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ORIGINAL RESEARCH ARTICLE

Morpholithodynamical changes of the beach and the nearshore zone under the impact of submerged breakwaters — a case study (Orłowo Cliff, the Southern Baltic)☆

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Summary Submerged breakwaters (SBWs) were used for the first time on the Polish coast in 2006, in the western coast of Gdańsk Bay, in the area of Orłowo Cliff. They were built to prevent the abrasion and inundation of areas situated in the hinterland, especially in the conditions of storm surges. The main objective of the study was to determine their effect on the morphology and grain size composition in the seashore and nearshore zone.

Based on the conducted research and analysis, it has been found that the construction has a minor impact on the modification of the shore and nearshore zone morpholithodynamics, which is evidenced by a sinuate shape of the shoreline and a relatively stable cape in the central part of the area, present both before (1966—2005) and after SBWs were built. Furthermore, the progressive abrasion, the lack of significant changes in the morphology and particle size distribution of the beach and the nearshore zone, as well as the fact that those changes are limited only to the immediate surroundings of the submerged breakwaters prove their neutral impact.

☆ The results presented in this paper come from the doctoral thesis: "The influence of submerged breakwaters in the region of Orłowo Cliff on morpholithodynamics of the coastal zone".

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1. Introduction

Submerged breakwaters are immersed, longshore constructions built mostly of stone, rarely of the concrete or flexible membranes filled with concrete, sand or water (Harris, 1996; Stauble and Tabar, 2003). The specific structure of the construction and the material used contribute to the fact that they are more friendly to the marine environment and have a minor impact on the esthetics of the protected area. Therefore, they are more and more frequently used to replace the traditional methods of the coast protection such as seawalls, groins or detached breakwaters.

Submerged breakwaters are mostly used to reduce the amount of energy reaching the shore by forcing the waves to break and by extending the residence time of sediments in a sheltered region (Basiński et al., 1993; Creter et al., 1994). They are usually built on sandy shores where the increased abrasion and the associated sediment deficit are the main problems. So far, this type of construction has been used in Italy, Spain, Egypt, Israel, Japan, Australia and the USA. In many cases, however, they have not produced the desired effects. Waves energy dissipation was too small (Lamberti and Mancinelli, 1996; Ranasinghe and Turner, 2006), while the bottom in the neighborhood and in the shade of the construction was extensively washed out (Burcharth et al., 2007; Funakoshi et al., 1994; Homma and Horikawa, 1961; Kuroki et al., 2002; Lamberti et al., 2005; Shiraishi et al., 1960; Sumer et al., 2005; Zyserman et al., 2005). Positive effects have been observed in addition to adverse ones. A *salient* depositional form occurred in the shade of the construction, and the shore moved several dozen meters toward the sea (El-sharnouby and Soliman, 2010, 2011; Tomassicchio, 1996). Both the efficiency of the construction in the protection of the coast, and the resulting transformation of the littoral zone are determined by several factors, of which the most important are: parameters of the structure (the depth of crest, distance from the shoreline), wave climate and the nearshore profile (Armono and Hall, 2003; Stauble and Tabar, 2003; Wamsley et al., 2002). The design principles of SBWs are well defined, and their verification is based on further modeling and experiments, as well as monitoring and results of tests performed on the existing constructions.

In Poland, the submerged breakwaters have been used on the coast in the vicinity of Kołobrzeg and Gdynia Orłowo. Especially the latter case deserves attention because the breakwaters have been built on the cliff coast with an intensive abrasion process and the average destruction rate of 0.9 m per year (Chrząstowska, 2010). Apart from highly dynamic coastal processes, the geological structure of the area is equally unique. The nearshore zone is an abrasive platform built of glacial till and covered with a thin layer of sandy-gravel deposits washed out from the beach and the cliff (Bogacka, 2003; Rudowski and Łęczyński, 2009; Subotowicz, 1971a, 1971b; Wicher, 2003).

The objective of this study was to determine the impact of submerged breakwaters on the morphology and particle size distribution in the shore and nearshore zone. The results of the presented study complement the existing knowledge about the use of the aforementioned constructions and help to understand their functioning in the marine environment.

1.1. The study area

The study area is situated in the western coast of Gdańsk Bay (the Southern Baltic) (Fig. 1).

In the region of Gdańsk Bay, wind from the western sector dominates. For Gdynia, ca. 59% of strong winds occur in the period from October to early April, and those are mostly westerlies, from NW, W and SW (Trzeciak et al., 1999). The NE-SE wind is particularly important. Despite its small contribution (ca. 25%), it generates the highest and the most dangerous waves in the coastal zone of the Southern Baltic (Pruszak et al., 2000). In the study area, the NE-E wind with a velocity of 10 and 15 m s^{-1}, generates 0.85—1.6 m high waves (Boniecka et al., 2004). For the other directions, the range of wind is limited and does not generate significant waves (Schönhofer and Szmytkiewicz, 2008).

The study area covers the southern part of the Orłowo Cliff stretching at the foot of Kępa Redłowska. It represents a 500 m section (from 81 to 81.5 km of the Polish coastline) located within a local bay, enclosed from the north by the most seaward fragment of Kępa Redłowska — so-called Cypel Orłowski, and from the south — by the northern stone groin, built next to a fishery harbor (81 km of the shoreline) (Fig. 2). The bay is divided into two smaller bays with the common part in the form of a cape in the central part, the position of which has been changing, both in the longitudinal and transverse profiles, depending on the hydrometeorological conditions.

There are two small coastal sediment transport streams in the study area, including one moving northwards and the other one — southwards of Cypel Orłowski. The southern creates a several meters long stream, which receives sediments from abrasion of Kępa Redłowska cliffs and, in particular, from washing out the coastal platforms situated at the toe of the cliffs (Musielak, 1980). The presence of longshore sediment transport is confirmed by several studies based on the analysis of grain size composition and the content of heavy minerals in the sediments of the coastal zone (Chmielowski, 1964; Gołębiewski, 1967; Masło, 1967; Musielak, 1967; Nowak, 1965; Subotowicz, 1971b). In addition, it is reflected in the accumulation of sediment in the groin area, situated in the southern part of the study area. The sediment is impounded on its up-drift side, resulting in abrasion on the down-drift side. In addition to longshore transport, silty and clayey fractions in the Orłowo Cliff area are transported toward the sea; the fractions come mainly from the cliff abrasion and the bottom of the nearshore zone.

The region is characterized by large lithological differences in the rock deposits within the shore and littoral zone, and the geological structure of the Orłowo Cliff — by a clear dichotomy. The stretch from the south of Cypel Orłowski is built of the Pleistocene sand, gravel and fluvioglacial silt (Bogacka and Rudowski, 2001; Kaulbarsz, 2005; Pępek and Olszak, 1995; Subotowicz, 1971a), whereas Cypel Orłowski (Orłowo Headland) is built of up to 20 m thick glaciotectonically disturbed till deposits (Bogacka and Rudowski, 2001; Kaulbarsz, 2005; Pępek and Olszak, 1995; Subotowicz, 1971a; Szopowski, 1961). Glacial till occurs also in the bottom of the nearshore zone. The contemporary sea sand (with an abrasive pavement at the floor) is deposited on the glacial till. The pavement within the abrasive platform contains large boulders, the content of

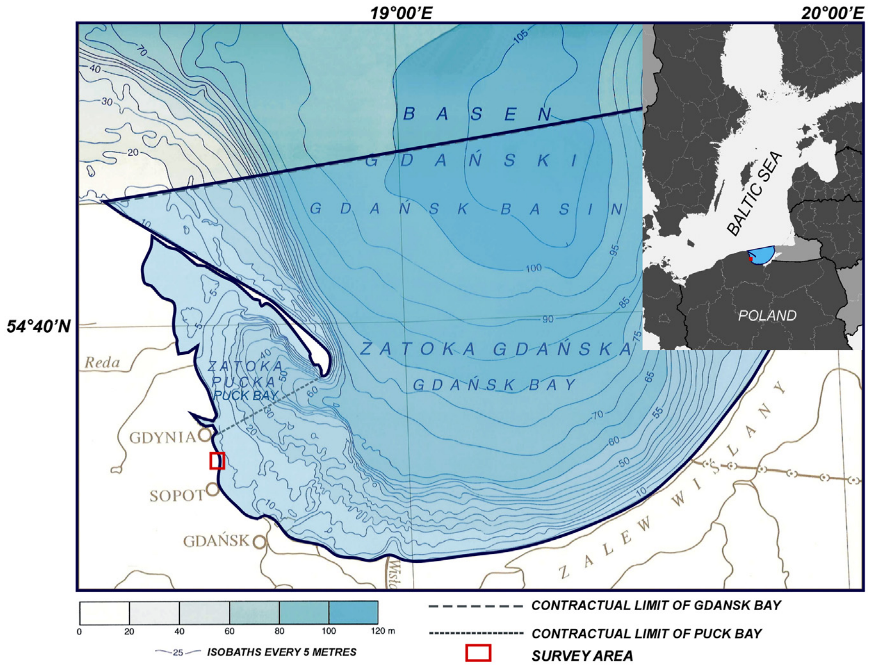

Figure 1 Location of the study area (Branch of Marine Geology of the Polish Geological Institute, 1995 — changed).

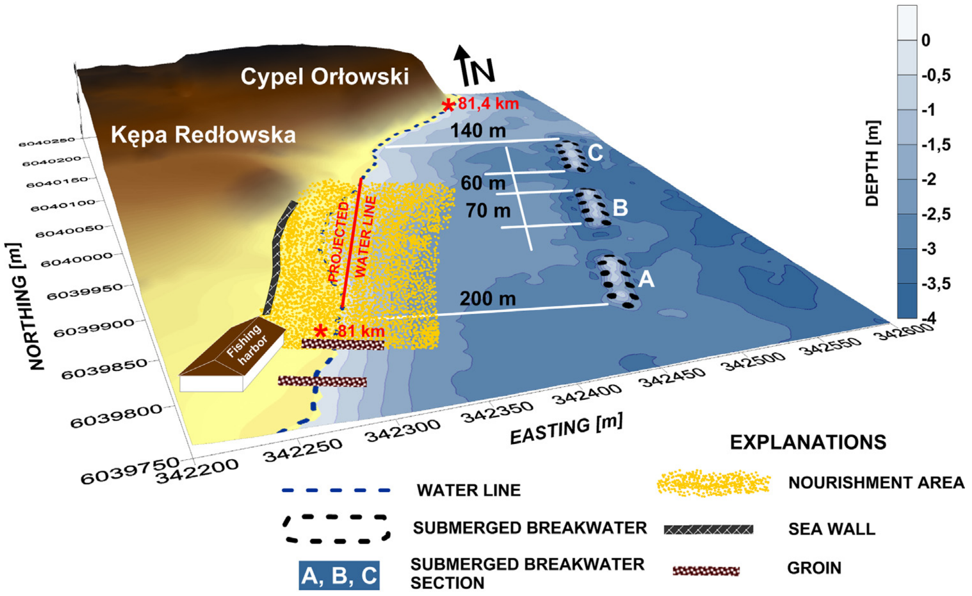

Figure 2 Location of submerged breakwaters in Gdynia Orłowo.

which decreases along the increasing distance from the shore in favor of thick gravel with single boulders of 0.5 m in diameter (Wicher, 2003).

Because of the direct threat of sea abrasion and inundation of areas situated south of Cypel Orłowski, in particular during storm surges, a project concerning the coastal protection system was conducted in 2006 in the region of Orłowo Cliff in Gdynia Orłowo, along the stretch of 800 m, i.e. from 80.6 to 81.4 km of the shoreline (Fig. 2). The protection system consists of three parts covering different methods of protection:

1. three submerged breakwaters (81.0—81.4 km of the Polish coastline),
2. artificial beach nourishment (80.6—81.24 km of the Polish coastline),
3. northern and southern stone groins (80.9—81 km of the Polish coastline).

According to the accepted premises, submerged breakwaters were to protect the coast section by suppressing a large part of the energy further away from the shoreline, and — together with groins — to prolong the residence time of the nourished material in the shoreline zone (Boniecka et al., 2004).

Submerged breakwaters were made of three basic stone fractions: 5—8 cm, 20—30 cm and 70—150 cm in diameter, arranged on geotextile fabrics in shallow trenches. The core of the construction made of 20—30 cm diameter elements was covered with two layers of stones with a diameter of 70—150 cm (Fig. 3) (Korzeński, 2005a).

SBWs were built in the shallow nearshore zone, at a distance of 140—200 m from the shore, at a depth of ca. 2.7 m. They were spaced at 60 m intervals, and the length of each SBW was 70 m (Fig. 2). Three-meter wide crests of breakwaters are submerged ca. 0.5 m below the mean sea level. Inclination of the landward and seaward escarpment was 1:2 and 1:3, respectively (Fig. 3) (Korzeński, 2005a).

In May 2006, the artificial beach nourishment was carried out, which covered ca. 600 m stretch of the shore (80.6—81.24 km of the shoreline) and part of the nearshore zone at a distance of ca. 120 m from the shoreline (Fig. 2 — artificial beach nourishment limited to the region with SBWs). For this purpose, ca. 38,100 m^3 of sand was used, including ca. 19,700 m^3 within the study area (Korzeński, 2005b). In accordance with the project (see Fig. 2 — projected water line), the abrasive bay stretching in the shade of the central breakwater B and the southern breakwater A was filled up (Korzeński, 2005b).

2. Material and methods

The research was conducted in 2007—2010. The profiling of the beach and the nearshore zone was carried out, and samples of the surface sediments of the beach and bottom sediments of the nearshore zone were collected. The survey covered the land part enclosed by the foothills of the cliff in the northern part, the concrete seawall in the southern part, and the underwater part which represents the nearshore zone, up to ca. 250 m seawards and up to a depth of ca. 3.5 m (Fig. 4).

Beach profiling was performed five times, i.e. in October 2007, May 2008, October 2008, May 2009 and October 2009, along nine profiles (Fig. 4). Each time, samples of the surface sediments were collected at characteristic sites such as a runnel, a coastal berm or a seaward slope of a berm.

Bathymetric measurements of the bottom in the nearshore zone were taken seven times. Profiling of the bottom for the whole study period was completed by the Department of Sea Measurements, the Maritime Office in Gdynia. The analysis of bathymetric changes in the nearshore zone included data from the previous years, i.e. 2005 year, before the implementation of the coast protection project.

In the nearshore zone, bottom sediment samples were collected four times (February 2008, September 2008, March 2009, November 2009), at the sites selected beforehand where major changes in the grain size composition had been expected due to the presence of submerged breakwaters (Fig. 4).

Sieve analysis was performed on sediment samples from the beach and the nearshore zone (Myślińska, 2001) using a set of sieves with a mesh size: 5.6; 4; 2.8; 2; 1.4; 1; 0.71; 0.5; 0.355; 0.25; 0.18; 0.125; 0.09; 0.063; 0.04 [mm]. The results of the granulometric analysis were compiled using the software GRADISTAT (Blott and Pye, 2001). The statistical part of the grain size composition analysis was conducted based on the method of moments (Krumbein and Pettijohn, 1938). Of the four moments: M1 — average diameter, M2 — standard deviation (sorting), M3 — skewness and M4 — kurtosis, the first three moments were taken into account; they are most often included in the sedimentological discussions (Gao and Collins, 2001).

3. Results

The shore in the study area has bay characteristics. Three sections were distinguished within the area (Fig. 5): (1) the abrasive section stretching at the toe of the active part of the Orłowo Cliff, flooded during storm surges; (2) the relatively stable section in the central part of the shore stretch, susceptible to abrasion during storm surges, with a clear contour of a berm; (3) the depositional section susceptible to abrasion during the autumn and winter season in the southern part, with a clear contour of a berm and a relatively high beach, composed primarily of nourished deposits.

In the northern part of the area, at the toe of the cliff, the shore is narrow and profiles of the beach with abrasive characteristics are incomplete, without berms, gently inclined toward the sea (Fig. 6). The course of the profiles results inter alia from waves bouncing off the cliff. A wave hitting the cliff toe loses some of its energy, while the diverted part has an intensified runoff, thereby prevents building of the beach and a berm (Leontjew et al., 1982). In the southern part, where the artificially raised beach is wider and higher, a coastal berm is emerging on the profiles, with periodic abrasive undercuts in its lower part. The thickness of the beach deposits systematically decreases with time, particularly within the stretch covered by nourished sediment (Fig. 6 — profiles P5—P9). The most important changes occurred from May to October 2009, mainly as a result of the October storm. At that time, traces of abrasion appeared in the upper shore zone. The height of the beach decreased by ca. 05—0.8 m (Fig. 6 — profiles P5—P8). Due to a large accumulation of broken roots, measurements were not performed on profile P9.

The situation is slightly different with changes in the beach height on profiles at the toe of the cliff (Fig. 6 — profiles P1—P4). An increase in the thickness of sediments, resulting in the "accumulation effect" during storm seasons, is associated with the presence of a colluvium, accumulated as a consequence of slope destruction.

Figure 3 Sketch of a submerged breakwater built in Gdynia Orłowo.

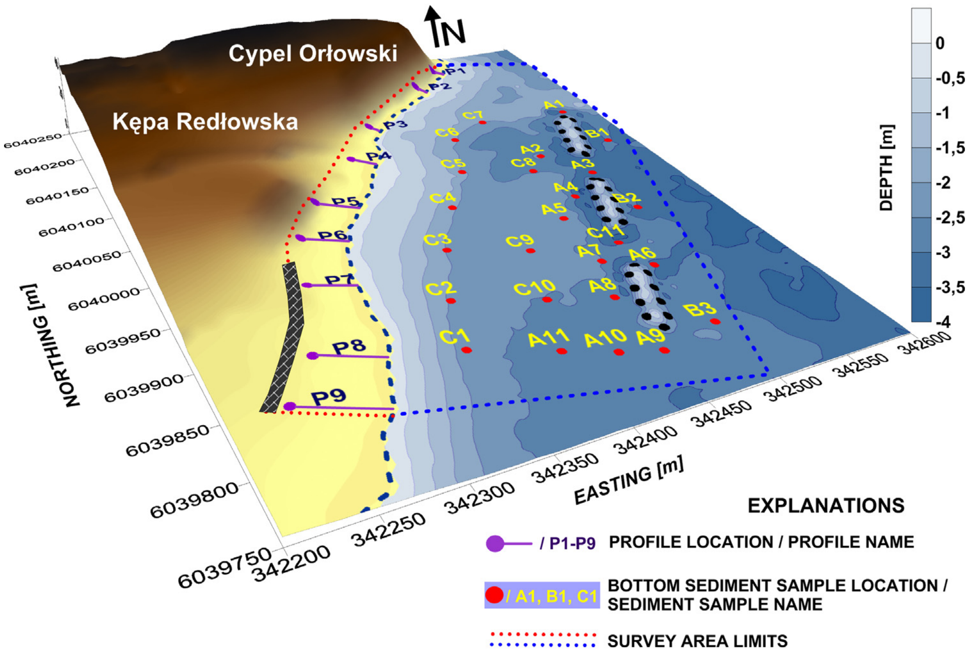

Figure 4 Location of profiles and bottom sediment sampling sites.

Surface deposits of the beach consist mainly of medium-grained sands. The presence of deposits with a larger grain size: coarse-grained sand, gravel, pebbles (Fig. 7 — October 2007, May 2008, May 2009), especially in the northern part of the area, is associated with the presence of a pebble streak reported by Subotowicz (1971a, 1971b). The streak emerges with the lowering sea level and becomes the lower part of the shore (Fig. 7 — October 2007, May 2008, May 2009), while it remains under the water during storm surges as part of the nearshore zone (Fig. 7 — October 2008, October 2009). Short-term directions of the sediment transport were determined based on the differences in average diameter and sorting of sediments. These are properties of sediments which do not change significantly over time, unlike the skewness which varies greatly (Racinowski and Baraniecki, 1989). Toward the south, the pebble streak becomes narrower, the diameter of rock crumbs decreases, their roundness and oblateness increase, the content of sand fraction (>1 mm) becomes reduced (Fig. 7), which is consistent with the dominant sediment transport in this area, on the way of which segregation and changes in the grain size occurs. The sorting increases with the increasing distance from the toe of the cliff (the source of sediment supply) (Fig. 8).

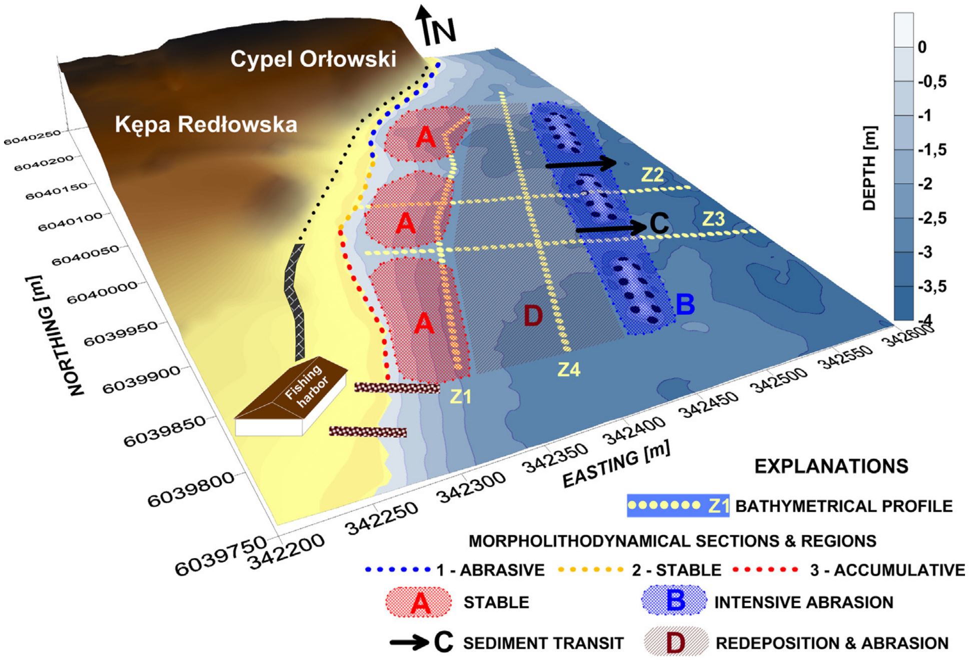

Figure 5 Morpholithodynamics of the beach and the nearshore zone.

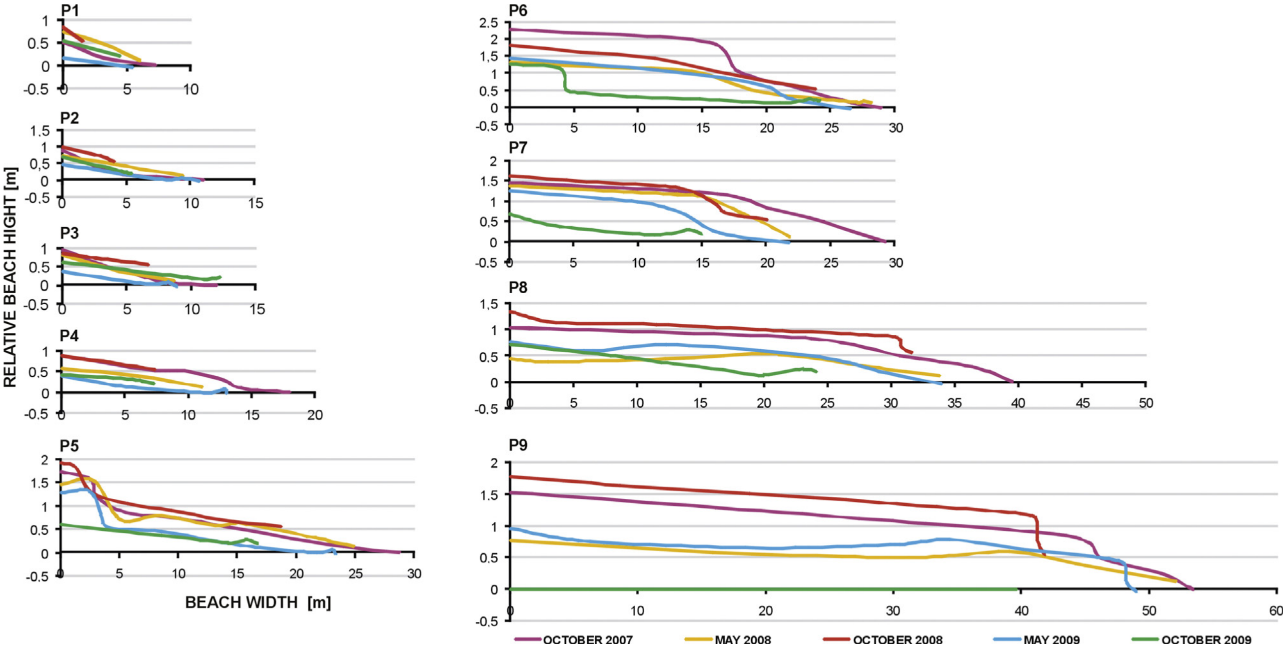

Figure 6 Morphological changes of the beach in October 2007—October 2009.

In some cases, certain differences can be observed in relation to the generally accepted pattern of longshore differentiation of sediment. The aforementioned transport of sediments is affected by a specific circulation of currents, most probably induced by the presence of submerged breakwaters. SBWs modify the wind-generated waves and hence disturb the longshore sediment transport, as a consequence of which linear differences in the grain-size distribution indices are disturbed, which is mostly reflected in the sorting values (Fig. 8 — May 2008, October 2008, May 2009) and the skewness (Fig. 9 — May 2008, October 2008, May 2009).

Slightly lesser sorting of sediments in the central part of the area may be a manifestation of changing dynamics of the sedimentary environment. Enrichment of sediments with fine fractions <0.125 mm (positive skewness) proves the existing tendency for deposition, so in this case — the presence of the convergence of sediment transport (Fig. 9 — May 2008, October 2008, May 2009). Obviously, during the storm fine sediments are washed out, while coarser sediments remain ashore. In the study area, the situation is different. After a storm the sediments are very well and well sorted (Fig. 8 — October 2009), moreover enriched with fine fractions <0.125 mm over the entire surface of the beach (Fig. 9 — October 2009). This may be associated with a long calm phase which took place after the October storm in 2009 and was conducive to smooth segregation and deposition of fine fractions, or most likely — with the loss of nourished material and exposure of the primary, abrasive beach surface, largely enriched with fractions of a smaller diameter compared to artificially deposited material.

The nearshore zone is an abrasive platform with a thin cover of loose, sandy and gravelly deposits derived from the destruction of the beach and the cliff, as reported by: Subotowicz (1971a, 1971b), Bogacka (2003), Wicher (2003), and Rudowski and Łęczyński (2009). Four morpholithodynamic areas are distinguished within the nearshore zone, three of which are parallel to the shoreline (Fig. 5).

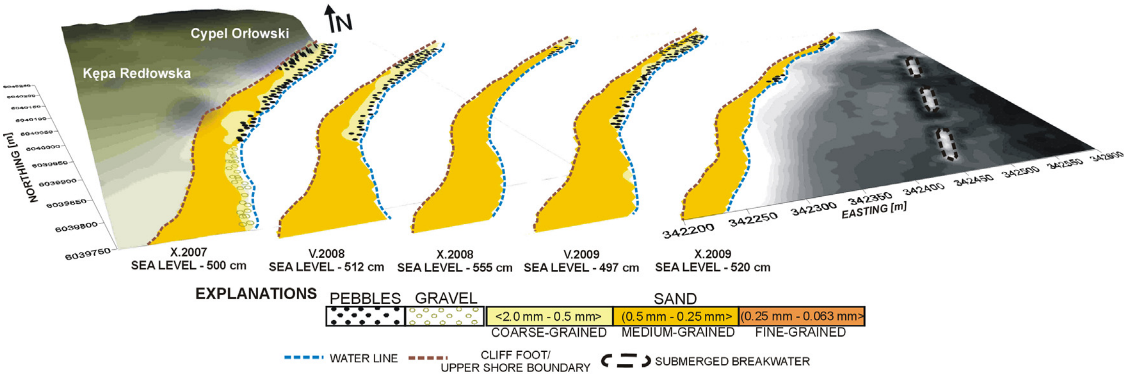

Figure 7 Distribution of mean diameter values of surface deposits on the beach.

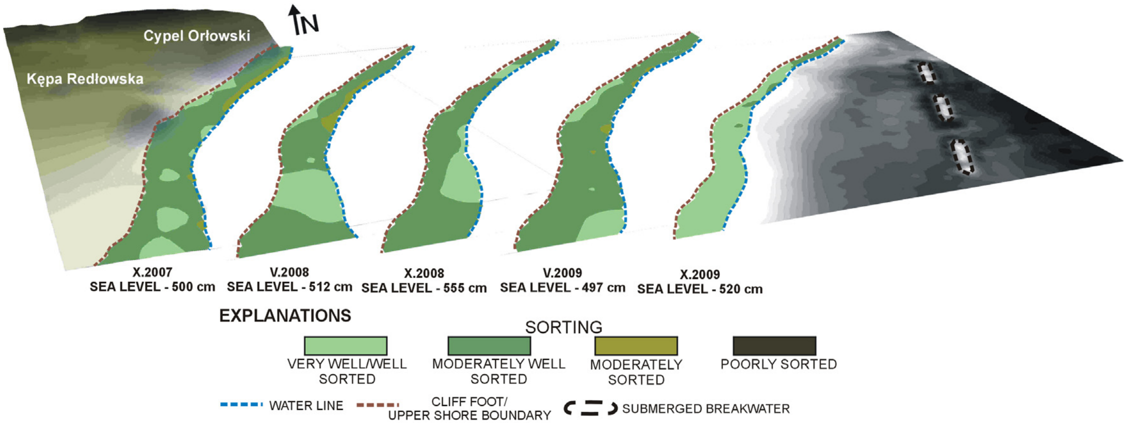

Figure 8 Distribution of beach surface deposit sorting.

The area A — a relatively stable area where conditions are favorable to deposition of sediments. It stretches in a shallow part of the nearshore zone, up to the 2 m isobath (Fig. 5). The material is arranged in two strips. Gravel and boulders occur up to a depth of 1 m, while sands of sediment flow — at a depth ranging from 1 to 2 m; the latter are mostly medium-grained sands with some admixture of fine-grained sands whose sorting and content of fine fractions (<0.25 mm) increase toward the south. The zone A covers a flow of longshore sediment and is of major importance to the dynamics of the seashore. The sediments come mainly from the destruction of the Orłowo Cliff and washing out of the beach, particularly during storm surges. They are the main source of material used to build the seashore and nearshore. The area A is characterized by discontinuity (Fig. 5). It results from the presence of gaps between SBWs, which are the main transit zone for sediment flows. The main course of transport and tendency for sediment deposition are evidenced by values of grain-size composition indices (Fig. 10).

The diameter of grains (M1) decreases and sorting (M2) increases from north to south (Fig. 10), which proves the differentiation of sediment during the transportation. Sediments of this zone consist mainly of medium-grained sands, and in one case after a storm — well-sorted fine-grained sands (Fig. 10 — M1, M2, November 2009). Positive skewness (M3) indicates favorable conditions for the deposition or large-scale transit. There are sites with negative skewness within this zone, susceptible to washing out of the bottom material (Fig. 10). Changes in the M3 index throughout the zone prove the heterogeneity of the sedimentary environment and may be associated with specific circulation of currents caused by SBWs.

At greater depths, between 2 m and 4 m isobaths, the area B is located in the vicinity of SBWs, with intensive processes of abrasion, and the area C — the transit of sediment between individual segments of SBWs (Fig. 5). Changes in the relief and granulometry of sediments in the nearshore zone are particularly apparent in profiles perpendicular to the seashore, running directly through SBWs and the gaps between them.

Dispersion of grain-size composition indices' values is much greater in profiles passing through SBWs (Fig. 11) compared to profiles in the gaps (Fig. 12). Along the direction from the shore toward the SBW, sorting (M2) is reduced and skewness (M3) is negative (Fig. 11). Slightly positive skewness, occurring just in front of the SBW (Fig. 11), may indicate a tendency for accumulation. Nevertheless, conditions conducive to washing out and redeposition of the bottom material prevail. The broad range of changes in the values of skewness indicates unstable dynamic conditions with a varying flow velocity. In the gaps, the bottom is leveled and the range of changes in the grain-size

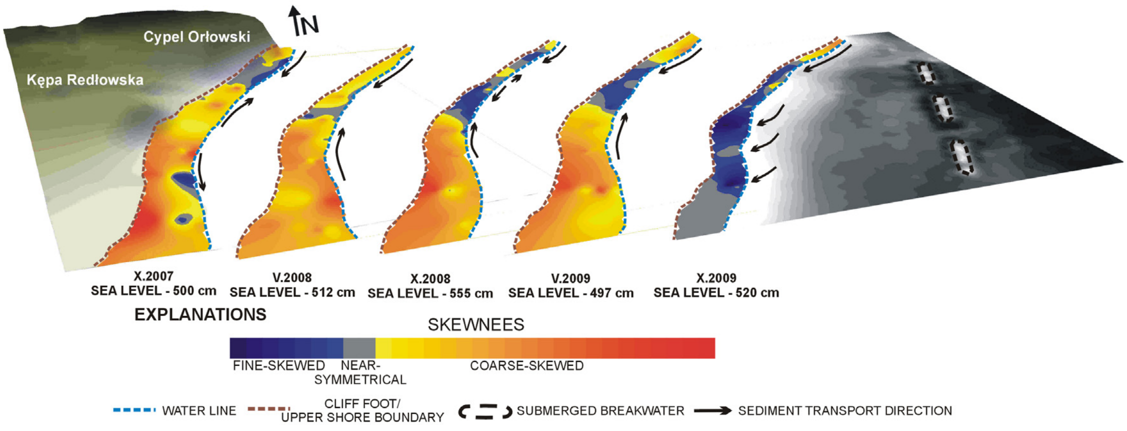

Figure 9 Distribution of skewness values for surface sediments of the beach.

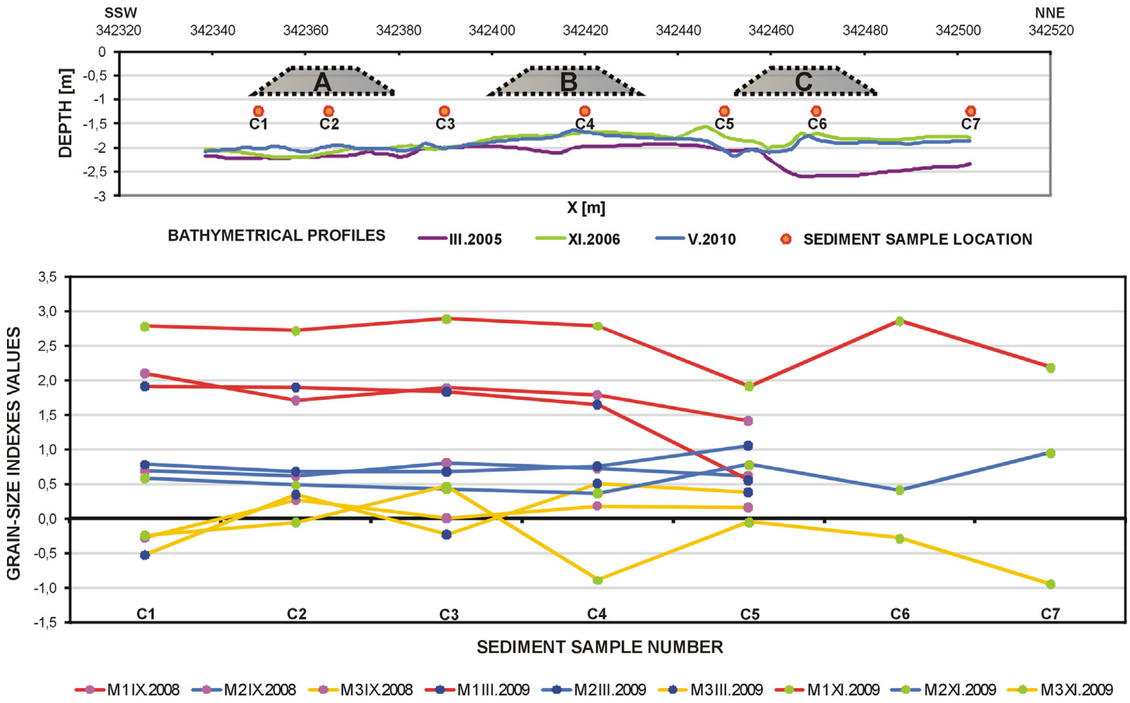

Figure 10 Changes in bathymetry and grain size composition along profile Z1.

composition indices is narrow (Fig. 12). Along the direction from the seashore toward the sea, sorting of sediments increases, and skewness becomes increasingly negative (Fig. 12). This is reflected in the large-scale transport of sediments. In the close vicinity of SBWs, an increase in the flow velocity is followed by the elimination of fine fractions. Scouring occurs in the surroundings of SBWs, both in the landward part (Fig. 11 — bathymetrical profiles) and in the gaps (Fig. 12 — bathymetrical profiles). Deepenings and scour holes range from 0.5 to 1 m, and they most likely result from the currents generated by phenomena referred to as *pumping effect*.

The area D is a zone covering the remaining part of the nearshore zone (Fig. 5) where processes of redeposition and abrasion dominate, while their course and extent are determined by the intensity of storm events during the year. This is caused by a periodic lack of deposits or their small amount in the deeper part of the bottom. In the case of the study area

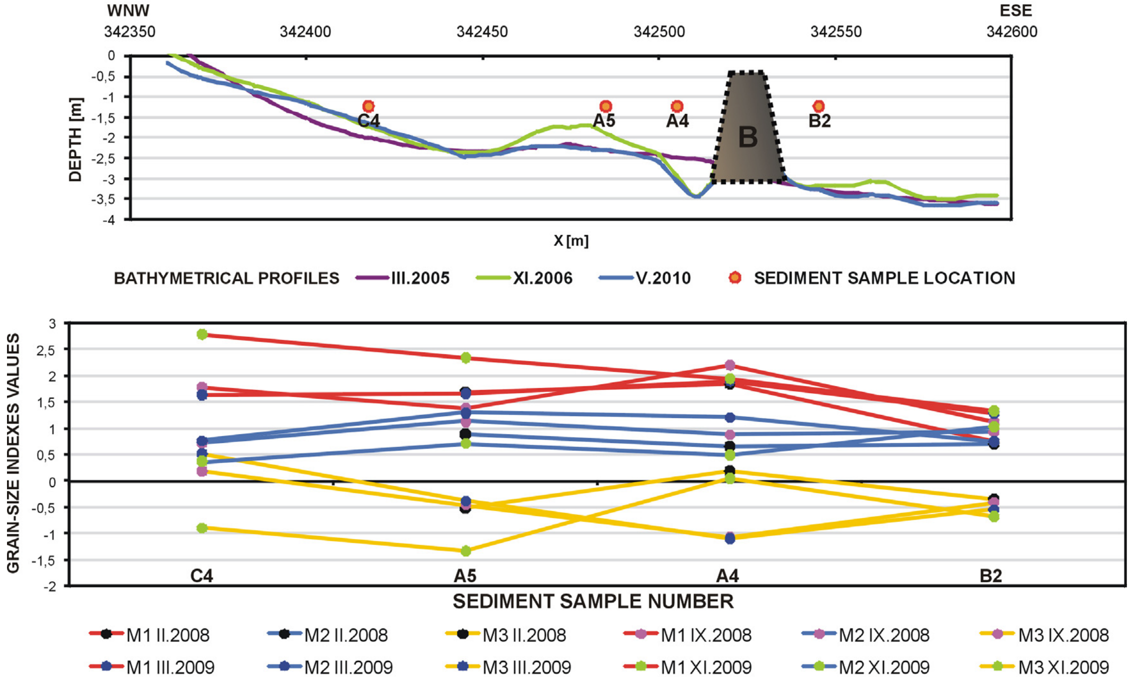

Figure 11 Changes in bathymetry and grain size composition along profile Z2.

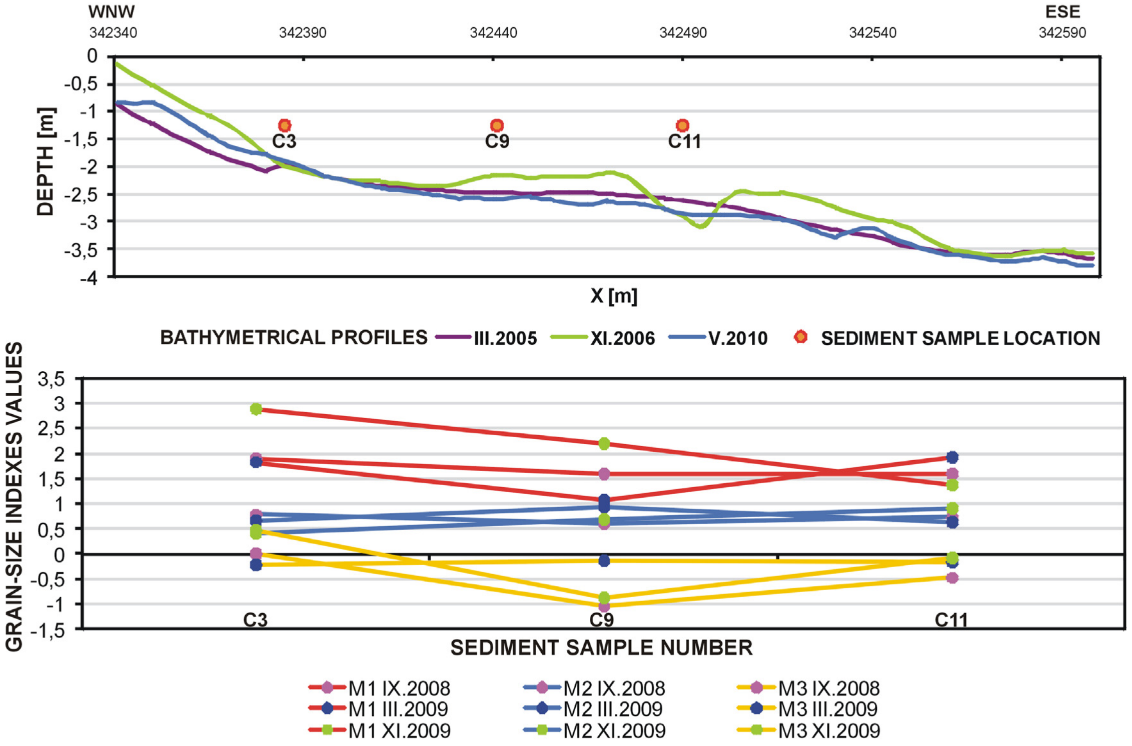

Figure 12 Changes in bathymetry and grain size composition along profile Z3.

the bottom is a bare abrasive surface, and the shoaled bottom slope of the littoral at an altitude of Cypel Orłowski is composed mainly of glacial till resistant to abrasion (Subotowicz, 1971b). Sediments in this part of the nearshore zone are composed of gravel and pebbles with sandy sites of varying granulation.

The presence of sediments with lesser and moderate sorting (M2) (Fig. 13) indicates changing dynamics of the sedimentary environment, while large differences in the skewness (M3) (Fig. 13) and the dominance of coarser fractions in the sediment indicate conditions favorable to washing out and redeposition of sediments. The areas of

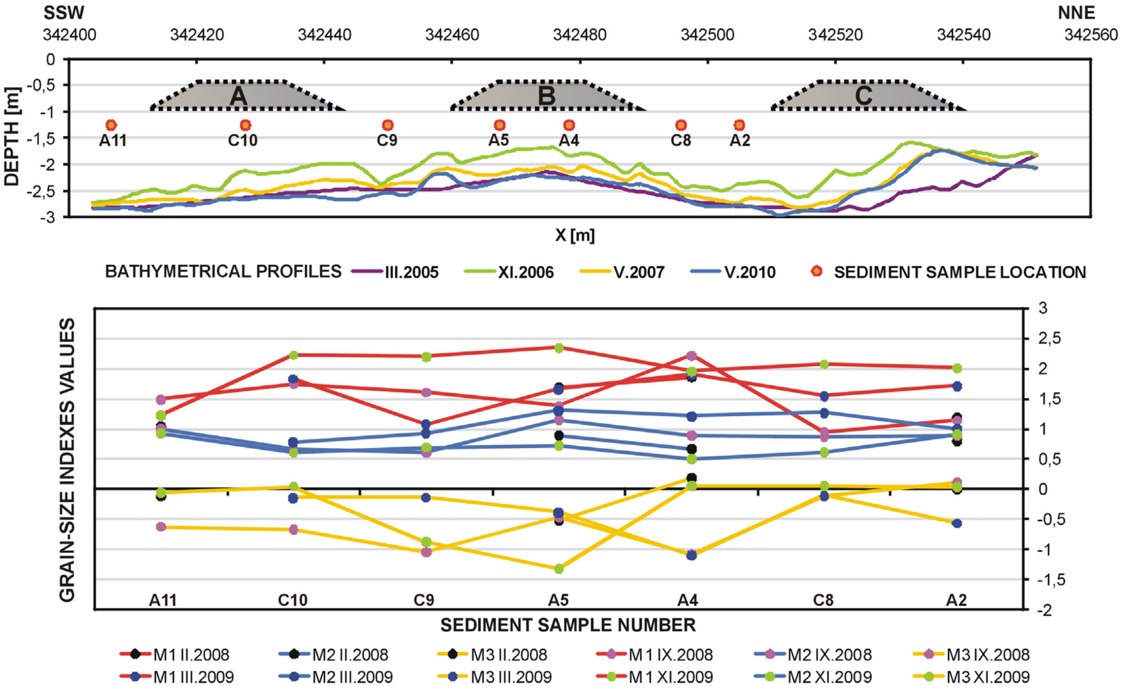

Figure 13 Changes in bathymetry and grain size composition along profile Z4.

deposition with positive skewness are of periodic nature and their occurrences are associated with favorable hydrometeorological conditions. Compared to the area A (Fig. 10), higher dispersion of indices occurring in the zone D (Fig. 13) results most likely from a stronger direct impact of SBWs.

Despite the partial reconstruction of the beach and the nearshore zone during calm seasons, both the seashore and the nearshore in the region of Orłowo Cliff are susceptible to abrasion.

4. Discussion

Assessment of the impact exerted by SBWs on the morpholithodynamical changes of the coastal zone in the area of Orłowo Cliff was performed based on the identification of coastal processes and developmental trends of the shore and the nearshore in the period preceding the construction of SBWs (1960—2005).

Based on the conducted research and analysis, it has been found that the submerged breakwaters have a minor impact on the modification of the shore and the nearshore zone morpholithodynamics. This is evidenced by a sinuate shape of the shoreline and the relatively stable cape in the central part of the area, which was present both before (1966—2005) and after SBWs were built (Fig. 14).

Already in October 2007, i.e. 18 months after the nourishment and the foundation of SBWs, an abrasive bay developed in the place where the artificial beach had been reconstructed (Fig. 15). After some time, the bay became deeper and the cape in the central part of the section became relatively stable. In the end, the shore developed into a sinuate shape, similar to that in 2005 year.

Furthermore, the neutral impact exerted by submerged breakwaters on the morpholithodynamics of the shore and the nearshore zone is reflected in the rhythm of morphological changes on the beach and varying indices of the grain size composition, similar to changes in the period preceding the implementation of the seashore protection project, i.e. 1966—2005 (Bohdziewicz, 1967; Boniecka et al., 2004; Burciu, 2006; Szabłowska, 2000; Wasilewska, 1983). The analysis of changes in the width of the beach on the short term (2007—2009) and long-term scale (1960—1982) revealed that starting from the 1960s, despite the presence of SBWs, the region of bays remains exposed to abrasion, while the central part is relatively stable. Abrasion processes occur over the entire

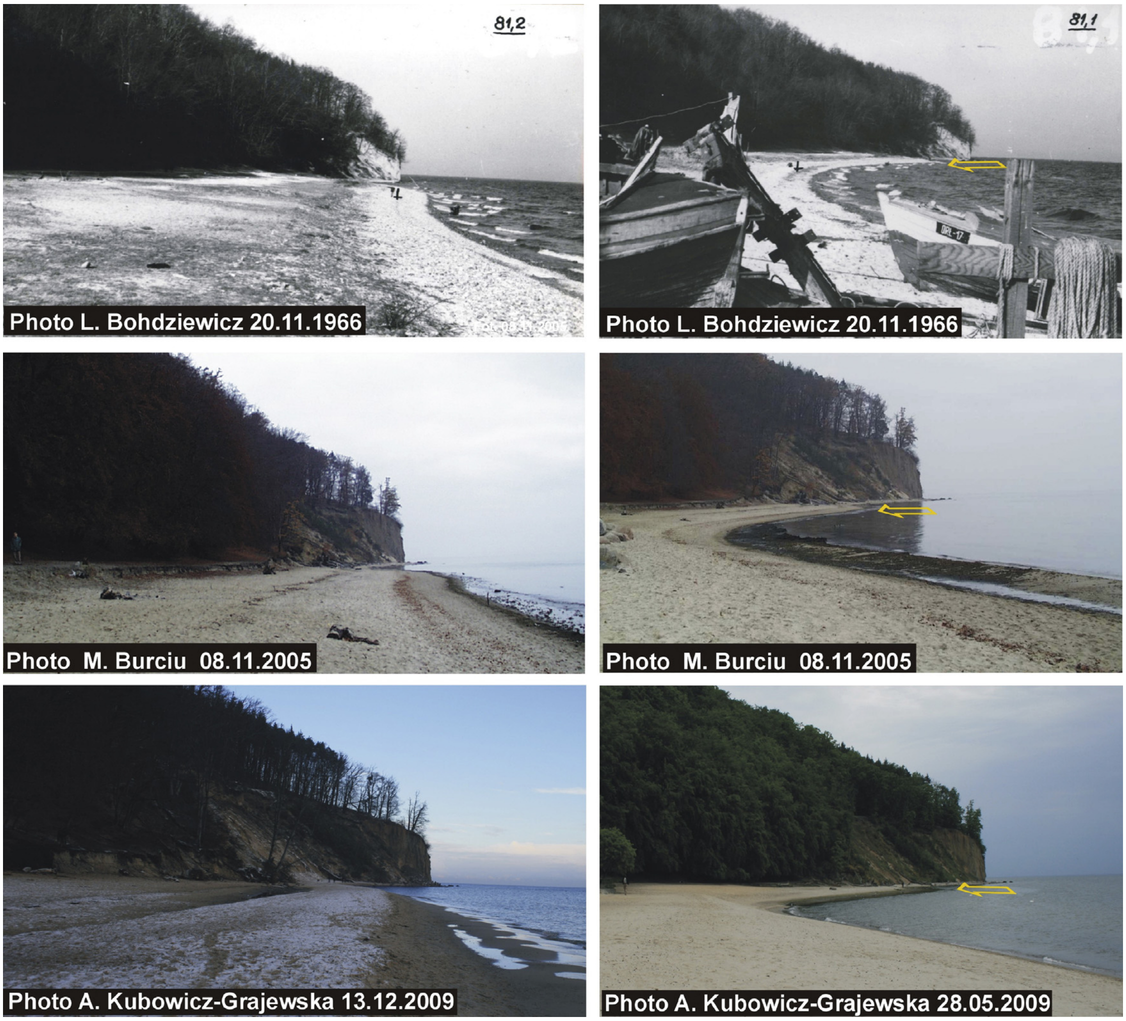

Figure 14 Sinuate shape of the seashore together with the shore cape in the central part of the study section (yellow arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

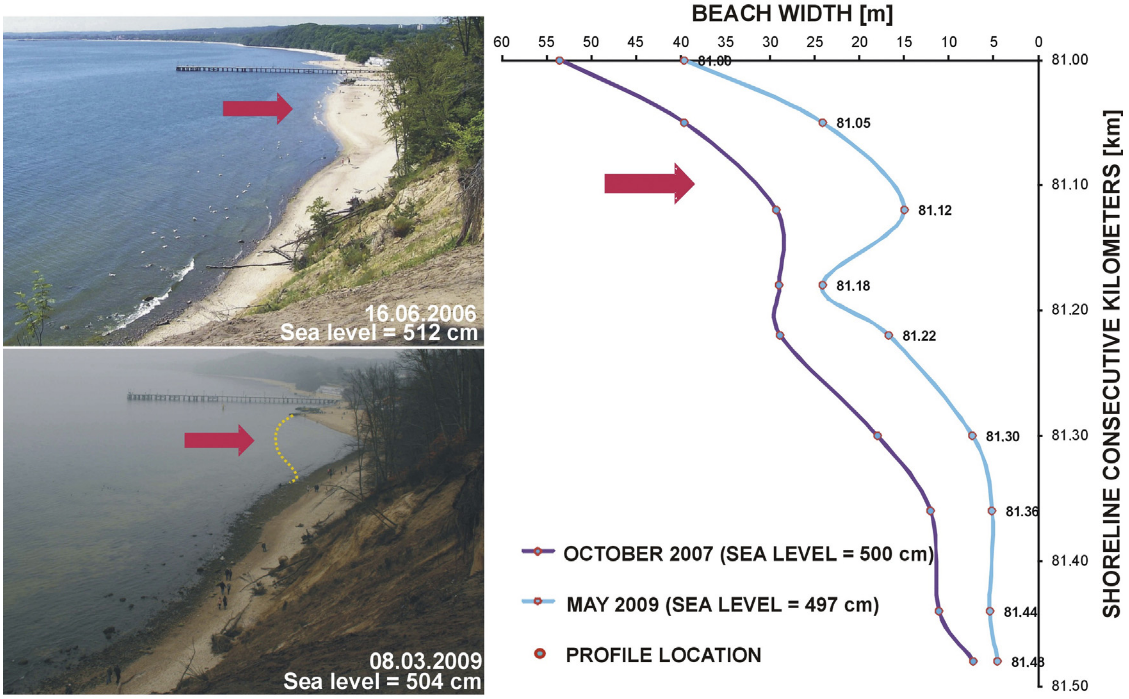

Figure 15 Changes in the width of the beach.

length of the shore and the nearshore zone, both in the long-term and short-term scale.

The impact of submerged breakwaters is primarily limited to the construction area. The most significant changes were observed in the vicinity of SBWs where deepenings occurred in the landward part, as well as in the area of gaps and crests, in some places up to 1 m deep (Fig. 16) (Kubowicz-Grajewska, 2013).

Most likely they are the effect of currents occurring in the vicinity of SBWs, induced by phenomena such as *set up*, *overtopping*, and *pumping effect* (Dean and Walton, 2010; Johnson et al., 2005; Lamberti et al., 2003; Mendez et al., 2001; Pruszak, 2003; Sánchez-Arcilla, 2003; Schüttrumpf et al., 2010; Van der Meer et al., 2005, 2010; Yanliang et al., 2010; Zyserman et al., 2005). The mechanism of these processes is activated when the wave passes over the SBW and its swelling on the landward side. In the phase when the wave trough passes over the construction, a large water gradient is produced, which results in a strong flow toward the sea (Cálabrese et al., 2003; Debski and Loveless, 1997; Diskin et al., 1970; Homma and Horikawa, 1961; Lesser et al., 2003; Longuet-Higgins, 1967; Penchev, 2005; Stauble and Tabar, 2003; Van Rijn, 2011; Zyserman et al., 2005). The process is all the more intensive when the SBW is higher than 0.7 of the water depth (Homma and Horikawa, 1961). Given the parameters of SBWs in Gdynia Orłowo (the construction height of ca. 2.2 m; the foundation depth of ca. 2.7 m; Korzeński, 2005a), the height of SBWs is ca. 0.82 of the water depth. Thus, the permanent washing out of the bottom is expected in the construction area. Because the natural run-off of water masses toward the sea is blocked by SBWs, part of the water is intercepted on the landward side. Then the longshore flow is generated, which abrades the substrate and carries away the deposits far from the construction site (Cáceres et al., 2005; Dean et al., 1994; Ruol et al., 2004; Stauble and Tabar, 2003). When the construction consists of a few segments, as in the case of submerged breakwaters in Gdynia Orłowo, the flows are concentrated in the gaps in the form of rip currents (Burcharth et al., 2007; Fulford, 1985; Van Rijn, 2011; Zyserman et al., 2005).

Similar effects of abrasion and scouring were observed on the coast of Japan, in the region of Niigata (the Sea of Japan) and Italy: in the region of Pellestrina, Lido di Dante (the region of Marche and Emilia Romagna) and Lido di Ostia (the mouth of the Tiber River). In the region of Niigata, the offshore abrasion of the bottom is up to 1 m (Funakoshi et al., 1994; Homma and Horikawa, 1961; Kuroki et al., 2002; Ranasinghe and Turner, 2006; Shiraishi et al., 1960). In the case of Pellestrina (the Adriatic Sea), the bottom was strongly abraded as a result of intensive flows and eddies (Lamberti et al., 2005; Sumer et al., 2005; Zyserman et al., 2005). Within 3 years, the construction sunk by ca. 0.3—0.5 m, thereby reduced its efficiency (Burcharth et al., 2007). In the region of Marche (Lamberti and Mancinelli, 1996; Ranasinghe and Turner, 2006) and Emilia Romagna (Burcharth et al., 2007; Lamberti et al., 2005), washing out of the bottom was observed in the gaps between the segments and at the base of the construction. In the second case — Emilia Romagna, deepenings of the bottom occurred even at a distance of up to 70 m from the SBW crest (Burcharth et al., 2007; Lamberti et al., 2005). As a result of intensive scouring and sinking of the bottom (in some places even up to 0.8 m), the submerged breakwater in Lido di Ostia (the mouth of the Tiber River) required renovation and raising of the crest (Burcharth et al., 2007; Lamberti et al., 2005; Ranasinghe and Turner, 2006; Tomassicchio, 1996). Scouring of SBWs and abrasion of the surrounding bottom is common and seems to be an intrinsic shortcoming of this type of construction.

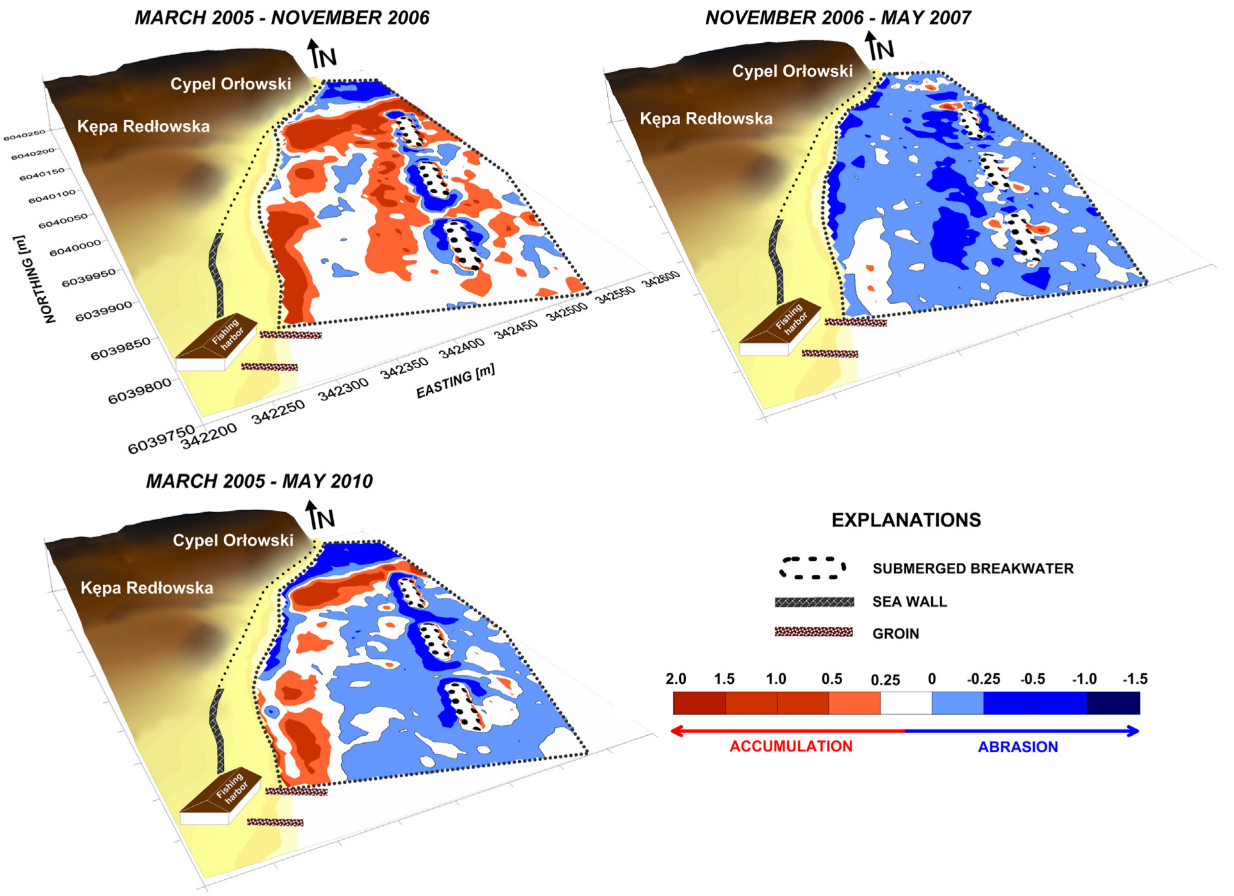

Figure 16 Bathymetric changes in the nearshore zone in the period of March 2005—November 2006, November 2006—May 2007 and March 2005—May 2010.

In addition to abrasive changes in the nearshore zone, the accumulation effect was observed and reported in papers referring to differences between bathymetric maps from different time intervals (Fig. 16). However, this does not result directly from the impact of SBWs, but from the longshore sediment flow. A shoal appearing within the shallow nearshore zone is periodic and supplied with sediments coming from abrasion of the cliff and the beach, deposited in favorable hydrometeorological conditions. The strongest accumulation effect covering the largest part of the bottom was observed in November 2006, i.e. 6 months after the SBWs foundation (Fig. 16). At that time, the nearshore zone was formed as a result of storms and the associated storm surges, which led to the transfer of artificially supplied sediments from the beach and the shallow nearshore zone into deeper regions of the bottom and their deposition on the landward and seaward side of SBWs. Six months later, most of the sediment was almost completely removed (Fig. 16), mainly as a result of extreme storm surges which took place in the first quarter of 2007.

Similar changes in the nearshore zone were observed on the Italian coast in the region of Lido di Ostia, near the mouth of the Tiber River (Burcharth et al., 2007; Lamberti et al., 2005; Ranasinghe and Turner, 2006; Tomassicchio, 1996). Within 12 months, the nearshore zone was strongly affected by abrasion, the rate of which remained unchanged compared to the conditions before the construction. Similarly as in the case of Orłowo, the analysis of grain-size composition indices showed a migration of deposits both toward the sea and along the seashore. Preservation of the beach required annual supplies of sediments (Lamberti et al., 2005; Tomassicchio, 1996).

Considering the bottom sediments, the grain size composition over the largest part of the area has not changed significantly, particularly in the zone of longshore sediment flows. The sustained type of grain size composition in this zone results from a small impact of SBWs on the longshore water current prevailing in the protected area, because they do not completely block the aforementioned flow, instead they only slow it down (Van Rijn, 2011). Changes were observed only in the shade of SBWs where sites of periodic sediment deposition occurred during low-intensity storm events (Kubowicz-Grajewska, 2013; Kubowicz-Grajewska and Piekarek-Jankowska, 2009).

5. Conclusions

To sum up, the submerged breakwaters have a minor impact on the modification of the seashore and the nearshore zone morphology and lithodynamics. The progressing abrasion of the shore section, no significant changes in the morphology and particle size distribution of the beach and the nearshore zone, limitation of these changes to the immediate surroundings of the construction, as well as the persistent sinuate shape of the shoreline, similar to the period preceding the foundation of SBWs, prove the neutral impact of the construction.

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