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Morpholithodynamic conditions of the tip of the Hel Peninsula, the Baltic Sea

by

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Abstract

The Hel Peninsula is a 35 km long spit that extends into water depths of almost 60 m. Unlike most sandy barriers, the distal end of the Hel Peninsula is prograding into the deep water. This affects unique conditions for the evolution of this section of the Peninsula. The aim of this study is to determine the morpholithodynamic changes on the tip of the Hel Peninsula. Shore studies were performed in 2006-2008 and 2012. Measurements included: beach profiling, determination of shoreline and dune base line positions, and collection of sediment samples. The different nature of the eastern, central and western part of the Hel tip is evident. The eastern part is accumulative, the central part is variable with the general nature of strong and differently directed redeposition and accumulative periods, while the western part is highly erosive.

Key words: morpholithodynamics, beach processes, sandy barrier, Hel Peninsula, Baltic Sea

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Introduction

Sandy barriers exist along the low shores with gently sloping bottom of the foreshore. These are various elongated accumulation forms which separate, in whole or in part, shallow-water reservoirs (lagoons) from the open sea. The most important in the formation of sandy barriers is the abundance of the delivered material and the possibility of its transportation and deposition, mainly due to the processes related to the movement of sea water (i.e. waves, currents, tides) in relation to the nature of the short- and long-term changes in the sea level (Leontiev et al. 1982, Reading&Collinson 1996, Davis&Fitzgerald 2004, Bird 2008, Huddart&Stott 2010).

The Hel Peninsula is a large sandy barrier partly separating the Gulf of Gdańsk from the open waters of the Baltic Sea. It is a spit about 35 km long and from 150 m (proximal part) to about 3 km (distal part) wide. This is an example of a barrier created by the processes associated with the waving of the non-tidal sea. Its structure and development are related to the transport of the material, both along and across the shore. As a result of the postglacial transgressions, along with the progressive abrasion of the cliffs of the adjacent to the west moraine plateau, the Hel Peninsula was formed from the sediments supplied by the longshore drifts. At the same time, it was extended and shifted toward the south (Bączyk 1963, Rosa 1963, Tomczak 1995, 2005). The accretion rate was rapidly decreasing because of the sands transported by the longshore drifts deposited at the progressively greater depths (Tomczak 1995, Uścinowicz 2003). The south-eastern part of the Peninsula was also broadened by accreting toward the north-east. The stages of its growth are delimited by the radiocarbon dates of the peat of 5640±120 BP (km 23 of the Maritime Office [MO]), 3000±60 BP (km 28 MO) and 1760±100 BP (km 31 MO) (Tomczak 1995). The latter date indicates the length of the Peninsula at that time: it could have been shorter by about 2-3 km than at present. The Hel Peninsula is a unique form among other sandy barriers, as it is prograding into the great water depths of the Gulf of Gdańsk. The bottom of the distal part dips with a steep slope to a depth of about 60 m (Rucińska-Zjadacz&Rudowski 2009).

The previous studies conducted on the Hel Peninsula provided important information about the coastal processes (Bączyk 1963, Furmańczyk et al. 1992, Furmańczyk&Musielak 1993, Furmańczyk 1995, Zawadzka-Kahlau 1999, Łęczyński 2009, Stachurska 2012). These studies, however, focused mostly on the shoreline displacement of the sea-facing coastal zone of the Hel Peninsula. The first descriptions of the changes in the position of the coastline of the tip of the Hel Peninsula, based on the comparative analysis of the cartographic materials, was presented by H. Wünche (1904) who compared maps from 1844 and 1903 and showed that the tip of the Hel Peninsula shifted both toward the south and east. Subsequent publications presented changes in 1803-1919 (Łęgowski 1925) and 1903-1956 (Bączyk 1963) indicating the same direction of the growth, though with smaller changes than those indicated by H. Wünche. According to J. Bączyk (1963), in the period of 1903-1956, the tip of the Hel Peninsula, and thus the Hel Peninsula itself, was extended by 5 m to the south and, at the same time, the coastline to the west of the Hel tip was shifted inland. The average rate of changes of the Hel tip in 1908-1972 was cartometrically calculated at 0.654 m (Grygorenko 1972). The accumulation character of the sea-facing shores of the Hel tip is also confirmed by the comparative analysis of aerial photographs from 1957 and 1991 (Furmańczyk&Musielak 1993, Furmańczyk 1995).

In 2001-2002, the Polish Geological Institute performed measurements of the position of the Hel tip shoreline with the GPS equipment (Graniczny et al. 2004). The measurements were performed four times: in October 2001 and in March, May and September 2002. The biggest changes occurred on the western side of the Hel tip. The coastline retreated there by approx. 20 m during a year. The changes in the eastern section of the tip were smaller. The growth and recession of the beach in this area in the reported period did not exceed 5 m. The comparison of the measurements from 2001-2002 with the topographic map at the scale of 1:10000 from the year 2000 shows a recession of the shore by about 50 m.

The only research carried out so far in the area of the Hel tip concerned changes in the shoreline displacement. It is difficult to compare the studies quantitatively, because they were all carried out by different methods and with different materials and

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accuracy of the measurements. Determination of morphological and lithological changes occurring on the Hel tip is important because it can be regarded as an indicator of the status and development of the whole Hel Peninsula. Determination of the morpholithodynamics of the Hel Peninsula tip will help to determine the course of its current development and indicate the processes and determining factors. The aim of this complex study is to determine the morpholithodynamic changes of the distal section of the Hel Peninsula, i.e. the Hel tip.

Study area

The study area is located in the western part of the Gulf of Gdańsk (the southern Baltic Sea), on the southern tip of the Hel Peninsula (Fig. 1A). The research area included the beach from the dune base line to the water line of the H35 to H36 km stretch of the Maritime Office's mileage up to the seawall at the harbor breakwaters in the town of Hel.

In the Hel tip area, there are contemporary coastal berms and dunes with older berms in its hinterland (Tomczak 2005). The former berms are located in the inner part of the Peninsula in the form of elongated elevations of up to 5 m, reflecting the location of the former shorelines that indicate a gradual build-up of the Peninsula from Jurata to Hel (Pawłowski 1922, Bączyk 1963, Rosa 1963, Tomczak 2005).

The relief of the sea bottom around the Hel tip clearly shows three morphological units: an offshore shoal at a depth of about 2-4 m, relatively flat "shelf" – a quite steep slope dipping to a depth of over 50 m as well as its flat and even foreground. The offshore shoal is a form of a depth of about 2-4 m. Its width on the eastern side does not exceed 50 m, while on the western side it is more than 500 m. The underwater slope is relatively steep. The maximum slope rating is locally almost 20° on the western side of the tip, while the average is about 5°. At a depth of 50-58 m, the slope gently transits into the slope base, which is almost flat, level surface (Rucińska-Zjadacz&Rudowski 2009).

The tip of the Hel Peninsula is exposed to strong

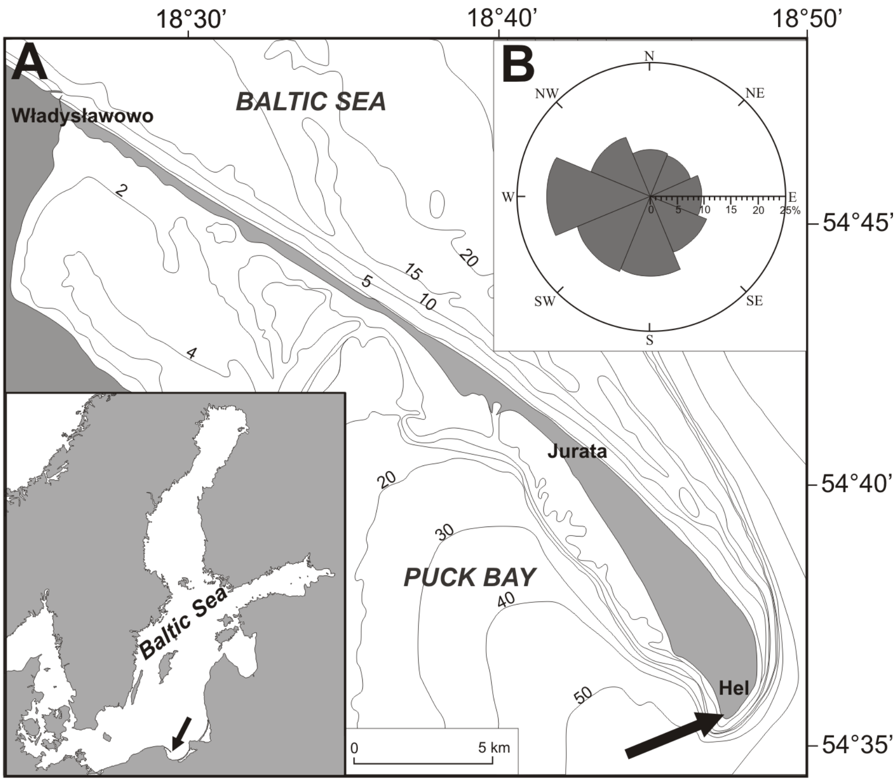

Figure 1

A: Location of the study area; B: Annual frequency of wind directions [%] in Hel during the period of 1986-2005 (Pilarski et al. 2011)

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waving coming from almost every direction. The area of the distal end of the Hel Peninsula is dominated by WSW, W and NW winds (Fig. 1B); the most frequent are those from the west (Miętus&Jakusik 2005, Pilarski et al. 2011).

The surface currents induced by the west wind move along the shores of the Hel Peninsula generally in an easterly direction up to the zone of disturbance of their course in the area of the Peninsula tip, especially on its inner side, less so from the side of the open sea. The turbulences on the inner side of the Peninsula are very strong and this is where the speed of the currents reaches its maximum (Kowalik 1974, 1990).

The existing wave conditions around the Hel tip are unique to the Polish coast; they result from the seashore exposure and the associated bottom relief. There is a significant and rapid change in the depth close to the shore (Rucińska-Zjadacz&Rudowski 2009) where a substantial transformation of the shape and the size of deep-water waves takes place: they suddenly get transformed into shallow water waves. Consequently, there is no significant dissipation of energy of waves approaching the shore. In addition, waves, which are subject to diffraction, refraction and interference, create specific systems of wave crests. These conditions are of exceptional, yet not described, hydrodynamic situation around the tip of Hel Peninsula.

Materials and methods

The research was conducted in 2006-2008 and in 2012. The investigations involved the construction of cross-shore profiles, studying the displacement of the water line and the dune base line, grain-size analysis by dry sieving, and the lithodynamic interpretation of the results.

The position of the water line and the dune base line was determined using the DGPS system. The water line as adopted in this study is a line located in the middle of the swash and backwash zone. The measurements of the water line were performed four times in 2006, 2007, 2008 and 2012; the dune base line position was measured three times in 2006, 2008 and 2012. The beach morphological profiles (Fig. 2) were performed at five fixed points (HEL I, HEL II,

Figure 2

Location of beach profiles HEL I – HEL V. Location of dated soil (14C) indicated by the star (photo: P. Młodkowski – ww.locolot.pl, 2007)

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HEL III, HEL IV, HEL V) from the dune base to the backwash zone. Each time the sea level was checked at the port of Hel to introduce a correction associated with a difference in the sea level so that all profiles have the same benchmark.

The samples of the surface sediment were collected along the profiles from the morphological forms of the seashore: the swash zone, a berm (if present), the central and upper parts of the beach and the foredune base. All the sediment samples were initially described macroscopically in the field, taking into account the fraction, sorting, moisture, color and admixtures. A hundred and sixteen sediment samples were sieved through a sieve set with an interval of 0.5 phi (from -2 to 4 in the phi scale). Based on the results of the sediment grain size analysis, the name of the sediment as well as the statistics of the particle size distribution were determined. The type and the name of the sediment was based on the classification triangle for sands (after Mojski 1995). The statistical indicators of the particle size were calculated with the GRADISTAT program 4.0 (Blott&Pye 2001) using the method of moments in the phi scale (Krumbein&Pettijohn 1938).

The natural outcrops in the undercut dunes were described; this is where fossil soil was found (Fig. 2). The fossil soil sample was sent to the Radiocarbon Laboratory of the Institute of Physics of the Silesian University of Technology in Gliwice, where absolute dating was performed using the carbon isotope ^{14}C with the conventional radiometric techniques.

Results

Morphology

Monitoring the changes in the water line position, especially its retreat, based on the DGPS measurements, is effective in short periods of time (Graniczny et al. 2004). These changes may reflect longer developmental trends, or result from the temporary sea level or short-term sea level changes between storms. The measurements based on recording the changes in the dune base line are much more reliable. This is because they are the least sensitive to short-term changes. The shore accumulative-abrasive trends are also described by the analysis of the cross-shore profile shape. The so-called complete profile is a concave-convex profile with a varied relief interpreted as an accumulation beach profile. The incomplete profile is a generally concave profile, sloping toward the sea interpreted as the profile of the erosional beach (Leontiev et al. 1982).

The shore of the Hel tip is a very dynamic form with significant changes in the position of the seashore elements, i.e. the dune base line and the water line (Dudzińska-Nowak&Furmańczyk 2005) as well as changes of the accumulative and abrasive nature.

Coastal dunes, which are in the direct background of the Hel tip, have developed in their classical form of strips of frontal dunes as well as fixed dune ridges – overgrown with pine forests – at the hinterland.

The border between the dune zone and the seashore, which is a base line of the dunes, is clear and well visible in places with a relatively fresh abrasive undercutting created by heavy storm surges. This situation usually occurs in the western part of the Hel tip. In the remaining part of the shore, an abrasive undercutting develops during storms, but it is usually quickly softened and backfilled with sand of the emerging frontal dunes.

The entire shore area in the eastern part of the Hel tip is taken by the beach of a considerable width, sometimes of over 100 m. There are series of coastal berms and depressions left by beach lagoons. In the western part, the beach is narrow, on one side sloping toward the sea at an angle of a few degrees, and bordered by a constantly occurring fresh abrasive undercutting in dune ridges.

The field measurements of the position of the water line and the dune base line were made with DGPS. The water line shows short-term changes, which are mainly dependent on the level of the sea, the state of the sea, the wind force and direction as well as wave conditions and the last storm. Nevertheless, the retreat of the shores can be observed on the western side of the Hel tip (Fig. 3). During the study period, the shore from the Bay of Gdańsk side retreated by up to 40 m.

The dune base line is much less sensitive to short-term changes. Between September 2006 and February 2012, the retreat of the abrasive undercut of dune ridges (in the western part of the Hel tip arranged perpendicularly to the shore) amounted to ca. 25 m (Fig. 4), which confirms that the direction

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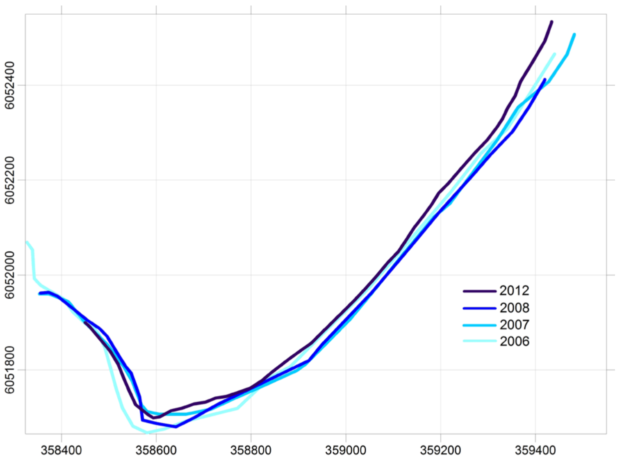

Figure 3

Shoreline displacements in the years: 2012, 2008, 2007, 2006

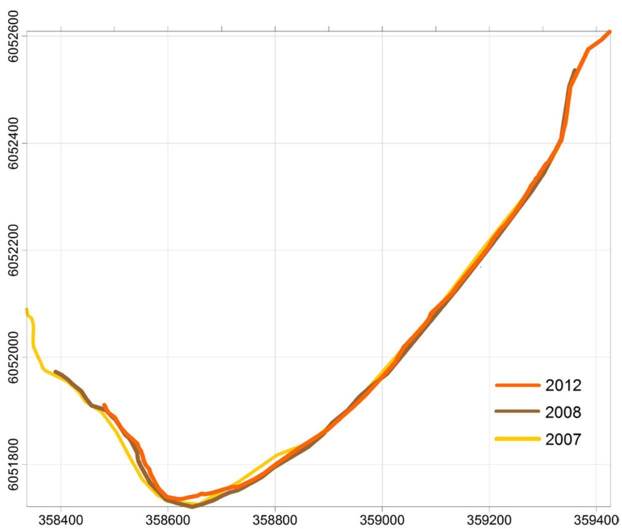

Figure 4

Dune base line displacements in the years: 2012, 2008, 2006

of change in this region is constant and the trends of erosion at this point are long-term. Changes on the sea-facing side were smaller: locally the dune base line moved toward the sea by about 10 m. In this area of the Hel tip, the beach has been overbuilt, and the dune base line got shifted toward the sea by an average of a few meters.

The most variable region of the Hel tip is its central, southernmost part. During the study period, the changes were significant and referred to both beach abrasion and accretion. This is due to the very high dynamics of this part of the Hel tip. The outline of the shoreline in this section is undergoing rapid and frequent changes depending on the conditions, the sea level and the wind direction.

The analysis of the morphological profiles of the beach made in May and September 2006, May and October 2007 and in May 2008 showed that the width of the beach changes (Fig. 5). By far the widest beach was in the area of profile HEL V. The maximum width of 125 m was recorded in the spring of 2007, and the minimum of 76 m in the spring 2008. The smallest width of the beach was recorded on the western side of the Hel tip, in the region of profile HEL I. In the analyzed period, the width of the beach did not exceed 20 m (in the spring of 2006 and 2008). The smallest width of 10 m was recorded in the autumn of 2006.

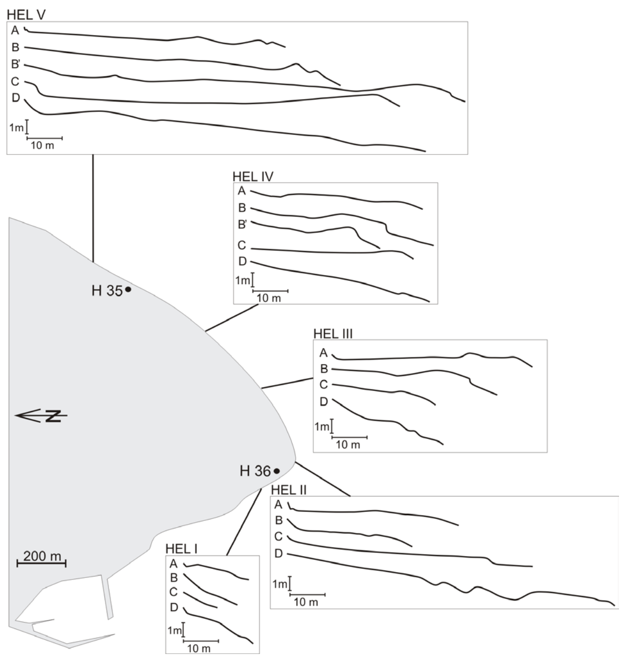

Figure 5

Beach morphological changes in HEL I – HEL V profiles in the period of 2006-2008; A – May 2008, B – October 2007, B' – May 2007, C – September 2006, D – May 2006

The hinterland of profile HEL I is composed of the abrasively undercut and wooded dunes (Fig. 6). In the analyzed period, the beach was mostly narrow, more or less inclined toward the sea, with the incomplete profile (*sensu* Leontiev et al. 1982). Often, as e.g. in the autumn of 2006 and 2007, the beach was completely covered by the swash (Fig. 6). The largest width of the beach – about 20 m – was

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Figure 6

Abraded dunes in the area of HEL I profile (September 2007)

observed in the spring of 2006 and 2008. Although the beach was of a similar width, the abrasively cut dune base line receded by several meters at that time.

At the hinterland of the dunes of profile HEL II, located at the central part of the Hel tip, there are steep sand dunes covered with lyme grass (*Leymus arenarius*), shrubs and trees. The greatest width of the beach of about 93 m was measured in the spring of 2006, while the smallest of 36 m in the autumn of 2007. The beach in this area had a complete profile throughout the study period (Fig. 5). Well-developed berms and beach lagoons were often observed. Microforms, such as small swash marks and beach pits (*sensu* Rudowski 1962), formed on the berms. At the bottom of the lagoon, current ripple marks developed. After storms, the dunes were usually abrasively undercut, and on the upper beach, traces of the storm sediment influx were visible (Fig. 7) in the form of accumulation of sticks, seaweed, fish skeletons and fish remains, rubbish (tires, bottles, boxes) and large logs. During the strong wind on the beach in the area of profile HEL II, patches of large accumulation of boulders were uncovered, and on the dunes, aeolian ripple marks with patches of aeolian pavement were formed. In the spring of 2008, the entire width of the beach was covered with large depressions and abrasive undercuts arranged both along and across the beach (Fig. 7).

At the hinterland of the beach in the vicinity of profile HEL III, there are sand dunes covered with lyme grass, beach pea (*Lathyrus japonicus*) as well as shrubs and trees. The narrowest beach of 30 m was observed in 2006, while the widest, i.e. 58 m in spring 2008. The beach in this area had generally a complete profile with one or two well-developed berms and a periodically occurring beach lagoon. The steepest slope was observed in the spring of 2006 (Fig. 5). After storms, the beach was covered with sticks and rubbish, sometimes even up to the very base of the dunes.

At the hinterland of profile HEL IV, there are sand dunes covered with lyme grass, shrubs and trees. During the study period, the smallest beach width of 36 m was noted in the spring of 2007; the remaining measurements were similar and were approx. 50 m (Fig. 5). In general, the beach in this area is accumulative and the most stable of the entire study area with a complete profile and varying berms on which swash marks and beach pits often occurred. With little stronger waves, the beach berm was undercut by the swash (e.g. in the autumn of 2007). The undercutting had a height of about 40 cm. Periodically, patches of aeolian ripple marks were visible on the upper beach.

At the hinterland of the beach in the area of profile HEL V, there are sand dunes covered with lyme grass, shrubs and trees. The beach here is a typical accumulation beach, with a complete profile and the largest width in the entire study area throughout the entire analyzed period. The largest width of the beach occurred here from the spring of 2006 to the spring of 2007 and was over 100 m (max. 125 m). The smallest width of 76 m was recorded in the spring of 2008. The surface of the beach was mostly poorly diversified. The land-facing

Figure 7

Undercut dunes and trash thrown by storm in the area of HEL II profile (May 2008)

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slopes of the beach berms were usually gentle, while the sea-facing ones – steep. They were covered with clear swash marks, often built of coarser sediment, as well as sea grass, sticks and rubbish. In the spring of 2007, there was an initial dune field visible on the upper beach (Fig. 5). Its presence indicates severe aeolian accumulation processes. The upper beach was covered with aeolian ripple marks throughout the study period.

A different morphological character of the eastern, central and western sections of the Hel tip is clearly visible. In the eastern part, the beach has a generally concave-convex profile with a varied relief – there are beach berms and beach lagoons, and the initial dunes develop. The central part of the Hel tip is diversified. Its morphology is strongly determined by the instantaneous meteorological and hydrodynamic conditions. In the western part, the beach is narrow with a concave profile, sloping toward the sea along its entire width, and is limited by a constantly occurring erosive undercut of the dune. Abrasion of the dune also occurs in the eastern part of the Hel tip during heavy storms, but undercuts are quite quickly alleviated and supplied with sand of the newly emerging foredunes in the post-storm season.

Granulometric framework and lithodynamic conditions

To determine the lithodynamic conditions of the distal end of the Hel Peninsula's coastal zone, a comprehensive analysis of three grain-size indices (mean, standard deviation and skewness) was performed (after Gao et al. 1994, Gao&Collins 2001, Mycielska-Dowgiałło 2007, Mycielska-Dowgiałło&Ludwikowska-Kędzia 2011). Such an analysis determines the directions of the sediment transport, the conditions of deposition, redeposition and transit, as well as the dynamics of the environment in which the material was deposited (McLaren&Bowles 1985, Racinowski et al. 2001, Martins&Barboza 2005). The high values of the average diameter, low values of the standard deviation and positive skewness values of beach sediments are generally interpreted as the conditions favoring the deposition, while the opposite trends in the changes of values – as the conditions favoring the redeposition or erosion (Racinowski et al. 2001).

The nature of the coastal dune sediments results from its complex structure. Their base is made of relatively poorly sorted sands, grained to a varying extent and containing a coarse fraction and isolated boulders. The upper, proper aeolian superstructure is made of fine-grained sands with sections of well-sorted and medium-grained sands, with characteristic cross-stratification.

On the western side of the Hel tip, after one of the storms, a fossil soil level was uncovered in a fresh abrasive undercut of the dune ridge. The soil – with a thin organic level and of initial character – was subjected to radiocarbon dating in the Gliwice Radiocarbon Laboratory. The dating result was 495±45 years BP (Table 1).

The beach in the study area is composed of medium- and coarse-grained sands which are moderately- to well-sorted (Table 2). In the eastern part of the Hel tip, the beach is composed of medium-grained sands, well-sorted and distributed symmetrically and moderately steep. Deposits of the central part are mostly coarse-grained with medium-grained sands on the upper shore, while the foreshore also includes gravel and sandy gravel. Generally, they are moderately- to well-sorted. The particle size distribution is slightly negatively skewed. The western part is dominated by coarse-grained sand, moderately well-sorted and with fine gravel on the foreshore. It is slightly better sorted on the upper shore than on the foreshore. The particle size distribution is slightly negatively skewed.

Table 1

Fossil soil dating results (Radiocarbon Laboratory, Institute of Physics, Silesian University of Technology, Gliwice). Location of the soil in Fig. 2.

Sample name	Lab. Gd- No.	Age ^{14}C (BP)	Calibrated age range 68%	Calibrated age range 95%
HEL 1/3a	Gd-20027	495±45	1405 (68.2%) 1450 calAD	1315 (11.4%) 1355 calAD 1385 (84.0%) 1475 calAD

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Table 2

Beach sediments statistical grain size parameters in the region of morphological profiles (location in Fig. 2); a – average, min – minimum, max–maximum values; M1 – mean, M2 – standard deviation, M3 – skewness

	M1		M2		M3	
	a	min max	a	min max	a	min max
HEL I	0.65	-1.10 1.20	0.51	0.32 1.08	-0.21	-1.14 0.44
backshore	0.91	0.69 1.14	0.45	0.32 0.52	-0.26	-1.14 0.25
foreshore	0.24	-1.10 1.20	0.70	0.37 1.08	-0.15	-0.86 0.44
HEL II	0.89	-1.06 1.37	0.53	0.29 1.18	-0.45	-1.75 1.43
backshore	0.99	0.15 1.37	0.53	0.29 1.18	-0.53	-1.75 1.43
foreshore	0.58	-1.06 1.27	0.59	0.31 1.00	-0.39	-1.59 0.42
HEL III	0.92	-0.85 1.36	0.53	0.33 1.31	-0.66	-1.93 1.32
backshore	1.08	0.80 1.36	0.48	0.35 0.78	-0.53	-1.87 1.32
foreshore	0.49	-0.85 1.36	0.68	0.33 1.31	-0.98	-1.93 0.26
HEL IV	1.27	0.24 1.72	0.42	0.23 1.11	-0.91	-1.81 0.89
backshore	1.31	0.69 1.72	0.39	0.23 0.57	-0.75	-1.81 0.89
foreshore	1.17	0.24 1.51	0.51	0.24 1.11	-1.33	-1.70 -0.82
HEL V	1.44	1.04 1.65	0.39	0.27 0.79	-0.30	-1.43 1.40
backshore	1.49	1.04 1.65	0.37	0.27 0.79	-0.22	-1.43 1.40
foreshore	1.23	1.14 1.41	0.47	0.36 0.53	-0.98	-1.52 0.56

The value of the average diameter (M1 in the phi scale) of the beach deposits decreases from profile HEL V – the average value of 1.44 – to profile HEL I – the average value of 0.65 (Table 2, Fig. 8). The average diameter of the deposits in the region of profile HEL V shows a much smaller range of the values (1.04 – 1.65) compared to the remaining area, in particular in the region of profiles HEL I and HEL II where the range of the average diameter is much wider, while coarser fractions predominate on the foreshore, reflecting the strong energy environment (Racinowski et al. 2001). Moreover, in the central and western parts of the Hel tip, large clusters of pebbles and debris are exposed during strong winds or after storms. They are mainly of anthropogenic origin, and their presence is primarily associated with washing and destruction of military fortifications, and – to a lesser extent – with the transport by the ice floe. The most common crushed anthropogenic material is brick, concrete, coke and slag. It is mixed with beach pebbles.

The deposits of the eastern part of the Hel tip are a bit better sorted than those in the central and western parts, although the average values are within the range of moderately- and well-sorted sediments (Fig. 8). The increasing value of sorting to a moderately well-sorted value may be a manifestation of greater variability in the dynamics of the sedimentary environment in this area of the Hel tip. In this region, the deposit is in transit or at

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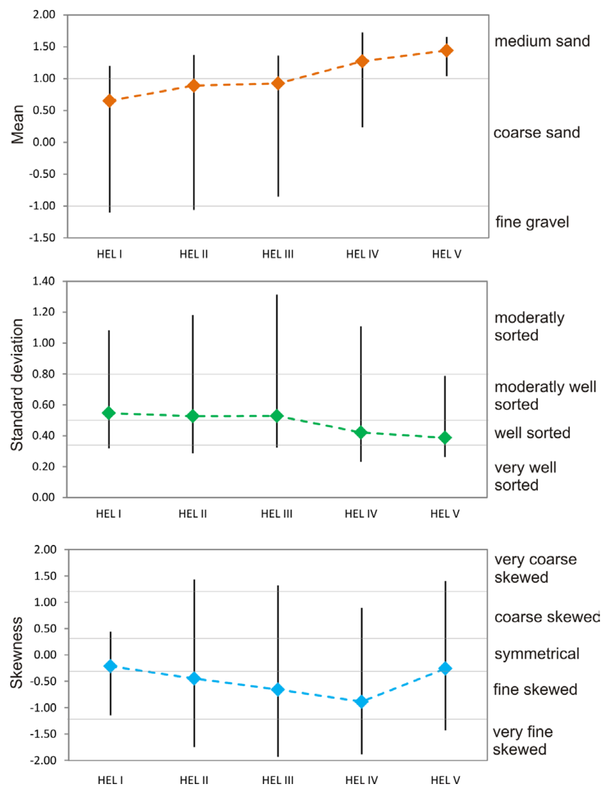

Figure 8

Differentiation of beach surface sediment values of statistical grain size parameters (in phi units) in the area of HEL I – HEL V profiles (location in Fig. 2); maximum, mean (colored markers) and minimum values

the stage of redeposition. In the eastern part where sorting is better, the deposit is either in transit or at the stage of deposition. In the entire research area, the skewness shows negative values. This reflects the elimination of finer fractions from the sediment by washing away or blowing out, and it is quite typical of beach sediments (Racinowski et al. 2001).

Discussion

The changes taking place on the Hel Peninsula result from the manner it grows and transforms. The material for building the Hel tip comes from the sea-facing shores of the Hel Peninsula. It builds the beaches of the Hel tip and causes an increase in the length of the Hel Peninsula, both in its above-water and underwater parts. The growth of the Hel Peninsula in its above-water section requires a corresponding increase in its underwater base.

The former beach berms in the region of the Hel tip in the form of elongated elevations of up to 5 m reflect the location of the former shorelines that indicate a gradual build-up of the Hel Peninsula from Jurata to Hel (Pawłowski 1922, Bączyk 1963, Rosa 1963, Tomczak 2005). The dune ridge, in which the dated fossil soil was found (Fig. 2), is now 300-350 m away from the parallel coastline (measuring from the axis of the Hel tip). The date, obtained from the fossil soil with a thin organic horizon and the initial profile, indicates that about 500 years ago the Hel Peninsula reached that place. The growth rate of the Hel Peninsula, based on the analysis of the cartographic materials, is estimated at 0.5-1 m per year over the last 200 years (e.g. Wünsche 1904, Łęgowski 1925, Grygorenko 1972).

The threat to the development of the Hel tip is posed by the intensified wave action and the growing deficit of sediment (Tomczak 2005). The sediment deficit is caused by natural and anthropogenic factors as a result of disappearance of the potential alimentation sources for the Hel tip and the entire Peninsula. The supply via the longshore transport from the neighboring shore section weakens. A large part of the sedimentary material from the abraded cliff of Kępa Swarzewska (adjacent to the west of the peninsula) washed into the sea (Jankowski 2005a, b; Rudowski&Wodzinowski 2005) and cannot provide a sufficient sediment supply for the bottom of the foreshore of the Hel Peninsula, regardless of a blockage of the Władysławowo port breakwaters.

Furthermore, the strengthening and building up of the shores to the west of Władysławowo as well as the protection of the shores of the very Hel Peninsula reduces the sediment supply (Tomczak 2005, Rudowski et al. 2009). Despite of the sediment deficit observed on the Hel Peninsula, there is an almost continuous supply of sediment material on the sea-facing shore of the Hel tip, while the bay-facing shore is retreating and experiences the sediment deficit. Due to a relatively great depth around the distal end of the Hel Peninsula, and hence small wave refraction, the transport of sediment on the bay-facing shores does not exist. A similar situation is described in the area of the distal end of Long Point on Lake Erie which is currently being built into the water that is more than 40 m deep and the distal bayside receives very little, if any of the sediment transported along the tip of Long Point (Davidson-Arnott&Conliffe Reid 1994).

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Conclusions

The changes of the Hel tip seashore, determined on the basis of the morphological profiles, changes in the position of the water line and the dune base line as well as lithodynamic conditions, allow determination of the developmental trends of the Hel tip seashore. A diverse morpholithodynamic nature of its eastern, central and western parts is evident. The eastern part has a redeposition-deposition character with a tendency to accumulate medium-grained sand. The central part of the Hel tip is diverse; generally it shows a strong and differently directed redeposition nature with periods or episodes of accumulation. The western part manifests its redeposition-erosive character and is eroded by waves and currents. The energy of waves approaching the bay-facing shores of the Hel tip cannot dissipate due to the relief of the seabed at the tip. The edge of the coastal shoal along the western side of the tip is located about 500 m from the shore; it is a sharp edge between a steep slope and the shallow and levelled bottom of the shoal (Rucińska-Zjadacz&Rudowski 2009). Thus, the waves break close to the shore, and only a small part of the energy is dispersed. Furthermore, most of the sediment supplied from the sea-facing shores get directly to the deep bottom along the extension of the Hel Peninsula's axis. All these factors, coupled with the abrasion of the bay-facing shores, which are usually not reconstructed after storms due to the sediment deficit, may cause "narrowing" of the distal end of the Hel Peninsula.

The shore of the Hel tip is directly protected only at its bay-facing side. Currently, the destroyed seawalls have been replaced with new embankments. The remaining area of the Hel tip requires no protection, but its state indirectly results from anthropopressure around the entire Hel Peninsula. The most significant threat to the Hel tip is the change in the supply of the sedimentary material. With the current sediment supply, the state of the sea-facing shores of the tip will remain stable.

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