2. Elements of the coast [21 with changes].

ment's works [6; 10; 13], allows for conducting quantitative surveys of transformations of the main morphological forms occurring on the beach-dune strip, as well as on the shoreface.

Data and the analysis

Area of the shore is characterized by significant dynamics, which is a result of the physical processes occurring in sea basin and constantly impacting on the shore. Other factors influencing coast development are plants and animals, as well as human activity. Earth surface forming processes in the land environment are also not to be underestimated. The most important of them are: weathering, mass gravity movements occurring on the slopes undercut by waves and currents, and aeolian processes affecting the sandy and more fine-grained material in the coastal zone. All these processes have impact on the lay of the coast by transporting the material throughout the coastal zone, forming various deteriorative and accumulative forms in effect.

The "coastal zone" term has much broader a meaning than word "shore", and it encompasses also the area remaining permanently underwater, and called "shoreface". On the seaward side, the shoreface's border is determined by the depth where wave motion starts affecting the seabed. The area beyond the range of seawater's direct impact is defined as backshore [18; 20; 21]. It encompasses various morphological forms: dunes, cliffs, and coastal alluvial plains (Figure 2/ *Rys.* 2).

The main morphological elements of the coastal zone are: beach, coastal slope, sandbanks zone, and the slope outside the sandbanks zone. Each of them influences the morpholithodynamic processes, as well as the entire erosive-accumulative system of the coastal zone.

The beach is an area constantly transformed by the wave motion, and the material it consists of is permanently on its way from the sea to the land, and back again. At different times of the year, a beach may be either deteriorated, or built up. In the temperate zone, the colder half of the year is characterized by a greater frequency of storms, and that is why in the winter period there prevails erosion, while in the summer – deposition. Apart from the wave motion, wind also plays a part in transportation of the material throughout the beach [1; 7; 8; 14; 20].

The beach zone can be divided into three parts: swash zone, berm crest, and storm berm. The swash zone is the area systematically swashed by the water in normal conditions. The berm crest is an accumulative form deposited on the coastal slope. Height of the berm crest is dependent on the height to which a wave runs up the beach scarp. It is good to mention, however, that short wave which occurs on the Baltic Sea does not favor formation of this coastal form. The storm berm is the fundamental part of the beach, usually taking the biggest part of it. It gets swashed by water during high tides. At the backshore side of a beach, there may occur dune crests, or a beach may form at the foot of a cliff.

Beaches consist of loose mineral grains, primarily of sandy fraction, usually quartz, and comparatively well rounded. There occur, however, also beaches made of much coarser material qualified as boulder fraction. This applies to the sections where rubble gets washed from the moraine eleva-

Fig. 1. Pebbly beach in the region of the Kępa Oksywaska (Obłuże) cliff (photograph by Boniecka, 2006).

Fig. 2. Sandy beaches near Międzywodzie (photograph by Boniecka, 2014).

Fig. 3. Sandy beach, refulled on the Hel Peninsula (photograph by Boniecka, 2012).

tions and the formed abrasive platforms undercut by the sea (Photos 1 – 3/*Fot. 1-3)*. Dunes are accumulative forms of an unambiguous aeolian origin, taking a form of sandy hills of a parabolic shape. Basically, they are reservoirs of sand ensuring balance in the beach zone. In the winter season, dunes are eroded, whereas in the summer, the excess of beach sand is included into the area of the dune strip. Frontal dunes are a morphological type peculiar to the coastal areas. They are long, low (up to 3 – 4 m tall) embankments spreading parallel to the shoreline. Their formation is favored by plants that keep the sand, thus forming banks, which are next colonized by vegetation and stabilized. On their outer side there may form parallel strips of frontal dunes. During the storms, the frontal dunes may undergo total, or partial erosion [1; 2; 4; 15] (see Photos 4-5/*Fot. 4-5*).

Cliffs are leading forms of the abrasive landscape. They are steep or vertical sections of the slope, practically rising directly from the sea. Their height is dependent on the character of the backshore's lay, and may be very varied. Cliffs consist of rocks of differentiated lithology, which has an impact on endurance of the rock center and translates into the cliff's steepness. On the Polish coast of the Baltic Sea there occur cliffs made of unlithified formations – sands and clays, built out of glacial and glacial cover formations, sometimes also out of chalk cliffs xenoliths [17; 22]. Various destructive processes participate in development of a cliff; both the ones connected with lithoral environment, and the "normal" surface processes. To the later ones, there belongs first of all the mass wasting, aided by the cliff's being constantly undercut by waves. It leads to an increase in the slope's steepness, and a loss of its stability. Depending on features of the bedrock, cliff coastlines are transformed by tearing and coming off of the fragments, deep rotational landslides, runoffs, and mudslides. The released rocky material piles up at the foot of the cliff, from where it gets washed away by waves and coastal currents. Thus, the cliff's base gets exposed again, leading to another episodes of mass wasting, and shifting of the cliff's crest, and sometimes even of the shore further inland [5], (see Photos 6-7/*Fot. 6-7*).

The open sea shores of the Polish part of the Baltic Sea are composed of dunes (77%) and cliffs (19%). These forms occur in the part of the coastal zone called backshore. The area is swashed with water only during significant storms, and it presents the last natural shield for protection of the zones situated at its hinterland.

From the point of view of quality (endurance) of the coastal zone, the most valuable are the wide (over 40 m wide), and comparatively high (above 2 m a.s.l.) beaches. Such parameters prevent formation of storm accumulations exceeding the average sea level by 1.5 m. Beaches of lower classes do not cause a total loss of energy of the oncoming wave, which leads to washing out of the frontal dunes, thus adding to the flood hazard for its hinterland [5; 10; 12].

Fig. 4. A devastated dune to the east of "Ptasi Raj" bird sanctuary (photograph by Boniecka, 2012).

Fig. 5. Dune shore in the neighborhood of Darłowo (photograph by Boniecka, 2015).

Not without significance is also the beach's gradient, calculated on the basis of its width and height. It is assumed that a beach moves towards a distribution of slope of 1:20. According to an established study, value of the height/length of a beach < 0.025 means that the beach is of average steepness, or moderately steep.

Backshore dunes constitute the most important barrier ensuring safety of the backside at times of high storm accumulations. When a storm comes, a single dune bank of small or medium altitude, and of width measured at the basis smaller than 20 m does not constitute a sufficient protection for the low-lying terrains of the dune's backside. It is assumed that within a timeframe of several decades, safety may be guaranteed by a dune of altitude over 5 m a.s.l., and width of 50 m.

In the parametric analysis of the forms occurring on the beach-dune strip there were employed printouts of tacheometric profiles obtained from the databank on the coastal zone. From 678 profiles corresponding with km H 0.0-H 36.0 – which is the open sea side of the Hel Peninsula, and km 125.0-428.0, there were read the linear and surface parameters of the beach-dune/cliff strip, as well as the range of sea level rises of 570 cm, 600 cm, and 650 cm (see Figure 1; Tables I, II, and III/*Rys. 1, Tab. I, II i III*). Height of the beach was determined at the point

Fig. 6. The Mechelinki Cliff (photograph by Domaradzki, 2013).

Fig. 7. Cliff coast in the neighborhood of Niechorze (photograph by Boniecka, 2014).

of clear change of the profile's gradient, and in cases when no such place could be found, at the point of the profile at the altitude of 2 m, as this height is assumed to be the average height of a beach on the shores of the South Baltic Sea. Height of the beach/cliff backshore was determined at the highest point of the backshore's profile viewed from the beach.

Shortages occurring in the measurements are caused primarily by the natural gaps in continuity of the coast (estuaries), or by the anthropogenic ones (ports, canals). In case of the backshore, shortages result most often also from an inadequate placement of the base point.

Average width of the beaches on the entire surveyed area is equal 39.1 m. Out of the 678 studied beach profiles, 52 of them are less than 20 m wide, and 264 are over 40 m. Out of 654 of all the studied profiles of the backshores, 633 exceed the height of 5 m (see Figures 3-6, Table I/*Rys. 3-6, Tab. I*).

The examined profiles obtained from the kilometers from 125.0 to 345.45 represent both sandbar/dune, and cliffy stretches of the coast. Characteristic for them are beaches of heights within the scope of the average height, with little standard deviation. Great discrepancies may, however, be observed when it comes to width of the beach. The average value equal 39.1 m is close to the minimum width required for safety reasons, however, the fluctuations in width reach up to 17.2 m (see Figures 3-6/*Rys. 3-6*). The average gradient of the beach is significant, and it equals approx. 0.06, which characterizes its steep slope. Deviation of this parameter is, however, very high (0.03), which signifies large heterogeneity. The average area of a profile is 35.5 m^2 with a deviation of 18.2 m^2, which places it in the medium class of quality (Table I/*Tab. I*). For instance, the beaches in the region of Białogóra subjected to processes of accumulation, pile up about 85 m^3 of sediments per one linear meter, while at the foot of the cliffs there seldom accumulates more than 20 m^3/lm.

The backshore of this section is very diverse, as located there are both low sandbars, and high cliffs. That is why the backshore's height oscillates between 2.1 and 65.9 m, with the average value of almost 8.4 m. Width measured from the beach to the top of the backshore crest also shows a large diversity, which is displayed by the standard deviation of 19.8 m with the average width of 28.8 m. Because of this, resistance of the shore on the entire section is very diverse. The average area of backshore's stretch in this section is equal 200.5 m^2, and the deviation is extremely high, as it exceeds the mean value over twice, i.e. 411.8 m^2. With such a deviation, it is difficult to determine the quality class precisely, but the mean value puts this section of the backshore within a high-ranking scope. Yet, one needs to remember that due to the cliffs occurring in this section, the grade is surely overstated (Table I/*Tab. I*).

The Hel Peninsula is situated in the area administered by the Municipal Office of Gdynia, and it is the longest of the sandbars examined herein. The studied profiles were obtained from the km H 0.0 – H 36.0, that is, from the seaward, more exposed to damaging effects side of the Hel Peninsula. The examined averaged values of the entire section of the beach comply with the safety standards for the coast. Some local values, however, differ much from the desirable parameters. The average width of the beach equals here 45.9 m, with a deviation of 17.6 m. The average gradient of the beach is considerable (0.05). Interestingly, deviation from the average value is the same as the average itself, indicating that in the surveyed section, there occur totally flat to extremely steep beaches. The average area of the cross-section equals 41.2 m^2 with deviation of 13.2 m^2, which places the beach of this region on the verge of classes of high and average quality (Figure 3, Table II/*Rys. 3, Tab. II*).

Height of the backshore in this section ranges between 2.5, and 10.4 m, with the average at the level of 5.8 m, and deviation of 1.4 m. The values of backshore's width are also very diverse. The average equals here 23.0 m, with a high deviation of 12.0 m, which means that a part of the stretch does not meet the minimum safety standards. The average area of the cross-section equals 90.1 m^2 with deviation of 57.5 m^2. So high deviation hinders a correct identification of the backshore section's quality class a lot; the average value places it on the verge of low and average classes (Figure 3, Table II/*Rys. 3, Tab. II*).

The sandbar stretches display highly varied lengths. Excluding the Hel Peninsula, the longest of the examined sandbars is the Łebska Spit (*Mierzeja* Łebska) (17 km), while the shortest profile belongs to the Długie Lake Spit (*Mierzeja Jeziora Długie*) (3 km). Short sandbars not exceeding 4 km in length are rare (3 out of 12 studied profiles). As many as four of them exceed the length of 10 km (Table II/*Tab. II*).

Beaches on the stretches of this kind are usually wide to average. The widest ones were observed in the profiles form the region of the Resko Lake Spit (*Mierzeja Jeziora Resko*) (57.8 m on average), and the narrowest beaches – in the profiles of the Cliff of Jastrzębia Góra (16.6 m on average). The spot where beach was the widest was found on the Hel promontory (km H 36.0) – 143.2 m. The spot where beach was the narrowest was found in the area of the Cliff of Jastrzębia Góra (km 131.5) – only 3.8 m (Table II/*Tab. II*).

The narrowest average taken out of the measurements of the sandbar beaches was the one calculated for the beach adjacent to the sandbar of Kopań Lake – 27.3 m, and the widest one was on the Resko Lake Spit – 57.8 m (Table II/*Tab. II*).

The cross-section areas of the beaches along the coast differ; on the sandbar shores there predominate the average quality classes. The smallest average cross-section area among the sandbar shores occurs on the sandbar of Kopań Lake (26.9 m^2), and the biggest one in the area of the Hel Peninsula (41.2 m^2), and the Łebska Spit (41.1 m^2). Both natural and anthropogenic factors have impact on such a diversity (Table II/*Tab. II*).

The dune belt of the coastal sandbars indicates a great changeability of the shore's dynamics. The state is recorded in the registered, changing lay of the shore, including also the diverse dune's cross-section area and width measured up to its maximum height. The highest sandbar backshore was registered in the area of the Długie Lake Spit, with its average height of 8.9 m, while the lowest – in the area of the Kopań Lake Spit, where the dunes reach the height of only 3.2 m. The spot where backshore is the lowest is located on the Kopań Lake Spit, where on the km 266.0 its height is 2.1 m, and 2.2 m on the km 244.0. Such low dunes are not sufficient to protect the shore's backside including Kopań Lake against a rise in the sea level, and storm surges (Table III/*Tab. III*).

The results of the measurements indicate that the cliffy coasts do not usually exceed few kilometers in length (6 out of 13 examined ones were not longer than 3.3 km). The shortest of the studied sections was only 150 m long (in Rowy), and the longest one was 14.5 km (on Wolin Island) (see Table III/*Tab. III*).

Width of the beaches in the sections of this kind is alarming. The averaged widths of only three beaches adjacent to cliffs can be counted among the average ones (the cliffs in Dębina, Trzęsacz, and Pobierowo), while the rest of them are narrow (Table III/*Tab. III*).

The narrowest average value taken out of the measurements of the cliffy beaches was found to belong to the section by the Cliff of Jastrzębia Góra, and it equals 16.6 m, while the widest one was in the region of the Cliff of Trzęsacz – 37 m, most probably resulting from the conducted there nourishment of the coastal zone (Table III/*Tab. III*).

On the cliff coasts, areas of beach cross-section are on the boarder of the low rank. The smallest average area of a cross-section among the cliff coasts is found in the cliff in Wicie region (19.0 m^2), while the biggest one is in the region of the cliff in Trzęsacz (36.8 m^2), as it remains under influence of the artificial beach nourishment conducted there with use of material taken from "Rewal" uptake point (Table III/*Tab. III*).

Examination of the backshore via this method is difficult in case of the cliff stretches, as in the method, a profile's first highest bending point is determined instead of the point called cliff's crest. Hence, data on backshore's height are not identical with the known heights of the cliffs.

On this basis, it was determined that although it is the cliff on Wolin Island that may boast of having the highest cliff crest, still the greatest average height of the backshore falls to the area of the cliff in Chłapowo (37 m). The lowest average height is attributed to the backshore of the cliff in Ustronie Morskie, the average height of which is 5.2 m. The highest points on the backshore neighboring directly with the seashore was found in the area of the cliff in Chłapowo (km 129.5) – 65.8 m high, and in the area of the cliff on Wolin Island (km 410.0) – 41.0 m (Table III/*Tab. III*).

Morphometric classification of dune coasts

Classification of the beach-dune belt was based on the morphometric parameters influencing safety of the hinterland [25]. Altogether, 678 profiles corresponding with 339 km of beach-dune//cliff belt were subjected to an analysis. From these profiles, there were interpreted parameters of 670 sections of the beach, and 654 sections of the backshore, 517 out of which are dune backshores. In the studied sections, a total of 52 profiles with very narrow beach (<20 m), 150 profiles with narrow beach (width of the beach ranging from 20 to 30 m), 204 with average beach (30-40 m), and 264 with wide beach were registered. Overall, it amounts to 132 km of beach of a width of over 40 m (the wide beaches), which constitutes about 46% of the analyzed beaches of the dune backshores (Figure 7, Table IV/ *Rys. 7, Tab. IV*).

Among the backshores of dune character there predominate the ones of average height (258 cases). There were not many of very low ones (2 – 3 m a.s.l.) – namely only 19; 125 low ones (3 – 5 m a.s.l.); 107 moderately high ones; and 8 cases of high ones. It gives a total of 186.5 km of dune backshores higher than 5 m a.s.l. (backshore of average height or higher). The cliff stretches damages of which are irreparable were not included in this number. The total length of the registered backshores higher than 5 m was 246.5 km (Table IV/ *Tab. IV*).

In the region of the Karniewska Spit, height of backshores exceeds locally the level of 15 m. These are the tallest dunes observed in the region of the open sea. Complexes of frontal dunes classified as moderately tall occur also on the spits of the Łebsko and Sarbsko lakes.

On the areas under investigation there predominate narrow and average beaches, the average height of which remains within the norm specified for the one-hundred-years-storm. The widest beaches were observed on the profiles of the Resko Lake Spit (on average, almost 58 m, with a standard deviation of less than 11 m). The narrowest ones were on the profiles of the Cliff of Jastrzębia Góra (on average, 16.6 m, with a deviation equal as much as 7.8 m). Gradation of the beach of all the examined profiles exceeds the level considered normal for the natural beaches (0.02). The highest level of the parameter was registered in the profiles from the region of the Cliff of Jastrzębia Góra (on average, 0.13, with deviation of almost 0.14), and the lowest one, in the Resko Lake Spit (on average, 0.03, with deviation equal less than 0.01).

Among the surveyed areas, the average greatest height of the sandbar backshore was found on the Długie Lake Spit, and it was almost 8.9 m, while the lowest height, namely 3.2 m, was on the Kopań Lake Spit. Despite the fact that the tallest cliff is situated on Wolin Island (Gosań Hill, 95 m a.s.l.), the cliff that can boast of having the greatest average height of the backshore among the cliffs, is the cliff of Chłapowo, the average height of which is almost 38 m, while the lowest height falls to the cliff of Ustronie, the average height of which is barely 5.2 m.

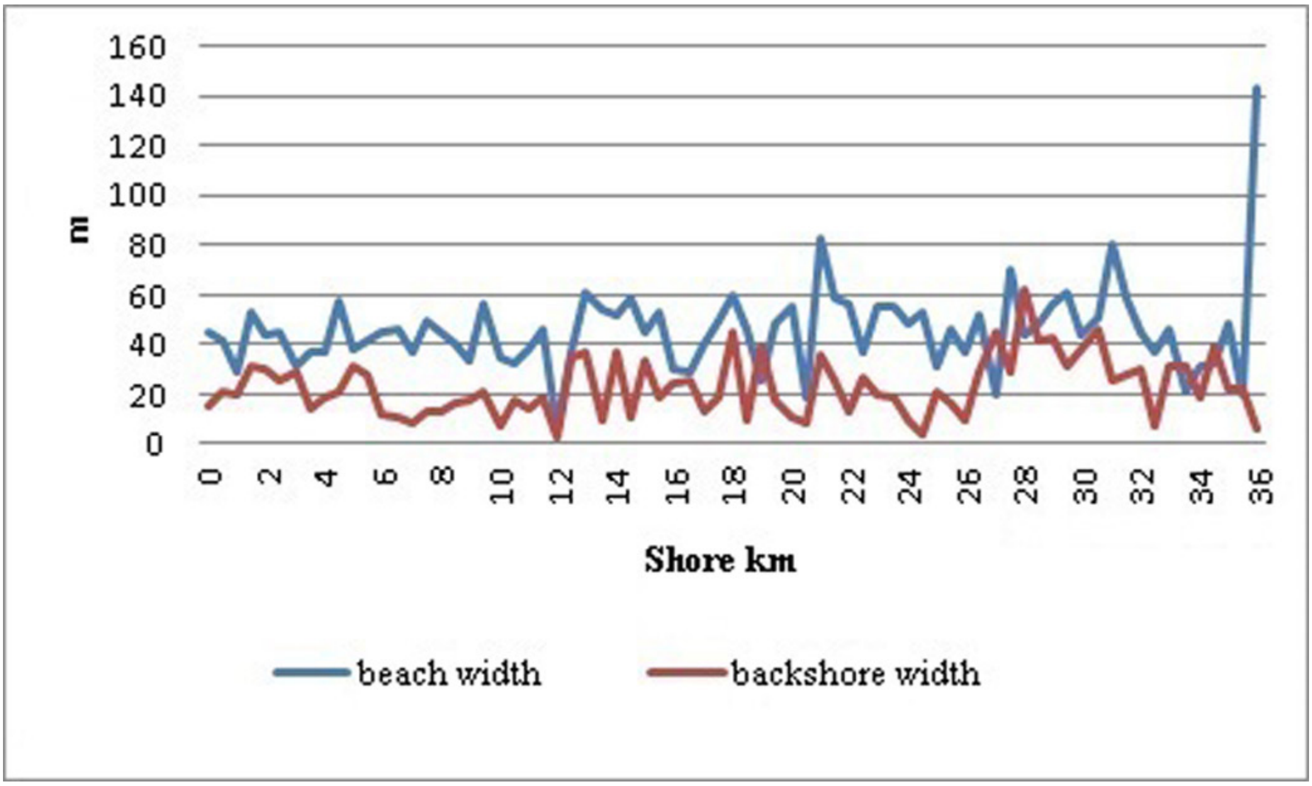

Fig. 8. Changes in the beach and backshore's width on the seaward side of the Hel Peninsula.

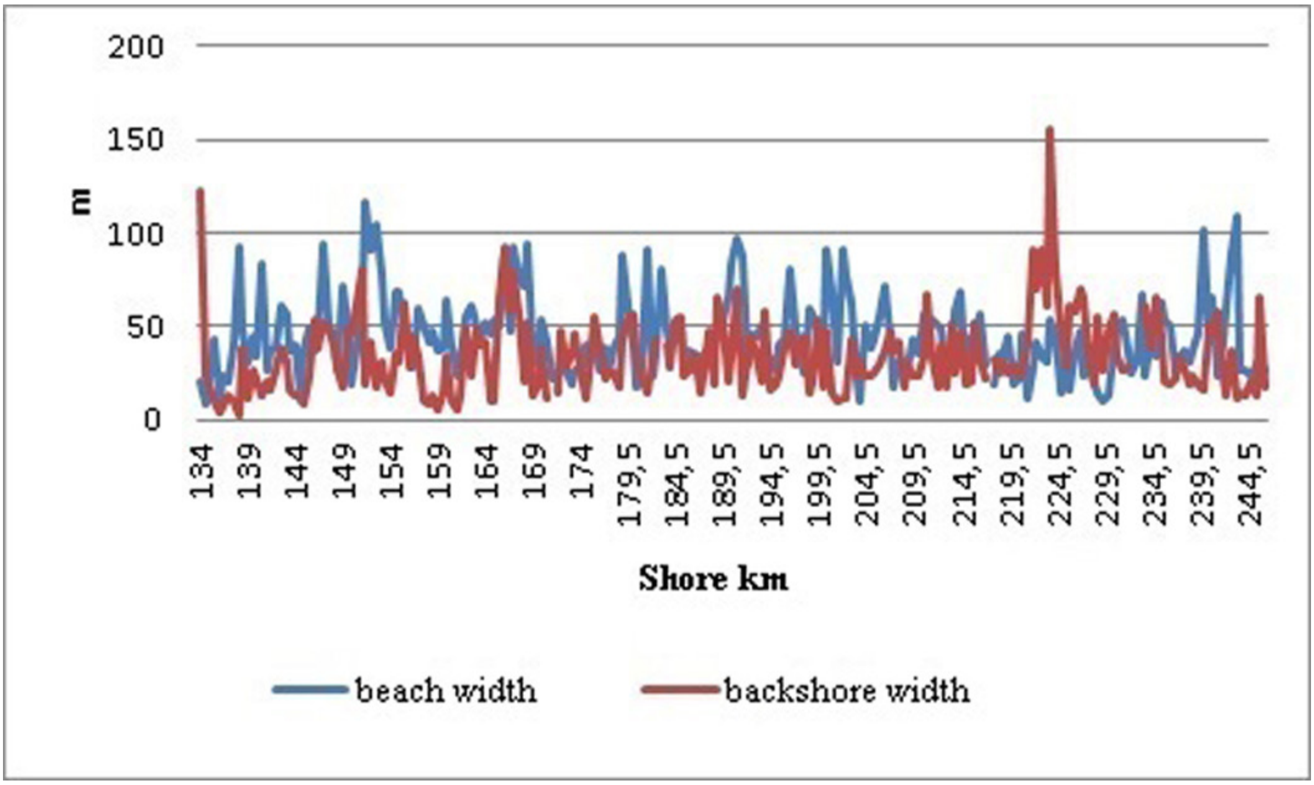

Fig. 9. Changes in the beach and the backshore's width in the Jastrzębia Góra – Jarosławiec section.

Conclusions

Results of the analyses show, first of all, the diversity that characterizes dynamics of the Polish coasts of the South Baltic Sea. The sections in jeopardy occur alternately with those, where accumulation takes place. Having had a closer look at the results, it becomes clear that in greatest danger are the stretches of cliff coasts, where narrow beaches occur. Although tall cliffs constitute a splendid barrier against the forces of the sea, it needs to be kept in mind that the waves irrevocably destroy

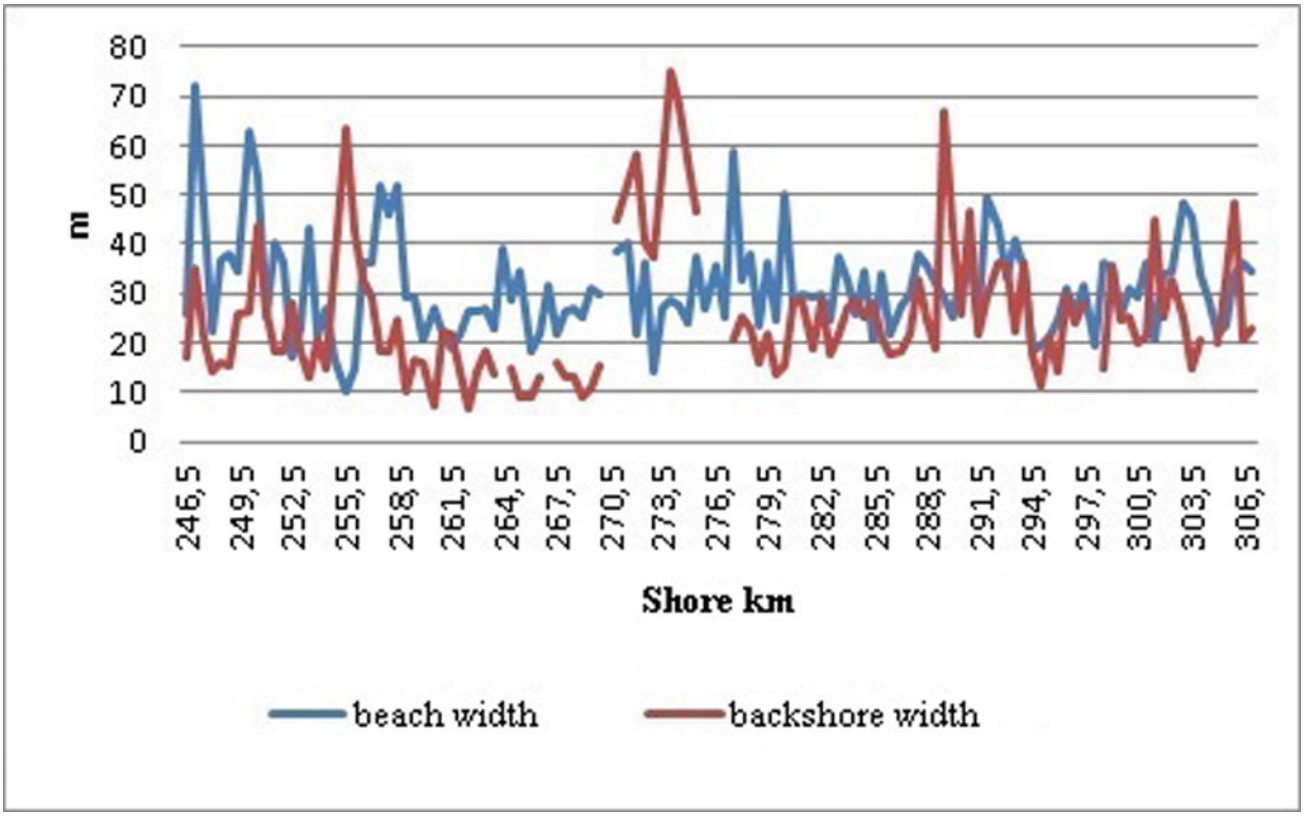

Fig. 10. Changes in the beach and the backshore's width in the Jarosławiec – Sarbinowo section.

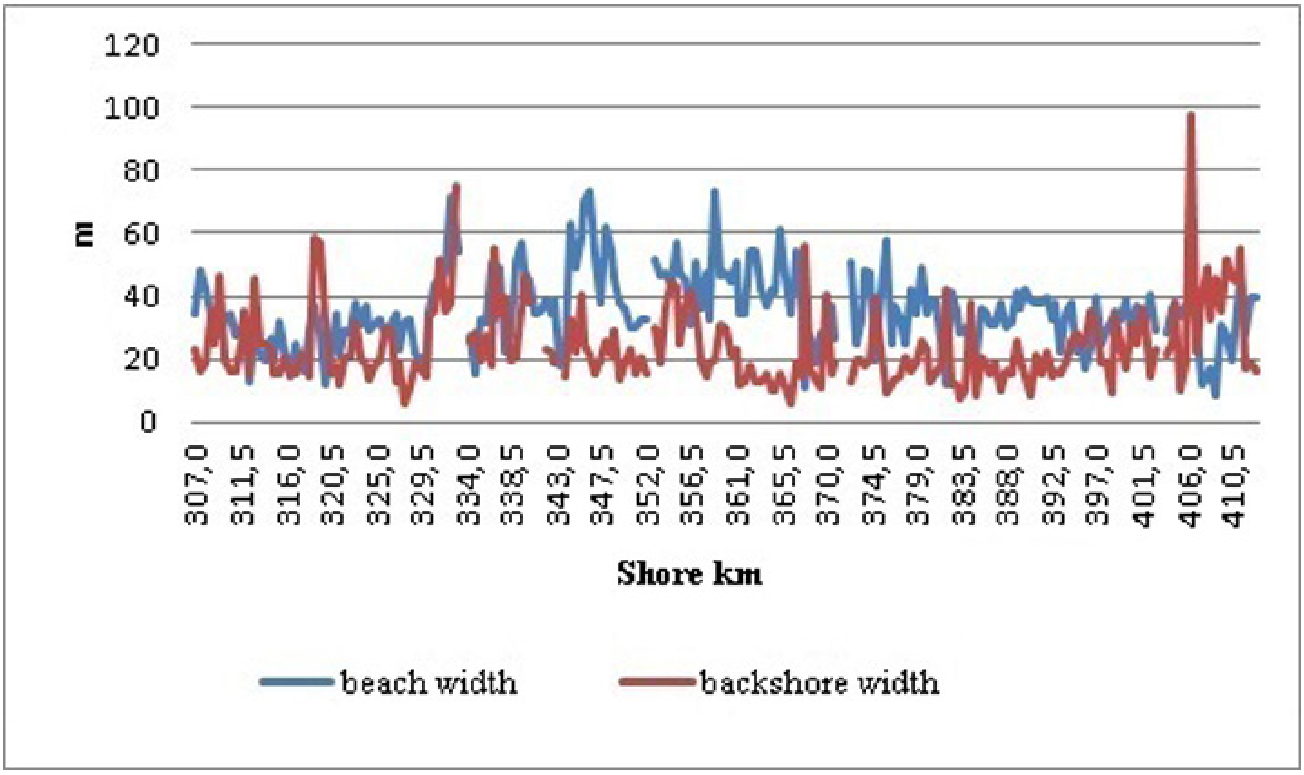

Fig. 11. Changes in the beach and the backshore's width in the Jastrzębia Góra – Jarosławiec section.

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Tab. I. Averaged shore parameters of all of the examined profiles.

	beach											dune/cliff				
	width [m]	height [m]	Cross-section area [m²]	Gradient	Filling [m³/m]	range of the water raises						width [m]	height [m]	Cross-section area [m²]	Gradient	Filling [m³/m]
						570	600	650	% 570	% 600	% 650					
All of the examined profiles: 0,0-36,0; 175,5-428,0																
MIN	6,5	0,8	2,909	0,006	0,272	0,5	1,5	2,5	0,051	0,164	0,297	2,2	2,1	9,950	0,027	0,367
MAX	143,2	3,0	151,287	0,462	2,004	138,9	143,6	145,4	1,061	2,444	2,778	155,0	41,0	2336,720	3,051	44,732
MEAN VALUE	38,236	1,913	34,434	0,059	0,899	13,281	23,353	32,894	0,358	0,618	0,866	26,954	7,784	159,139	0,240	5,287
STANDARD DEVIATION	15,902	0,261	16,533	0,030	0,203	9,302	12,479	14,665	0,168	0,193	0,173	15,924	5,622	213,257	0,213	3,710

Tab. II. Averaged parameters of the sandbar stretches

	beach											dune/cliff				
	width [m]	height [m]	cross-section area [m²]	gradient	filling [m³/m]	range of the water raises						width [m]	height [m]	cross-section area [m²]	gradient	filling [m³/m]
						570	600	650	% 570	% 600	% 650					
Hel Pennisula, profiles km: 0,0-36,0																
MIN	6,5	0,8	12,661	0,006	0,272	0,5	1,5	2,5	0,077	0,231	0,385	2,2	2,5	9,950	0,053	0,367
MAX	143,21	3	73,970	0,462	1,948	138,86	143,57	145,4	0,970	1,050	1,433	62,66	10,4	281,940	1,318	44,732
MEAN VALUE	45,861	1,942	41,161	0,052	0,931	15,208	28,676	39,016	0,310	0,598	0,835	22,966	5,752	90,088	0,219	4,349
STANDARD DEVIATION	17,626	0,376	13,234	0,052	0,214	16,375	18,917	18,601	0,133	0,168	0,134	11,971	1,351	57,467	0,175	4,896
Karwieńska Spit, profiles km: 134,5-149,0																
MIN	8	0,1	0,376	0,013	0,047	3,5	4,5	7	0,081	0,204	0,477	3	2,4	7,617	0,138	2,539
MAX	93,5	2,15	92,045	0,211	1,192	41,65	59,49	91	1,063	1,088	1,125	53,5	15,8	317,959	1,100	7,559
MEAN VALUE	41,942	1,86	39,033	0,057	0,897	14,312	23,413	36,058	0,384	0,581	0,854	23,227	6,679	111,446	0,382	4,426
STANDARD DEVIATION	21,946	0,387	21,891	0,038	0,204	8,707	13,485	20,743	0,195	0,169	0,122	14,245	2,4250	82,413	0,230	1,179
Sarbska Spit, profiles km: 175,0-181,0																
MIN	17,5	1,3	10,685	0,021	0,285	10,5	14,5	18,5	0,182	0,282	0,692	18	4,1	69,261	0,102	1,974
MAX	88,5	2,4	87,057	0,075	2,004	26	32	80	0,675	0,831	1,057	56,5	13,2	323,259	0,398	6,590
MEAN VALUE	39,875	1,813	34,714	0,051	0,861	15,583	22,250	35,458	0,450	0,631	0,908	34,792	7,671	155,072	0,180	4,444
STANDARD DEVIATION	19,157	0,363	23,974	0,015	0,431	4,348	5,146	16,434	0,169	0,195	0,107	14,204	2,738	83,901	0,084	1,340
Łebska Spit, profiles km: 184,0-201,0																
MIN	24,5	1	13,629	0,021	0,478	13	18,5	22,5	0,181	0,261	0,330	13,5	2,9	33,075	0,046	0,831
MAX	96,5	2	99,947	0,082	1,136	31	74	87	1,061	2,000	2,324	70,5	11,95	300,025	0,299	22,224
MEAN VALUE	48,943	1,759	41,104	0,040	0,804	20,229	30,529	45,157	0,474	0,714	1,003	34,286	6,243	158,121	0,142	6,250
STANDARD DEVIATION	19,304	0,236	22,294	0,014	0,142	4,923	9,924	16,780	0,213	0,360	0,424	16,119	2,091	85,133	0,067	5,538
Długie Lake Spit, profiles km: 206,5-209,5																
MIN	17	1,65	10,180	0,028	0,599	9,5	13,5	15,5	0,229	0,552	0,880	18	6,95	88,490	0,178	4,284
MAX	71,5	2	57,100	0,097	0,971	27	52	65	0,639	0,794	0,944	47	11	332,360	0,275	8,009
MEAN VALUE	37,357	1,907	30,235	0,059	0,783	16,214	25,929	33,929	0,473	0,710	0,911	33,286	8,886	199,122	0,217	5,776
STANDARD DEVIATION	17,495	0,159	15,981	0,022	0,125	5,936	12,098	15,699	0,153	0,102	0,020	10,246	1,639	88,923	0,037	1,190

this bar, which unlike the dunes, stands no chance of getting reconstructed.

There exist numerous natural and anthropogenic factors shaping the morpho- and lithodynamic processes taking place in the coastal zone. The main subjects to erosion are: the outermost breakwaters of the ports, port fairways, jetties and piers cutting across the coastal areas, protective bands encasing the dune slopes and cliffs, and other systems of shore preservation. Their impact on the directions and volume of sediments transportation in the coastal zone and over the backshore caused fragmentation, and further acceleration of the changes in the shore system. Included into the group of natural erosion centers can be also the channel forms occurring in the shoreface, remnants of the berm crests, offshore banks, monadnocks, or proglacial stream valleys and river valleys [16; 23; 24]. This is reflected in the expanding range of erosion in the sections devastated in the previous century, especially to the east of the anthropogenic centers. The situation will call for restoration of the sediments of the coastal zone and the shoreface by means of artificial nourishment, and enhancement of sustainable protection on the sections where there are investments in the hinterland. In accordance with the guidelines for seashore protection, the coastal processes should develop naturally on the other sections [9].

The conducted parameterization of the main forms of the shore and backshore make it possible to assess the state of the coastal forms and their endurance on the basis of a ranking analysis of the morphometric parameters in the system of various levels of the South Baltic Sea's coastal system. Combined with the assessment of the shoreface, it is crucial for identification of the erosion hazards, and evaluation of safety of shore's hinterland, as well as for beach maintenance and ensuring

Tab. III. Averaged parameters of the cliff stretches.

	beach											dune/cliff				
	width [m]	height [m]	cross-section area [m^2]	gradient	filling [m^3/m]	range of the water raises						width [m]	height [m]	cross-section area [m^2]	gradient	filling [m^3/m]
						570	600	650	% 570	% 600	% 650					
Cliff of Chłapowo (126,75-130,70), profiles km: 126,5-130,5																
MIN	19,98	1,8	18,310	0,042	0,916	4,53	7,86	15,92	0,135	0,234	0,538	26,24	15,82	300,030	0,308	6,678
MAX	49,42	2,1	50,070	0,096	1,359	11,13	22,7	44,71	0,386	0,545	0,905	192,41	65,85	6477,400	0,853	33,665
MEAN VALUE	30,411	1,961	31,453	0,071	1,026	8,550	14,018	23,835	0,299	0,468	0,772	84,649	37,810	1992,066	0,482	19,415
STANDARD DEVIATION	10,585	0,093	12,209	0,021	0,144	2,314	5,523	10,746	0,086	0,102	0,114	52,453	15,561	2019,850	0,179	8,352
Cliff of Jastrzębia Góra (131,70-134,50), profiles km: 131,5-134,5																
MIN	3,82	0,1	0,376	0,013	0,047	0,57	0,81	2,97	0,149	0,212	0,694	24	15,8	181,412	0,264	7,559
MAX	26,27	2	25,260	0,429	1,196	16	18,5	20,5	1,063	1,088	1,125	148,48	46,82	3965,850	0,658	26,710
MEAN VALUE	16,606	1,563	14,043	0,127	0,817	8,009	9,913	14,154	0,496	0,596	0,868	83,824	31,796	1747,767	0,426	18,862
STANDARD DEVIATION	7,837	0,712	9,922	0,137	0,450	5,035	5,750	6,443	0,333	0,317	0,152	41,983	9,077	1206,350	0,142	6,026
Cliff of Rowy(218,30-218,45), profiles km: 218,0-218,5																
MIN	19,5	1,7	14,246	0,056	0,731	11	15	18,5	0,507	0,690	0,873	25	4,25	113,157	0,077	3,577
MAX	35,5	2	28,474	0,087	0,802	18	24,5	31	0,564	0,769	0,949	33	6,4	118,038	0,176	4,526
MEAN VALUE	27,500	1,850	21,360	0,072	0,766	14,500	19,750	24,750	0,536	0,730	0,911	29,000	5,325	115,597	0,127	4,052
STANDARD DEVIATION	11,314	0,212	10,061	0,022	0,051	4,950	6,718	8,839	0,040	0,056	0,053	5,657	1,520	3,452	0,070	0,671
Cliff of Dębina (221,25-224,0), profiles km: 221,0-224,0																
MIN	11	1	8,948	0,037	0,590	8,5	11	13	0,362	0,536	0,866	24,5	7,65	122,068	0,151	4,982
MAX	54	2	46,273	0,091	0,869	25	33,5	47	0,773	1,000	1,182	155	38,85	1730,563	0,534	19,550
MEAN VALUE	35,000	1,771	26,740	0,056	0,753	18,429	24,286	32,429	0,559	0,733	0,961	76,000	27,000	1118,601	0,362	14,293
STANDARD DEVIATION	13,856	0,368	13,045	0,017	0,123	6,147	7,931	10,876	0,132	0,148	0,110	42,695	11,119	596,395	0,142	5,404
Cliff of Ustka (228,90-231,30), profiles km: 229,0-231,5																
MIN	10,5	1,5	7,561	0,038	0,582	5,5	6,5	9,5	0,429	0,619	0,786	26,5	6,1	120,693	0,155	4,554
MAX	53	2,1	37,703	0,162	0,849	28,5	37	49	0,654	0,808	1,000	57	20,8	745,247	0,351	13,075
MEAN VALUE	30,000	1,808	21,663	0,086	0,735	15,917	21,417	27,250	0,531	0,709	0,905	41,167	13,142	387,668	0,268	8,610
STANDARD DEVIATION	19,670	0,258	13,738	0,051	0,099	10,730	14,119	18,060	0,078	0,062	0,070	13,783	5,558	249,412	0,084	3,254

their functionality. Consequently, the right choice of the sections to be subjected to protection will enable elimination of hazards for the objects in the zone, and orderly management of the backshore strip that would guarantee preservation of the natural processes shaping the environment of the strip on the other sections of the shore.

In general, along the coast of the South Baltic Sea there occur a high irregularity and changeability of the character of the analyzed sections. In case of some of them, however, we can distinguish some clearly outlined subsections where the erosive processes predominate, which confirms that certain unfavorable changes are taking place there, the morphometric parameters are getting reduced, there is a deficit of sediments. There are also longer stretches where accumulation processes predominate, but there are very few of them across the entire coast (in the regions of the Łebsko and Brama Świny spits, the nourished fragments of the Hel Peninsula, and the Dziwnów Spit).

On the basis of the research similar to the ones presented herein, fragments that require protection can be determined more easily, and decisions what actions should be taken to make the protection efficient can be made. But before any actions may be undertaken, attention should always be first paid to the coast's hinterland in order to determine whether the preservation is sensible. The processes of erosion and accumulation are natural, and it would not be right to halt them altogether. Thus, the choice of sections of the coastal zone and backshore to be interfered with needs to be made after mature consideration.

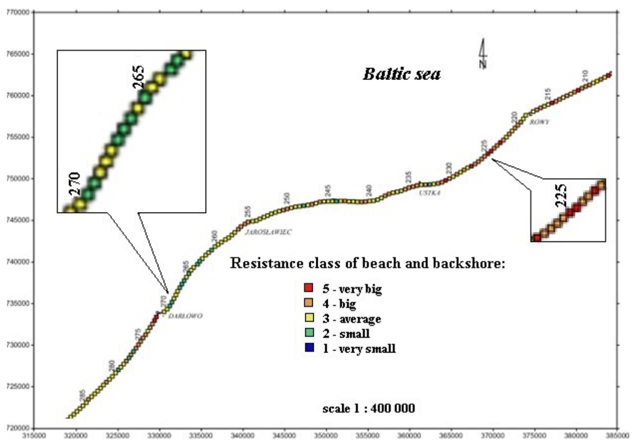

Fig. 12. Map fragment of the coast with marked shore resistance class on the basis of the monitoring measurements edge

Tab. IV. Morphometric classification of the beach and dune of the analyzed cross-sections.

DUNE		BEACH	
Classification	No. of the profiles / %	Classification	No. of the profiles / %
very low	19 / 3.7%	very narrow	52 / 7.8%
low	125 / 24.1%	narrow	150 / 22.4%
average	258 / 49.9%	average	204 / 30.4%
moderately tall	107 / 20.7%	wide	264 / 39.4%
tall	8 / 1.5%		
Total:	517	Total:	670

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