DETERMINATION OF CHANGES OF SOUTH BALTIC SPITS AND CLIFFS

Abstract

Observations and cartometric measurements along the South Baltic Coast on spit forms and cliff coast sections indicated an increase of erosion processes.

Basing on long and short term trends, the prediction of the coastal changes on selected stretches of spits and cliffs due to sea level rise was attempted.

1. INTRODUCTION

The intensifying processes of sea coast destruction endanger, to the largest degree, the spit forms and cliff coasts; this results in increased risk level to coastal hinterland and its infrastructure.

History of coastal evolution indicates that erosion and accretion processes along accumulative (dune) coasts are of cyclic character, allowing for restoration of destroyed forms. Process of cliff erosion results in irretrievably loss of land. At the present and the predicted rate of sea level rise [5, 7, 20], during the nearest 100 years, increased erosion of the South Baltic coast is expected.

The contemporary trends of evolution of coastal forms was evaluated basing on cartometric measurements on maps of various scale from the last 100 years and 20 years (1960 - 1983). 1:25 000 Prussian and Polish maps, 1:25 000 plans of the technical belt, and 1:5 000 photointerpretation maps were used [31, 32]. Obtained results allo-
wed to determine the erosion/accretion system of the South Baltic coast [33], the elements of which are also the spit and cliff segments of the coastline.

The paper presents a morphologic characteristic of spits, and the trend and magnitude of coastal changes, which were determined within the boundaries of contemporary reach of coastal lakes. The characteristic of cliff coasts was presented by Subotowicz [28]. Cliff stretches are taken into account in accordance with that characteristic, and their trend and evolution is evaluated basing on own data.

Rates of coastal change, occurring within various temporal scales, are an indispensable element necessary for forecasting coastal erosion, and should be taken into account in coastal management and protection plans. For selected stretches of the coast, “safe investment boundaries” have been calculated basing on the obtained rates of coastal changes.

2. MORPHOLOGICAL CHARACTERISTIC OF SPITS

2.1. VISTULA SPIT

The Vistula Spit coast is an aligned accumulative coast of lagoon subtype [14]. Its origin is connected mainly with wave processes.

The spit is formed by a belt of dunes 500 m wide, of up to 30 m height above MSL. It consists of a system of old fordunes, secondarily transformed, consolidated by a soil cover and by vegetation [23]. Origins of dune complexes of the Vistula Spit are connected with the Postlitorina period, during which littoral accretion occurred on top of the old coastal slope. The thickness of littoral deposits was 12-15 m, and relative height of recessive dunes was 1.5 to 2, at maximum 3, metres. After the recession, in conditions of relative sea level stabilization, the youngest dunes of the Spit developed, covering the older ones [23]. The Vistula Spit fordunes are dunes of medium and moderate height of 5-8 and 8-12 m. In the area of Piaski dunes do not exceed 8 m, on the stretch Stegna - Krynica Morska dunes are over 8 m high. The average width of beaches, built of fine and medium sand, is about 40 m, allowing to classify them as wide beaches. Erosion of the Vistula Spit coast is mainly connected with dispersion of kinetic energy of wave runup, i.e. with mechanical abrasion [14].
2.2. LAKE ŁEBSKO SPIT

The Lake Łebsko Spit is a part of coast formed under the influence of coastal and eolic processes [10]. The Spit limits from the north the area of the Gardno-Łeba Lowland, most of which is taken up by organogenic accumulation lowlands and coastal lakes. The contemporary phase of evolution began at the break of XV and XVI-th centuries [8]. Increased intensity of eolic processes occurs in the central part. A stretch of 5 km length and 1 km width is built of moving dunes, consisting of barkhans and arc-barkhan dunes, moving at a rate of 3.5-9.7 m/year [13]. In the west and east parts of the Spit are systems of parabolic dunes, developing together with vegetation. Mobility of these dunes is rather low - 3 m/year [13]. In the west part of the Lake Łebsko Spit, fordunes are of 11-12 m height, behind which there is a belt of parabolic dunes. The complex is within the boundaries of the Słowiński National Park.

The dune coast in the Łeba region is one of the few stretches of the Polish coastline on which there is a slight prevalence of the tectonic factor over the eustatic factor [21]. Probably this is one of the reasons for the dynamic equilibrium or even accumulation in the nearshore zone and on the beach and dune. Erosional changes, observed during the last several dozen years east of the port of Łeba, are caused by the inerence of port breakwaters, the effects of which are difficult to determine accurately [12].

2.3. LAKE GARDNO SPIT

On the coast in the Rowy area are dunes of 7-8 m height, the appearance of which is connected with wind erosion of older stabilized dunes. Landwards of the fordune, the system of old, 10 m high dunes is still present. The width of beaches, built of mean and fine sand, is 20-50 m. On stretches where erosion processes are intense, beach width decreases to 10-15 m.

2.4. LAKE WICKO SPIT

The dune area east of Jarosławiec is built of Wicko, Modelsko, Lędowski and Zalesko dune complexes. In the area of Wicko Morskie
(km 251), the dune coast is formed by a single for dune of about 50 m width and 7 m height. Beach width is 20-30 m.

2.5. LAKE KOPAŃ SPIT

Genesis of the Lake Kopan Spit is connected with the Postlitorina, period of South Baltic evolution [22]. Lake Kopan formed in one of the intermoraine depressions, separated from the sea by a spit. The spit formed mainly on Pleistocene substratum, and on peats and lake gytias. It is no coincidence that the most protruding part of the spit is located in the area where Pleistocene formations are present. Peat outcrops on the beach, i.e. outside the present area of Lake Kopan, in the region of km 257.800-258.100, indicate that previously the lake reached further seaward [3]. Peat and gytia is also present in the shallow foreshore in vicinity of Darłowo.

The coastline between Darłowo and Jarosławiec is generally convex [29]. The shape results from geological conditions. In the maternal bed, down to 5 m below sea level, dominate boulder till, and fluvioglacial and organogenic formations.

Beach substratum is built of till or peat, lying relatively close to beach surface. Maximum depth of till layer ceiling is -3.2 m MSL; as a rule till ceiling is at -1 to -2 m MSL, and the ceiling of peat is at +0.1 to -0.5 m MSL. The thickness of sandy beach deposits is small and is between 1.1 -1.7 m. The poor resources of beach material are an insufficient source of supply for building the foredune [3].

Detailed investigations of the dynamic layer in the nearshore zone indicate that resources of material which could supply the beach and dune are at present very small. It is supposed that in this region of the coast larger resources of sandy material never existed, since dunes in the hinterland do not appear in the form of large complexes or dune fields.

2.6. LAKE BUKOWO SPIT

The Lake Bukowo Spit is the youngest spit on the Polish coastline, and originates from an older, at present not existing spit form. This fact is connected with the general retreat of coastline, resulting from slow sea level rise [21]. Contemporary Baltic Sea transgression, super-
imposed on proceeding land subsistence, results in southward displacement of the coastline, onto adjacent peat fields [21].

Deposits of the spit, the foredune and the beach rest on lake deposits, under which is peat and silt. Continuation of these layers, covered by a thin layer of sand, was found in the sea bottom 6 km into the sea. Basing on this fact, conclusions may be drawn as to the reach of the Bukowo Lake in the Preboreal period.

Maternal bed formations are easily subjected to erosion, taking the form of a concave profile [1]. On the maternal bed rests the dynamic layer. Thickness of the dynamic layer is 1.5-2 m in the inter-bar zone, up to 3 m on the seaward slope of the sandbar, and up to 5 m within the sandbar crest.

The single line of foredune along the stretch km 277-287 is of 4.5-8.6 m height, and therefore is classified as low and medium dune, locally moderately high. Dune width is between 10 and 100 m. Beach width does not exceed 40-50 m. Along stretches with intensive erosion beach width falls to 5-10 m.

2.7. LAKE JAMNO SPIT

The Lake Jamno Spit is formed by two dune lines separated by a 800-1000 m wide spit flatland. The foredune is slowly retreating onto the spit flatland [23]. Fordune height is 7-8 m, beach width is 15-30 m.

Lake Jamno Spit genesis is connected with sea level changes in the pre- and post-Litorina periods. The old spit form was superposed on lake and peat deposits. Below them appear lake gyttias resting on peat. These deposits have their continuation into the sea, to -15 to -16 m depth contours [30]). The large amounts of material accumulated on the coast should be connected with accretion resulting from passing stabilization of sea level [21].

Pleistocene deposits in the form of boulder tills with uneven ceiling, on which appear lake deposits of various thickness (mainly gyttia), form the direct substratum of the narrow zone of sandy bottom. Gyttia is no source of sandy material. Local boulder till outcrops in the active bottom zone are such a source only to a very limited extent. This is the main reason for the significant deficit of sandy sediment in a large part of the Koszalin Bay. Resistance of maternal bed formations to scour delays coastal erosion, in spite of the large deficit of sandy
material. The process consists in gradual evening and cutting of the irregular bottom profile which is formed by several underwater platforms. The platforms are limited on their seaward side by sills of various height. The presence of sills has a negative influence on the run of lithodynamic processes, deepening the zone of division of sediments transported in the nearshore zone. After crossing over the sills, fine material is irretrievably discharged into the deepwater zone [27].

2.8. LAKE RESKO SPIT

The Lake Resko Spit appeared in result of closing up of a postglacial depression which for a time became a bay of the sea, by a gradually growing bank [23]. Marine sands of the spit were deposited on peats of the coastal lowland, directly neighbouring with the spit.

Average width of the Lake Resko Spit is 400 m. The west part of the spit - west of the lake's outlet is longer (3.2 km), the eastern part is shorter (0.5 km) [2].

In general, the width of the dune belt does not exceed 250 m, though locally it reaches 500 m. The fordune does not exceed 5-6 m height, except the area of km 343.8, where it is 8-9 m high. Behind the fordune are dune fields reaching +2.5-3 m MSL. Locally, older dunes, 10-15 m high, are still present. Beach width is rather small (25-30 m), only near km 343.8 (in 1972) the width was more than 30 m. Beach height is 1-2 m above MSL. Directly behind the dune belt is the coastal lowland, the terrain of which lies at about +1 m MSL.

The ceiling of Pleistocene formations is directly below the dune sand on the coast, and below a very thin layer of sand on the sea bottom. This is confirmed both by cores and inspections of the bottom. In sea bottom, the ceiling of Pleistocene should be expected as shallow as -3 m MSL. Pleistocene deposits form an underwater coastal platform along the whole stretch Kołobrzeg - Dźwirzyno - Mrzeżyno. Scouring of the underwater platforms proceeds from the west, probably at least in part due to the extension of the groyne system.

Coastal changes of varying intensity were observed in the area of Lake Resko Spit since about 100 years. In all the analized time intervals, the beach east of Lake Resko outlet showed erosional characteristics.
2.9. DZIWNÓW SPIT

The dune coast in the Dziwnów Spit region is about 12 km long. Two different in coast character stretches may be distinguished: The Martwa Dziwna region, and the strongly eroded stretch of km 388-389.

The Martwa Dziwna region is characterized by a narrow, 16-25 m wide beach, and a relatively low (5-6 m high) fordune, showing erosional trends. Maximum height of Dziwnów Spit dunes is 6-10 m. Beach width varies between 20 and 40 m.

The general, observed in the past, equilibrium of coast and bottom of the Spit, became radically put out of balance after the port at Dziwnów was built. Erosion east of the port forced construction of protective structures. Therefore, contemporary formation of the beach and dune zone remains in close dependence of existing structures [9].

In the nearshore zone, one, sometimes two, sandbars are present. The proceeding erosion of low to medium dunes and medium to narrow beaches, together with low terrain level (+0.5 to +2.0 m MSL) behind the dunes, results in high risk levels for the hinterland. Stretches along which fordune width does not exceed 10 m are in high risk of being flooded by storm waves.

2.10. STRETCH MIĘDZYDZROJE - ŚWINA OUTLET

Accumulated between Międzyzdroje and Świnoujście sandy deposits form one of the larger spits of the South Baltic coast. Its parts neighbouring with Uznam and Wolin consist of three lines of dunes, differently and inconsistently oriented, and contacting discordantly [21]. Dunes of the Świna Gate (Brama Świny) were formed in conditions of bidirectional sediment supply. The Świna Gate Spit started to develop during the second phase of the Litorina transgression. Sandy sediments were deposited on the bottom of the Szczecin Lagoon, initiating generation of the oldest dune lines [23].

In the Postlitorina period a next series of yellow dunes was formed. During Subatlantic transgression, and directly after it, the grey and white dune series appeared. Maximum height of the forudunes reaches +15 m MSL, and their width is 35-45 m. Beaches before the dunes are 30-60 m wide, and the widest beaches occur west of Międzyzdroje.
The dune coast between Międzyzdroje and Świnoujście is one of the few stretches along the Polish coastline with coast and bottom in equilibrium, even with local accumulation trends. It is thought that the large amounts of sandy material collected in the nearshore zone and the well developed dune complex form good protection even in case of high storm surges. Danger during high sea levels may appear only along the km 425 segment, because along that stretch only one line of dunes is present.

3. COASTAL CHANGES ALONG SPITS IN THE PERIOD 1889-1983

Appearance of the spits of coastal lakes, formed during the maximum of Litorina transgression, resulted in significant straightening of the coastline, filling depressions in the Pleistocene surface. The spits are located mainly within marginal ice valleys or marginal depressions [21]. Changes in coastline position are characterized by alternatively located erosion/accretion stretches of various length.

Balance of changes of the coastal lake spits, made for the last 100 years, shows a slow loss of land areas. Average rate of retreat was -0.08 m/year. Except the Lake Łebsko Spit and the spit of Lake Gardno, all were being destroyed at small and medium rates. In the 100-year period, largest displacement occurred along the Lake Bukowo Spit (-0.47 m/year). The spits of lakes Sarbsko, Dołgie and Resko retreated at rates of -0.24 to -0.37 m/year. Low rates of retreat showed spits of lakes Jamno, Wicko and Kopań (between -0.07 and -0.14 m/year) (Fig. 1, 2).

The Lake Łebsko Spit was characterized, in the 100-year period, by a rather small rate of accretion, evaluated at +0.27 m/year. Very low accretion occurred in the area of the Lake Gardno Spit (+0.07 m/year).

In the period 1960-1983, along nearly all coastal lake spits rates of erosion increased, or direction of trend changed. The average rate of coastline displacement for all the spits was -0.96 m/year. Highest rates of retreat occurred along the spits of Lake Łebsko (-2.1 m/year), Lake Wicko (-1.6 m/year) and Lake Dołgie (-1.12 m/year). The highest factor of retreat rate increase with respect to the 100-year period is for the spits of lakes Łebsko, Gardno and Wicko. Erosion weakened only along the Lake Bukowo Spit. It cannot be excluded that this stretch went into a stage of passing stabilization due to supply from...
the intensely at that time eroded Lake Jamno Spit.

In the period 1970-1983, the average rate of erosion for all the analyzed coastal lake spits of the open sea coast was -1.5 m/year. Maximum rates of displacement occurred along the spits of lakes Łebsko (-2.8 m/year) and Dolgie (-3.14 m/year). Along the Lake Kopań Spit the rate was -2.5 m/year. Along the Lake Jamno Spit, the beach zone narrowed at a rate of -0.8 m/year. Analysis of rates of displacement of the dune foot line and waterline for the last 20-30 years, showed that displacement of both these lines does not necessarily proceed proportionately.

Along the Lake Jamno Spit the trends of waterline and dune foot line displacement were in accord. The ratio of rates was 2:1. Along the Lake Bukowo Spit, in the period 1960-1983, the rate of dune foot displacement was higher than the waterline displacement rate, whereas in the years 1971-1983, erosion of dune foot occurred parallelly with accretion at waterline. Along the Lake Kopań Spit, depending on analyzed period, both higher rates of dune foot than of waterline retreat were observed (period 1960-1983) as well as a waterline displacement rate two times higher than the rate of dune foot line displacement (period 1971-1983). Along the Lake Gardno Spit in the periods 1960-1983 in spite of significant beach erosion, the fordune accreted at a rate of 0.3 to 1.4 m/year.

The above data are indicative of very high dynamics of the coastline along coastal lake spits. Because of the sequence of erosion, accretion and stabilization processes, the balance of changes made within Gardno Spit shows opposite trend in comparison with the general trend of evolution of neighbouring segments of the coast.

4. CHANGES ALONG CLIFF COAST STRETCHES IN THE PERIOD 1875-1983.

Cliff coasts form about 1/5 of the Polish coastline [28]. Because of the large heights and slopes, and the geological structure, lithodynamic processes along cliff coasts proceed in a different manner than along dune coasts, with often appearing landslides and colluvial phenomena. A separate analysis of coastal changes was made for the cliff coasts because of their special significance in the overall lithodynamic process proceeding along the South Baltic coast. Previous investigations
Fig. 1 Average velocities of coastline changes on the spits and cliffs (m/year) during: 1875 - 1979, 1960 - 1983 and 1971 - 1983 (part 1)
Fig. 1 Average velocities of coastline changes on the spits and cliffs (m/year) during:
Fig. 2  Average velocities of dune foot changes on the cliffs and spits (m/year) during:
Fig. 2  Average velocities of dune foot changes on the cliffs and spits (m/year) during:
show that cliff coasts are the beginnings of local streams of sandy material transported in the nearshore zone [3, 19].

Cliff coasts of the Gulf of Gdańsk were characterized, during the last 100 years, by lower rates of coastline displacement than the open sea cliff coasts. This is probably connected with exposition of the coasts to winds from east and north. The average rate of coastline displacement during the 100-year period was -0.11 m/year (Fig. 1, 2). The rate of Gulf of Gdańsk cliff coastline displacement decreases northwards. Highest erosion appeared during that period at the Orłowo cliff (-0.5 m/year). The Swarzewo and Puck cliffs were in stabilization phase. The slowing down of cliff erosion is connected with the formation of accumulation platforms, which provide natural protection against erosive action of the sea [14].

During the 100-year period, coastline erosion along cliffs of the open sea coast proceeded at an average rate of -0.34 m/year.

The Ustka cliff was eroded at a very high rate (-1.6 m/year). Among others, the process is connected with the negative influence of the Ustka port, the breakwaters of which disturb lithodynamic processes in the region [26]. Medium rates of cliff coast erosion were found for Jarosławiec (-0.9 m/year), Rowy (-0.8 m/year), Ustronie Morskie (-0.6 to -0.7 m/year) and Chłapowo (-0.6 m/year). Low rates occurred along cliff coasts of Wolin (-0.4 m/year), Śliwin and Jastrzębia Góra (-0.3 m/year), and Wicie (-0.26 m/year).

Some short stretches of cliff coasts were in equilibrium or even beach was accumulating in result of a temporary supply by material transported in the longshore stream or by material from landslides. For the investigated period, these stretches formed only 2% of the total length of analysed cliff coasts.

In the period 1960-1983, on most of the open sea cliff coasts erosion increased. Highest factors of retreat rate increase occur on short cliff stretches which became active at the end of the investigated 100 year period. At the Rowy cliff, which was retreating in the 100-year period at -0.8 m/year, the rate attained -2.3 m/year. The average rate of displacement of coastline on cliff coasts between Chłapowo and Ustronie Morskie was -0.50 m/year. Highest rates occurred at the cliffs of Ustka (-2.5 m/year), Dębina (-0.5 to -2.1 m/year) and Jarosławiec (-1.3 m/year).

In the period 1971-1983, erosion became even stronger. The average rate of open sea cliff coast retreat was about -0.96 m/year. Extreme
Lithodynamic processes

Rates were found for the cliff coasts at Rowy (-4.4 m/year), Ustka (-2.7 m/year), and Dębina (-1.6 to -2.65 m/year). A very high increase of erosion rate appeared at the cliffs at Ustronie Morskie and Sarbinowo.

Comparative analysis of the rates of cliff foot line change and of waterline change, shows that in most cases both morphological elements are displaced in the same direction.

In the 20-year period, best agreement of cliff foot line and waterline displacement occurred at the Ustka and Ustronie Morskie cliffs. Average rate of retreat of cliff foot along the open sea cliffs between Chlapowo and Wolin was -0.39 m/year in the 20-year period, and -0.58 m/year in the 10-year period.

Very high rates of cliff foot line retreat occurred at the cliffs at Ustka (-2.3 m/year) and Dębina (-1.15 m/year). Also some segments of cliff foot at Ustronie Morskie were intensely eroded (-0.5 to -1.3 m/year). Comparison of average changes of cliff coasts and average changes of the whole open sea coastline shows that during each of the analysed periods erosion of cliff coasts proceeded at higher rates. However, at the same time the rate of retreat of dune coasts kept growing even quicker. For the 100-year period the ratio of cliff coastline retreat rate to the rate for dune coastline was 1.6:1, for the 20-year period the ratio is 1.2:1. These results are indicative of the growing in the last 20 years intensity of changes along dune coasts.

5. AN ATTEMPT AT PREDICTING COASTLINE CHANGE

The determined century trend of coastline displacement, and knowledge of fluctuative changes superposed on the century trend, were used to determine the displacement of the coastline within selected time horizons [6, 11].

The position of the boundary of natural variability of coastline was evaluated from the formula:

\[ G_1 = W_{tn} + 2A_{max} + x_{max} \] (1)

where:

\( G_1 \) - extreme landward displacement of coastline during given time horizon,

\( W \) - century trend coefficient,
tn - time horizon,
A_max - maximum amplitude of coastline position variability,
x_max - possible maximum retreat of coastline during maximum storm.

Width of the coastline variability zone $S_z$ is determined with a larger margin of safety, using the formula:

$$S_z = W_{tn} + 4A_{max} + x_{max}$$ (2)

The boundary of safe investment was determined for selected dune and cliff coasts from the formula:

$$D_1 = fG_1$$ (3)

where:

$D_1$ - distance of boundary of safe investment from initial position of coastline,
$G_1$ - width of zone of natural coastline variability,
$f$ - coefficient of safety (uncertainty) for $D_1$.

Position of the boundary of safe investment was calculated for two time horizons, assuming the same rate of sea level rise as occurred during the last 100 years (Table 1).

Table 1. Predicted coastline changes for selected spit and cliff coasts.

<table>
<thead>
<tr>
<th>Region</th>
<th>Time horizon</th>
<th>Boundary of natural variability</th>
<th>Boundary of safe investment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Kopań</td>
<td>25 years</td>
<td>-34,7 m</td>
<td>-62,4 m</td>
</tr>
<tr>
<td>Spit</td>
<td>50 years</td>
<td>-38,0 m</td>
<td>-68,0 m</td>
</tr>
<tr>
<td>Lake Bukowo</td>
<td>25 years</td>
<td>-34,7 m</td>
<td>-62,4 m</td>
</tr>
<tr>
<td>Spit</td>
<td>50 years</td>
<td>-46,5 m</td>
<td>-83,7 m</td>
</tr>
<tr>
<td>Lake Jamno</td>
<td>25 years</td>
<td>-15,7 m</td>
<td>-28,3 m</td>
</tr>
<tr>
<td>Spit</td>
<td>50 years</td>
<td>-17,5 m</td>
<td>-31,5 m</td>
</tr>
<tr>
<td>Cliff at</td>
<td>25 years</td>
<td>-58,0 m</td>
<td>-104,0 m</td>
</tr>
<tr>
<td>Jarosławiec</td>
<td>50 years</td>
<td>-81,0 m</td>
<td>-145,0 m</td>
</tr>
</tbody>
</table>
Assuming sea level rise by 0.6 m during 100 years, in the nearest 25 years coastline will retreat by 7.5 to 11 meters, and in 50 years by 15 to 22 m.

If the more pessimistic - 1 m per 100 years - sea level rise forecast is assumed, than in the nearest 25 years, only in result of the SLR, the coastline will retreat by 12 to 17 m, and in the 50 year period by 24 to 35 m (Table 2).

<table>
<thead>
<tr>
<th>Horizon of forecast [years]</th>
<th>Changes in coastline position due to SLR [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+0.6 m/100 years</td>
</tr>
<tr>
<td>25</td>
<td>-7.5 ± 11</td>
</tr>
<tr>
<td>50</td>
<td>-15 ± 22</td>
</tr>
</tbody>
</table>

In the considered time horizon of the forecast, both changes resulting from contemporarily observed erosion processes, and from changes in the conditions of sea level rise should be taken into account. It should be mentioned that the presented values are of tentative only character.

The boundary of safe investment along spit coasts should therefore run not closer than 45-97 m for the 25 year horizon, and 70-120 m for the 50 year horizon, from present position of coastline. Along cliffs with high activity of coastal processes, depending on the horizon of the forecast, the boundary should be situated 120-170 m inland of the present position of the dune/cliff foot line.

REFERENCES


