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Polish coast - two cases of human impact

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Abstract The paper presents two cases of engineering activities affecting coasts. Both examples concern neighbouring and interacting areas. The former describes destructive human impact, related to the construction of coastal structures (Władysławowo harbour), the latter highlights protection and stability of a heavily eroded coastal segment. Details of artificial beach nourishment in the 2nd case, whose objectives include both coastal protection and development of recreational beach use of the eroded segment, situated along the Hel Peninsula, were depicted extensively. These areas, being of paramount importance to local communities due to their current and future economic potential, related to growing tourism and holiday making, are exposed to permanent erosion that may intensify as a result of the observed climate change.

Keywords *Polish coast, shoreline evolution, coastal erosion, artificial beach nourishment.*

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INTRODUCTION

Marine coasts form sea-land boundaries exposed to actions of various, powerful forces. Apart from wind, waves, currents or tides the shore and the neighbouring areas can be additionally subjected to the damaging impacts of extreme events and anthropogenic activities. Since withdrawal from coastal regions by humans is not feasible nowadays, it becomes a necessity to minimize their negative environmental impacts including prevention of coastlines from various types of destruction. Each engineering construction or artificial beach rearrangement is a stranger to marine environment, frequently being an unaccepted intruder. Therefore, current coastal protection schemes are designed to avoid excessive disturbances to natural processes.

The growing human expansion enhancing pressures on coasts has been observed during last centenary. In recent decades though, it has been intensified considerably. Many large and small harbours, marinas and constructions related to their development have been built. In many cases they triggered disturbances of the existing equilibrium in form of undesired erosion or accumulation, sometimes in areas fairly remote from those establishments. A perfect example of such a process is the Władysławowo harbour, constructed just before World War II, *cf*. Fig. 1. Built on an open, morphologically dynamic coastal segment, it has been acting as a perpendicular, long, high and impermeable structure, which disturbed natural lithodynamic regime, producing profound shoreline response. The updrift, western side experienced rapid beach accumulation producing shoreline advance, whereas the lee, eastern side started suffering abrasion, which has become a problem until nowadays. The major reason of such response was connected with the disruption of natural west to east sediment flow. The interruption of longshore sediment transport with the harbour, situated at the root of Hel Peninsula, initiated negative processes for a few kilometres of coastline. Sediment deficit on the lee side of the harbour resulted in intensive erosion not only in direct harbour proximity but also in some remote parts of the Peninsula. Due to the fact that this region has a high economic and recreational value, it now requires permanent protection to guarantee beach stability in longer time perspective. Since the major concern is sediment deficit, artificial beach nourishment has become a routine to maintain overall shoreline stability with relatively wide beaches. Given these circumstances artificial beach nourishment is an optimum protection strategy, as belonging to the group of 'soft measures' it introduces only mild disturbances to local environment and ensures the existence of beaches.

The main goal of the paper is comprehensive presentation of two various instances of anthropogenic impacts on coastlines. Both are interrelated, because they concern neighbouring areas. The Władysławowo harbour case study demonstrates a negative human interference, whereas artificial beach nourishment of a segment of the Hel Peninsula shows a positive intervention, aimed at retaining stability of the protected area.

POLISH COAST

The Polish open sea coast is about 500 km long and consists of two basic types - dune and barrier beaches as well as cliffs. Dunes and sandy beaches occupy most of the coast, while cliffs comprise about 100 km. Coast barriers between the sea and lakes are well developed in the central and eastern parts of the coast. The Hel Peninsula is a narrow spit separating the Gulf of Gdansk from the open sea and is experiencing intensive erosion and flooding during severe storm surges. Poland's coastline has two major gulfs - the Pomeranian Gulf and the Gulf of Gdansk, and two large lagoons connected to the sea by narrow straits: the Szczecin Lagoon and the Vistula Lagoon (Fig. 1). Subsidence is limited, only locally reaching 1mm/yr.

Wave motion in the South Baltic is strongly related to wind waves and swell. The maximum significant wave heights (H_s) in the coastal zone measured by a wave buoy (at the depth of about 20 m) attains almost 4 m and the maximum period is up to 6-8 s. Most frequently, the wave period varies in the range 4-6 s. NE and N winds produce the highest and most dangerous waves and storm surges due to the largest fetch. These events are much more rare than waves from W and SW, which are predominant in the South Baltic. The 100-year design water level is assumed approximately 1.5 m above MSL.

Average rates of translation of the cliff and dune foot and of the general shoreline suggest a gradually increasing trend of erosion. Long-term (1885 to 1979) observations of the open coat shoreline changes indicate the average rate of coastal retreat was 0.12 m/year. During the period 1960–1983 it was 0.5 m/year, whereas during the period 1971–1983 it reached 0.9 m/year. Erosion also occurred along increasing lengths of the coastline: during the 100-year period – 61%, in the 24-year period – 72%, and in the 13-year period – 74% of the open coast eroded, respectively (Zawadzka-Kahlau 1999). The dune/cliff foot eroded less than the coastline. In the period 1960–1983 the dune/cliff foot line retreated at an average rate of 0.16 m/year and in the period 1971–1983 at 0.3 m/year. Changes of land area have also shown a decrease in accretion processes. In the whole 100-year period, natural beach reconstruction (accretion) occurred over 69% of the areas eroded by storms, in the period 1960–1983 it was 20%, and in the period 1971–1983 only 14%. These figures suggest that erosion is increasing in Poland (sandy coasts of the Baltic Sea).

Various types of coastal protection structures have been built along 26% of the Polish coastline. About 98 km of the coast are protected with groins, while light and heavy revetments protect 41 km. The Hel Peninsula is protected along 34% of its length. The highest level of coastal protection exists along the Jarosławiec-Świnoujście part of the Polish open coastline, where coastal defence structures are built along 71 km of the 126 km long coastline. Local coastal erosion was induced by the development of small ports on the western coast, and by the contemporary transgression

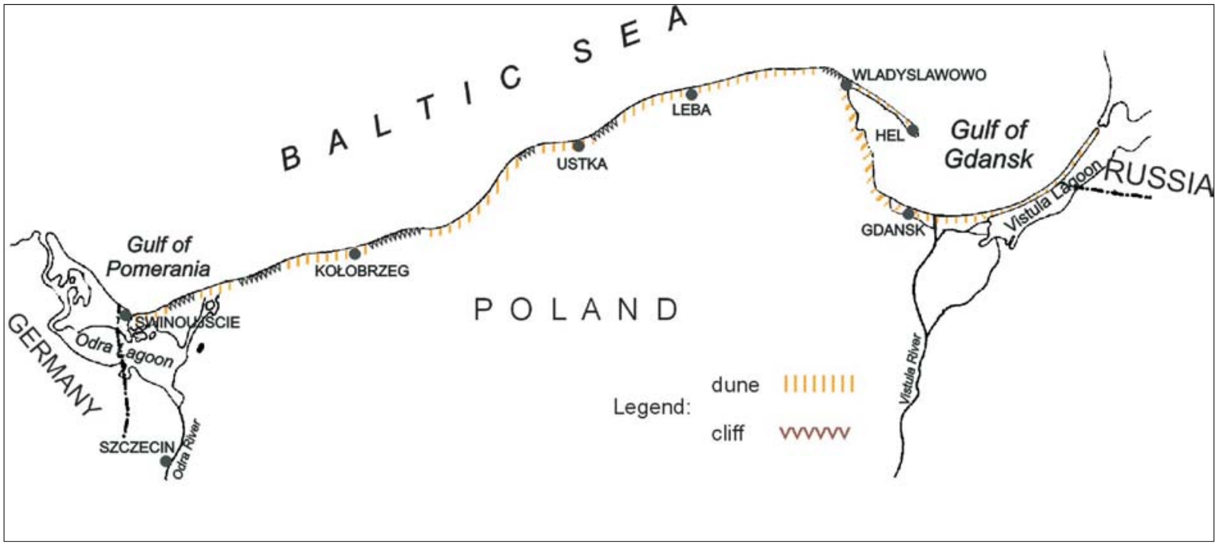

Fig. 1. Polish coast.

Fig. 2. General view of Władysławowo harbour (photo by J. Kapiński, 2003).

of the sea. From the 1900s to the 1940s groins were mainly used and some light and heavy revetments were built. However, it has been observed that groins and revetments are not fully effective, so these methods of coastal protection in Poland are now much less used. Evaluation of coastal changes in the period 1875 to 1979 within these systems of groins downstream the ports shows a four times higher rate of retreat than the mean rate for the overall 104-year period. Within groin systems built along stretches not connected with port erosion, the rate of retreat was 2.5 times higher. The obtained results cannot be interpreted as a success of coastal engineering, since protected stretches continued to be destroyed. At the end of the 1970s artificial nourishment was introduced and is often used now, protecting about 60 km of shoreline.

LONGSHORE SEDIMENT FLUX DISTURBED BY MAN-MADE STRUCTURES

Case study: Władysławowo harbour and its vicinity

Construction of Władysławowo harbour was started in early 1936 and was completed in late autumn of 1937. Immediately after construction, breakwaters reached about 400 m offshore. The first group of groins at the root of Hel Peninsula, on the eastern side of the harbour, was built after heavy storms in February and March 1946, which severely hurt the Peninsula along the first 3 kilometres of its stretch. They were made of wood as single palisades, each 100 m long. The spacing between them was 90 m. Afterwards, further systems of groins at consecutive distances along the Hel Peninsula were built, always causing erosion on the lee (i.e. east side) of the previously built structures.

Construction of Władysławowo harbour evidently changed existing conditions causing significant shoreline migrations (Figs. 2, 4, 5). After the construction of the harbour, the longshore transport was totally interrupted by breakwaters. This effect appeared rapidly and the rate of deposition became the basis for longshore sediment transport assessment in the harbour vicinity (Fig. 3). It resulted in gradual shoaling of the harbour channel and dredging became indispensable as early as in 1945. The shoreline westwards from the harbour advanced 200-300 m north (Fig. 4).

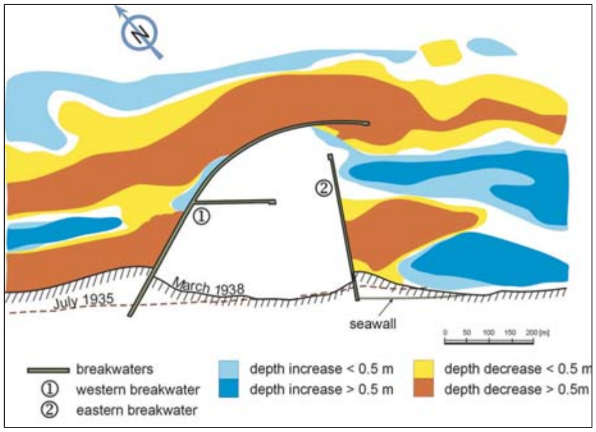

Fig. 3. Bottom depth changes from May 1936 to March 1938 (after Adamski 1977).

The assessment of sediment budget in the vicinity of the harbour was done upon estimation of the volume of material deposited at the head of western breakwaters, the volume of material dredged during the systematic maintenance work of the navigational channel and upon additional calculations (Fig. 6, Szmytkiewicz 2003).

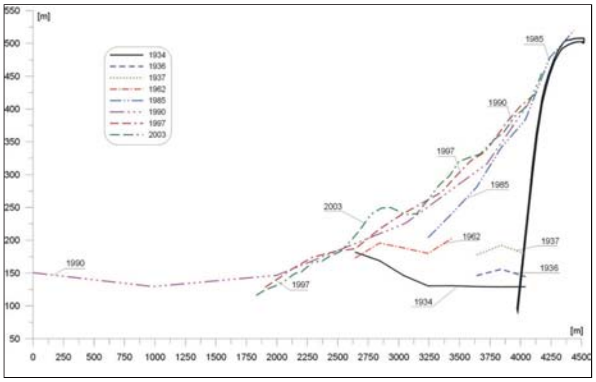

Fig. 4. Shoreline migration west of the harbour in 1934-2003.

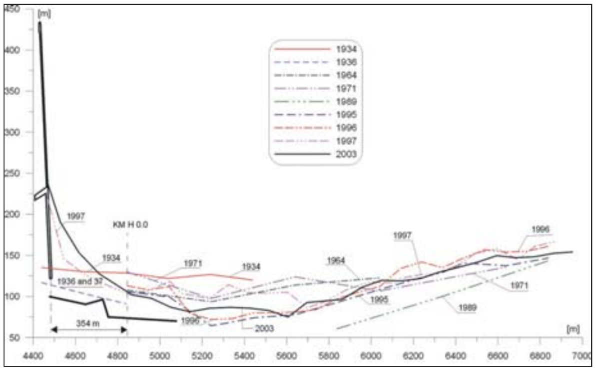

Fig. 5. Shoreline migration east of harbour in 1934-2003.

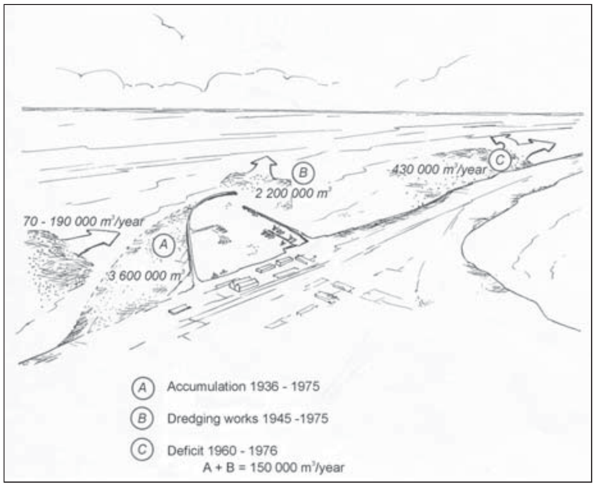

Fig. 6. Sediment budget for shore segment nearby Władysławowo harbour (after Szmytkiewicz 2003).

Calculation of shoreline change near a structure normal to the beach

Compute the time t of silting-up and shoreline advance up to ½ and ¾ of the length of a shore-normal, impermeable breakwater with length L_B=400 m (Fig. 7). The initial isobaths layout was shore parallel and the length of the assumed structure equals the offshore range of the Władysławowo harbour. Mean angle of wave incidence at breaking is assumed φ_z=5°, wave height at breaking H_z=2 m and active depth of seabed h_D=9 m. Longshore sediment transport parameter is A_0= 0,77, CERC formula (Pruszak 2003).

Solution

Assuming the shoreline change ($\partial x / \partial t$) along the x axis in time t, is driven by longshore sediment transport gradient ($\partial Q_y / \partial y$) across the y axis, the most simple one-line model formula reads (Pruszak 2003):

$$\frac{\partial Q_y}{\partial y} + h_D \frac{\partial x}{\partial t} = 0 \tag{1}$$

where h_D is a depth of closure (active depth of seabed)

The general solution of equation (1) is given by:

$$x(y,t) = 2tg\varphi_z \sqrt{Kt}\left[\frac{\exp(-u^2)}{\sqrt{\pi}} - \frac{y \cdot E(u)}{\sqrt{4Kt}}\right] \tag{2}$$

where $E(u)$ is a tabulated Fresnel integral and u is its argument equal to $u = -y / \sqrt{4Kt}$.

The parameter K in the above equation can be calculated from the relation:

$$K = \frac{\partial Q_y}{\partial \varphi} \frac{1}{h_D} = \frac{\partial (0{,}2796 A_0 H_z^{5/2} \cos 2\varphi_z)}{\partial \varphi} \frac{1}{h_D} = 0{,}270 \quad [m^2/s] \tag{3}$$

We search for the solution for y=0, i.e. where the breakwater (impermeable long groin) meets the shoreline, thus equation (2) is transformed to the form:

$$\frac{x}{2\sqrt{Kt} \cdot tg\varphi_z} = \frac{1}{\sqrt{\pi}} = 0{,}56 \tag{4}$$

Substituting to this equation x=0.5L_B and x=0.75L_B respectively we obtain the time given wave conditions produce the assumed shoreline advance: t=1.543×10^7 s ≈ 179 days, and t=3.47·10^{7}s ≈ 402 days. Thus, theoretically after 179/402 days of the continuous wave action (H_z≈2 m, φ≈5°), the shoreline will translate up to half/three quarters of the length of the breakwater (groin). It can only occur upon the theoretical assumption longshore sediment transport remains constant and undisturbed throughout this period. In reality, it varies significantly in a year, ranging from just a few days with high waves and sediment transport intensity to long calm periods, when it hardly exists. Practically, it can therefore be assumed the actual time of shoreline advance will be several or even a dozen or so times greater than theoretical considerations suggest. From the statistical analyses of winds for the Władysławowo region and the corresponding wave climate calculations it follows that the waves with *H* = 2 m from the N and NW, generating west to east littoral transport occur about 10 days in a year, the shoreline will reach half the length of western breakwater after about 20 years. It can be assumed in a simplified way that the new shoreline configuration, reaching half the breakwaters length, will appear after 18 years and three quarters of breakwaters lengths will be reached after approximately 40 years. The calculated new shoreline configuration after 40 years, despite considerable simplifications, shows high agreement with observations (Fig. 8).

ARTIFICIAL NOURISHMENT OF THE HEL PENINSULA

General

Artificial nourishment of the Peninsula started at the end of 1970s and was also associated with maintenance of the navigation channel of the harbour (Fig. 9). Before that time, the sediment was deposited offshore. Later, it was dumped closer to the shoreline at depths of 3-5 m. Such nourishment was executed at different locations along the Peninsula. Since 1989 the sediment has been dumped directly onto the beach along the whole Hel Peninsula. In 1990-1998 the stretch of the first 3 km of the Hel Peninsula shore was nourished with 1.5 million [m³] of sandy material. The deposit was mainly delivered from the Puck Bay (the other side of Hel Peninsula) and from dredging of the harbour area. In 1989-1998 the open shore of the Peninsula received with 8.8 million m³ of sand in total. Nowadays, the amount of nourishment of the shore adjacent to the harbour equals 0.14-0.3 million m³ a year.

Kuźnica 1985, 1986 and 1987

The nourishment in those years was executed using a hopper dredger, which pumped the mixture of sand and water close to the beach using the 'rainbow method'. The hopper capacity was 1,000-m³ and emptying time of its hold about 1-1.5 h. The sediment used was sand with the mean diameter D_{50}=0.22-0.25 mm, approximately resembling the native material. In 1985 the nourishment took place between 9th July, 9 and 28th September and was executed at 2 locations about 200-300 m offshore the shoreline. The nourished area was

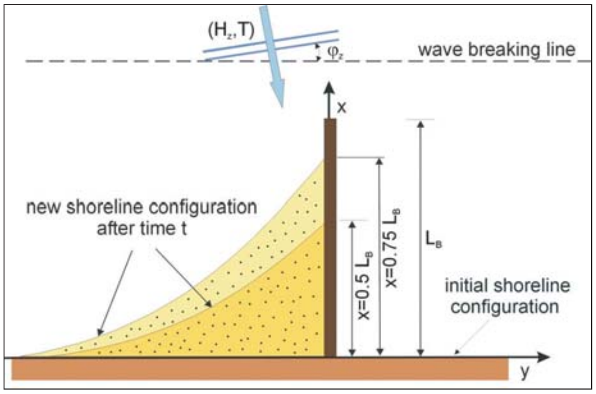

Fig. 7. Scheme of calculation of shoreline changes on the updrift side of the structure.

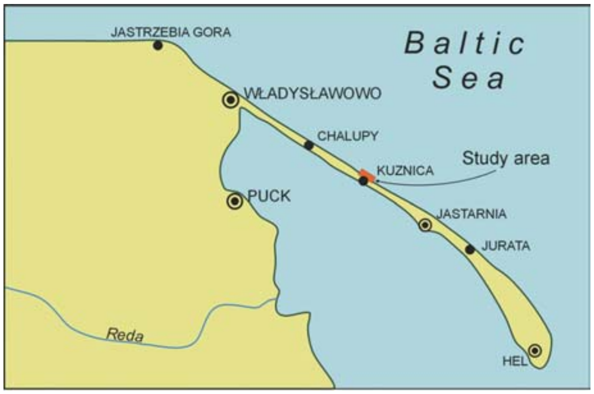

Fig. 8. Shoreline configuration at Władysławowo before harbour construction in 1936 and 40 years later (1975).

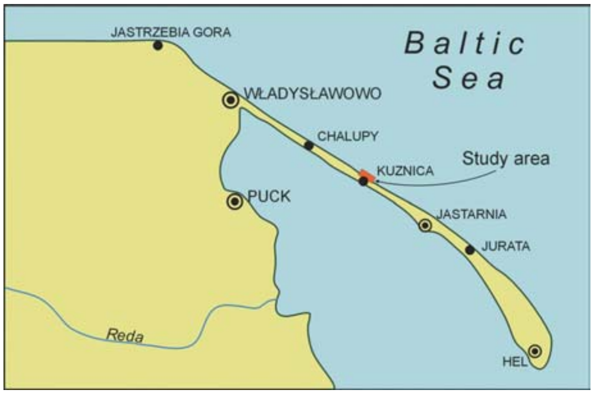

Fig. 9. Hel Peninsula.

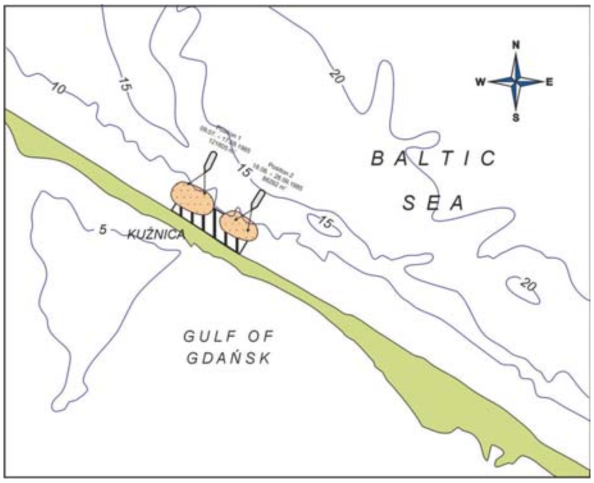

Fig.10. Nourished area and dredger locations.

Table 1. Major parameters of artificial beach nourishment of the Hel Peninsula in 1985-1987.

Site & year	Beach segment length	Phase	Volume [m^3]	Mean hydrological conditions	Efficiency	Mean efficiency
Kuźnica 1985	200 m	I II	121,605 86,292	H_{mean}<0.5 m on the depth of 2m H_{mean} up to 1.25 m	60% 45%	52%
Kuźnica 1986	300 m	I	70,000		47%	47%
Kuźnica 1987	400 m	I II	62,781 32,364	Shore normal wave incidence	82% 77%	80%

about 12 km from Peninsula's root (Figs. 9, 10 and 11). Key parameters and characteristics of this event are put together in Table 1.

The nourished segment that previously experienced heavy erosion had a system of groins (Fig. 11). One month after completion of the nourishment cross-shore profiles were surveyed revealing that:

- offshore shoreline displacement (in the nourishment area) – 20 m on average,
- enlargement of underwater bar,
- mean cross-shore speed of migration of submerged artificial sand forms up to 2m/day, longshore up to 4 m/day,
- alongshore beach segment undergoing a change 400 m,
- width of beach profile undergoing a change h=5 m.

In the summertime of 1986 and 1987 the neighbouring segments were nourished. In 1986 a 300 m segment adjacent to the groins was filled, whereas in 1987 the fill was done at another 400 m segment, situated on 13th kilometre of the Peninsula from its root. The sand was placed at locations of the innermost nearshore bar.

The filling technology in 1987 varied from the previous one; unlike before, continuous deposition of sediment was applied on the protected area. The fill was placed at depths between 2 and 4 m, see Fig. 12. The filling period as well as the time following it was characterized by different hydrodynamic conditions than it was in the preceding years. Most importantly, the wave incidence was nearly shore normal, resulting in low longshore current velocity and substantial cross-shore water flows. The filling parameters and the fill efficiency are demonstrated in Table 1.

The measurements of submerged and emerged beach just after the end of nourishment revealed exceptionally high efficiency; it was estimated to have reached 80%. Such a high effectiveness could be attributed to:

- more perpendicular wave incidence producing low longshore currents,
- alongshore continuous sand deposition,
- less accurate calculation of the nourishment efficiency originated from the necessity of processing

Fig. 11. Location of fill in 1985 (photo by M. Skaja).

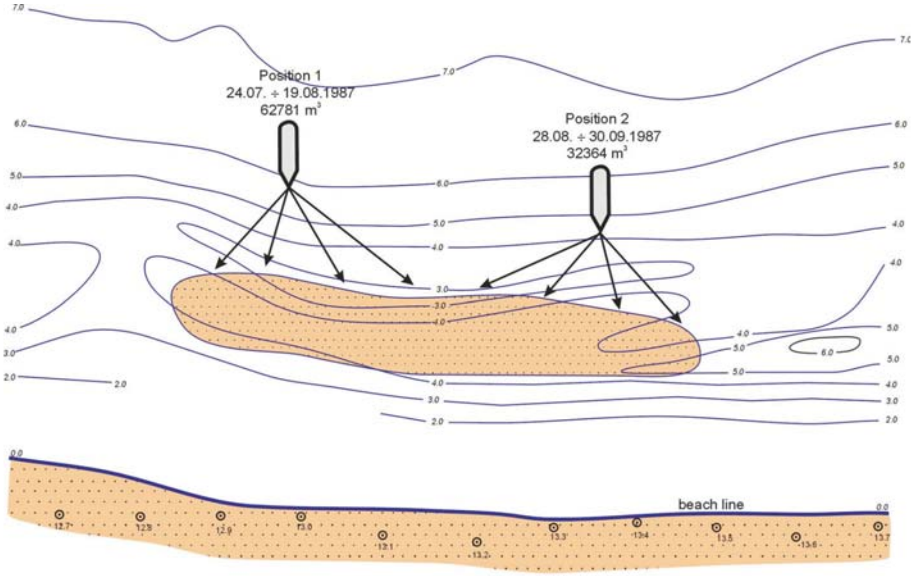

Fig. 12. Location of fill in 1987 and sediment deposition technology.

larger amount of data and greater deposition length.

About 5 m offshore shoreline displacement was observed just after beach nourishment and 10-25 m after 3-4 months of sand filling. The nourished area also revealed a vivid shoaling of the foreshore in form of an underwater terrace.

CONCLUSIONS

When a perpendicular structure is built in a system with natural longshore sediment transport, accumulation on the updrift side of the structure can be expected in connection with erosion on the lee side. The rate and extent of these phenomena depend on the intensity of wave climate and currents, availability of sediment and structure characteristics. The impact of harbour construction on the lee side erosion can reach many kilometres.

When artificial beach nourishment is implemented very fine sediment should be avoided. If the grain size D<0.2mm then this material will be easy mobilized by waves and currents and only about 10-20% will stay in the nearshore zone. Thus, it requires increase of volume of the fill by 2.5 times. Therefore, the fill should be coarser or at least not finer than the native sand,

Top effectiveness of beach nourishment can be achieved by placing material directly on the beach or dune. Sand fill should be alongshore continuous.

Up- and downstream the nourished beach segment shoreline erosion can be expected with various intensity; more severe erosion is usually anticipated in the downstream region and just behind groins, if they exist.

Nourishment efficiency strongly depends on the wave climate, the angle of wave incidence in particular. In the case of dissipative, sandy beach showing tendencies towards erosion, e.g. the South Baltic coast, we can expect returning to initial situation at some places due to sand dispersion. In the analysed case it is about 2 years after the beach nourishment.

Some time after the beach nourishment (2 years in the case studied) much better downstream situation was observed due to alongshore-sand displacement. Beach nourishment efficiency after 2 years was equal to 24%; (66000 m^3 vs. 280000 m^3).

Artificial beach nourishment should be well prepared. After completion of the fill it should be monitored to trace its displacements and disintegration. If the erosion continues on time re-nourishment is recommended.

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