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Sediment Transport Issues Related to a Planned Cross-cut through the Vistula Spit, Poland

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Abstract

In order to make a navigable connection between the Vistula Lagoon and the Baltic Sea independent of an attitude of the Russian authorities, a cross-cut in the Polish part of the Vistula Spit is planned. The cross-cut will constitute an alternative waterway with respect to the existing one, leading through the Pilawa Strait which belongs to the Russian territorial waters. The new outlet will require breakwaters and an approach channel on the open sea side, as well as a waterway across the Vistula Lagoon to the harbour of Elbląg. The planned cross-cut is located about 3 km from the root of the Vistula Spit, at Skowronki village. The paper comprises an analysis of regional wave parameters in a mean statistical year on the basis of the Baltic wave climate reconstructed for the period of 44 years, together with a calculation of the longshore sediment transport rates. An influence of the planned coastal structures on the shoreline evolution, as well as the approach channel silting-up rates, in the first 10 years after the construction of the cross-cut, are estimated. An optimised layout of the planned approach channel and lengths of the planned breakwaters are recommended to facilitate the maintenance of the coast and the new waterway.

Key words: Vistula Spit, cross-cut, waves, sediment transport, breakwaters, silting-up, shoreline changes

1. Introduction

A new investment planned as a waterway in the Vistula Lagoon and a cross-cut through the Vistula Spit will be an important enterprise in the Baltic coastal and harbour engineering. The planned venture causes numerous discussions among engineers, sailors, fishermen, biologists, ecologists and politicians. Results of these discussions echo with publications in scientific journals and in press, as well as in the other mass media. The stakeholders and decision makers are slightly confused because a spectrum of the specialists' opinions is very wide and varies from enthusiastically positive to totally negative. This is because the topic is extremely complex and multidisciplinary. The argument involves professionals from various disciplines and attracts an interest of the society, public opinion and authorities of all levels, from the local to the governmental.

The idea of the cross-cut, accepted in 2007 by the Polish government, particularly attracts attention of the authorities of Elbląg city and Warmia-Mazury voivodeship (province). The investment is regarded as crucially important in the economical and political context. The Vistula Lagoon partly belongs to Poland and partly to the Russian Federation. Aside from a few small fishery harbours and marinas, there is a larger harbour of Elbląg located in the Polish part of the Vistula Lagoon. The only waterway from the Lagoon to the Baltic Sea goes through the Pilawa Strait, near Baltiysk, on the Russian side, as shown in Fig. 1. Very frequently, Russian authorities have made difficult or impossible for foreign (even Polish) ships to sail through the Pilawa Straight. The construction of the cross-cut in the Polish part of the Vistula Spit will facilitate operation of the Polish harbours in the Vistula Lagoon, and will ensure convenient links of these harbours to the harbours in the Gulf of Gdańsk. Aside from the political success, the venture will bring considerable financial benefits to the Polish maritime economy, ensuring a sustainable development of the Elbląg harbour, undisturbed by any political turbulence. The concept is supported by many companies comprising almost all branches associated with the maritime economy: sea and inland water transport, fishery, tourism, yachting and many others. The new planned waterway will play an important role not only on regional, but also on national and international scales, since it will activate navigation in the Vistula Lagoon and in the South Baltic. Many towns and villages located on the shores of the Vistula Lagoon will gain better conditions for the development of water sports, improvement of touristic infrastructure and establishment or upgrade of recreational facilities.

On the other hand, the planned venture is said to be catastrophic to environment, including the flora and fauna (both water and inland). According to some opinions, the Vistula Lagoon water will be polluted due to dredging works. Further, the investment will allegedly be unprofitable due to enormous costs of maintenance of the waterway through the Vistula Lagoon and the approach channel to the cross-cut on the Gulf of Gdańsk side.

In this situation, the Maritime Office in Gdynia (acting on behalf of the Polish Ministry of Infrastructure) ordered a feasibility study on the cross-cut. The results of the Feasibility Study (2007/2008), have shown that the venture will be economically profitable and that the environmental impact of the cross-cut will be scarce.

Independently of the above-mentioned initiative, the Institute of Hydro-Engineering of the Polish Academy of Sciences (IBW PAN) in Gdańsk has undertaken a research-developmental project (Kaczmarek et al 2008) funded by the Polish Ministry of Science and Higher Education. The project, entitled "Analysis of hydro- and lithodynamic processes nearby the planned Vistula Spit cross-cut, prediction of its impact on neighbouring beach segment and assessment of silting-up intensity of the navigational channel between the cross-cut and the Elbląg harbour", has been carried out in collaboration with the University of Warmia and Mazury in Olsztyn.

Fig. 1. Location of a planned cross-cut through the Vistula Spit and a planned waterway in the Vistula Lagoon

The project has resulted in an assessment of the influence of the planned cross-cut on the sea shores of the Vistula Spit. Secondly, the silting-up of the planned waterway in the Vistula Lagoon and the planned approach channel to the cross-cut on the Gulf of Gdańsk side. Additionally, optimising recommendations concerning the breakwaters at the entrance to the cross-cut on the Gulf side have been formulated. The project objectives have been achieved by means of field investigations and numerical computations. The computations (theoretical modelling) have comprised a number of physical processes, i.e. waves, wave-driven currents and sediment transport in the coastal zone of the Gulf of Gdańsk, as well as hydrodynamic and lithodynamic processes in the Vistula Lagoon.

Aside from the above-mentioned practical engineering usefulness of the present study, one should point out at least two research aspects, indicating an improvement of the knowledge on physical processes occurring on the Polish coast. Identification of the resultant direction of sediment motion along the Vistula Spit is the first scientific achievement of the study. The computations carried out by the Dutch software have shown that the arched shape of the Vistula Spit coast is a reason of a gradual decrease of the eastwards directed longshore sediment transport to a zero rate at a point where the net sediment flux reverses and starts to be directed westwards. These results have then been validated using the IBW PAN model for size-graded sand transport. Application of this approach to the modelling of the longshore sediment transport and to the predictive calculations of silting-up of the planned waterway has not only given rise to verification of practical capabilities of the model, but has also confirmed an importance of grain-size distribution features in the mathematical modelling of sediment transport. This can be regarded as the second aspect of novelty of the present study.

2. Problem Description

Maintenance of waterways and approach channels is always associated with some costs of necessary periodical dredging works. These costs, correlated with the frequency and intensity of dredging activities, depend on many factors, i.e. on a bathymetric situation of the area adjacent to a waterway, local wave climate, features of seabed sediments and navigational requirements which imply the waterway course and depth. In basins shielded by capes and peninsulas, as well as in case of channels dredged at relatively large natural depths (e.g. approach channels to the harbours of Gdańsk and Gdynia, 15–17 m deep, at the natural depths of about 10 m), the silting-up volumes are quite small. The maintenance of such waterways requires rare dredging activities at small scale. In case of harbours located on open coasts, with breakwaters spreading not far seawards and reaching limited depths, the silting-up process is much more intensive and the navigation safety requires regular and frequent dredging (in practice, the approach channel and the harbour entrance must be dredged after each strong storm).

Silting-up of the approach channel and the harbour entrance is substantially reduced if the breakwaters spread offshore to larger depths. In such a situation, however, the breakwaters affect adjacent shore segments, usually causing coastal accumulation on one side of the harbour and the compensating erosion on the other (a so-called lee-side effect). In this context, the contemporary coastal engineering should impose, first of all, an optimisation of the breakwaters layout and length and secondly a prediction of the above-mentioned side effects, together with an anticipation of mitigation actions to maintain lithodynamic equilibrium nearby the harbour structures, most often by use of a sediment bypassing system.

According to the Polish regulations, every constructional activity in the coastal zone requires previous assessment of the influence of the planned venture on the seashore and the coastal environment. The influence of the planned cross-cut and the breakwaters on the adjacent coastline of the Vistula Spit has been investigated at IBW PAN (reported in detail by Kaczmarek et al 2008) and is described concisely in the present paper. The environmental issues have been partly clarified in the Feasibility Study (2007/2008). In that study, a number of problematic questions have been considered, among which the increase of salinity in the Vistula Lagoon due to the inflow of seawater through the cross-cut has been analysed. It has been found out that the Vistula Lagoon ecosystem will not be harmed by salt water as the increase of salinity in the adjacent part of the Lagoon will not exceed 1 p.s.u. (even if a lock in the cross-cut will be operating continually). The Feasibility Study (2007/2008) has comprised many other ecological and biological issues (e.g. linked to ease of migration of animals along the Vistula Spit), not reported in the present paper.

The planned enterprise will cost hundreds million Euro. Such a huge investment requires prior thorough consideration of all technical aspects (implying the costs) of the maintenance of the new waterway. In addition, any influence of the venture on the seashore ought to be minimised. To this end, optimising numerical simulations have been run, yielding recommendations for construction engineers who are now able to produce a sustainable design.

One should bear in mind that technical interference in natural hydrodynamic and lithodynamic coastal processes can result in fatal consequences in the form of an increased shore abrasion. The Polish Parliamentary Law of 28 March 2003 on a multi-year programme entitled "Shore Protection Programme" anticipates "stabilisation of the shoreline at its position of 2000 and prevention of beach disappearance". The Law indicated coastal segments which should be subject to protection and thorough monitoring. Fortunately, the coast in the region of the planned cross-cut is rather stable and no protective measures are suggested there. The preservation of the current state of the coast along the Vistula Spit is a *sine qua non* condition of the planned operation.

Since the concept of the cross-cut through the Vistula Spit is not new, there have been many papers dealing with this idea, among which the most important ones are the publications by Gajewski et al (1995), Jednorał (1996), Dubrawski & Zachowicz (1997), Zadroga et al (1997), Dembicki et al (2006) and the latest ones by Kaczmarek et al (2009a, b and c).

3. Natural Coastal Conditions nearby the Planned Cross-cut

The bathymetric-tachymetric survey in the coastal zone of the Vistula Spit on the Gulf of Gdańsk (the Baltic Sea) side nearby the location of the planned cross-cut was carried out in autumn 2007. The measurements comprised the beach (up to the dune toe) and the nearshore zone stretching about 800 offshore and 2 km alongshore. The bathymetric-tachymetric profiles, perpendicular to the averaged shoreline course, were spaced by 100 m.

The survey has shown that there are two bars in the coastal zone: the first one is located about 80 m and the second one about 250 m from the shoreline. The mean slope of the sea bottom amounts to about 1%, see Fig. 2. The shore is typically dissipative, which means that the wave energy is gradually and mildly dissipating while waves are approaching the shoreline.

It has been found from the analysis of soil samples collected in autumn 2007 that the seabed in the region consists of sandy sediments with various grain sizes along the cross-shore transect. Far offshore, at water depths of 5–9 m, fine sand has been

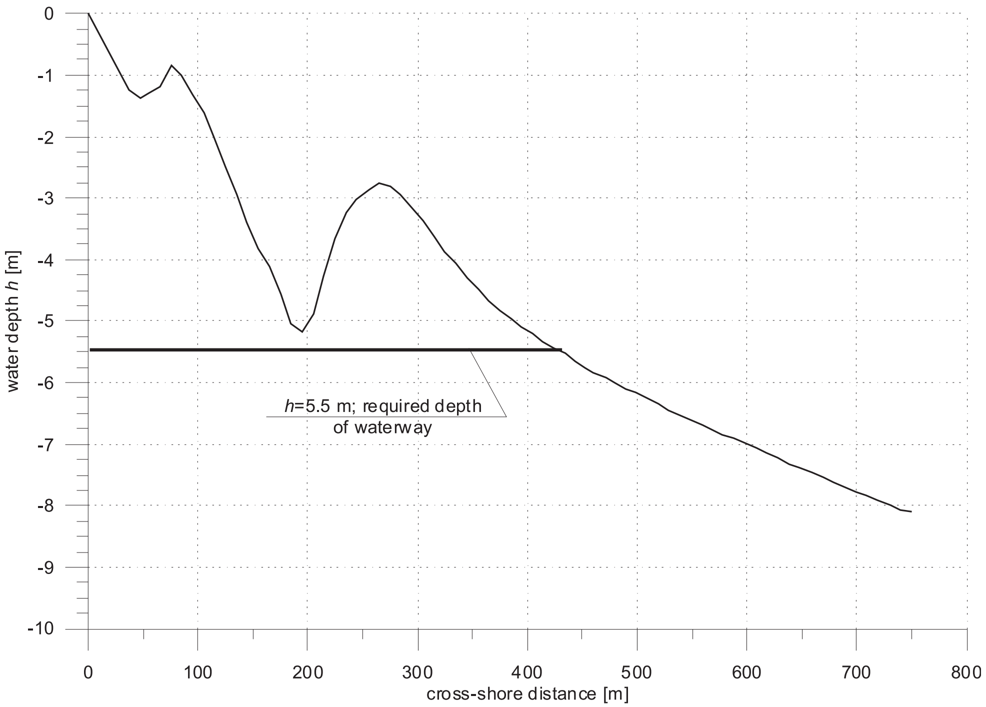

Fig. 2. Characteristic cross-shore profile on the seaward side of the Vistula Spit (the Gulf of Gdańsk, the Baltic Sea) nearby the planned cross-cut; survey carried out in November 2007

detected, with the median grain diameter d_{50} = 0.12–0.15 mm, while in the nearshore zone, at depths of 1–4 m, coarser sand occurs, having the median grain size d_{50} = 0.17–0.25 mm. In the direct vicinity of the shoreline and on the emerged part of the beach, the median grain diameter d_{50} amounts to 0.21–0.38 mm.

Cumulative grain size distributions of sediment collected at various depths nearby Skowronki (where the cross-cut through the Vistula Spit is planned) are shown in Fig. 3. The water depths at which the samples have been collected, are given in the figure legend, while the locations of seabed samplings on the cross-shore profile are as follows (cf. Fig. 2 for the cross-shore profile shape): 31M-4, 46M-3, 41M-4, 36M-4, 31M-5, 51M-3 and 41M-5 – seaward slope of the second (offshore) bar, 41M-6 and 31M-6 – landward slope of the second (offshore) bar, 36M-6, 46M-6, 51M-4, 36M-7, 31M-7, 46M-7, 41M-7 and 51M-5 – seaward slope of the first (nearshore) bar.

In the analysis of vulnerability of the approach channel to silting-up, parameters of sediment samples were used which had been collected at the point named 31M-7, at water depth of 2.2 m, as well as the sediment features averaged from samples collected at depths 0.8–4.0 m and 4.0–6.0 m (see Fig. 3). Besides, the silting-up analysis comprised a case of uniform (non-graded) sand, with the grain diameter of d_{50} = 0.22 mm.

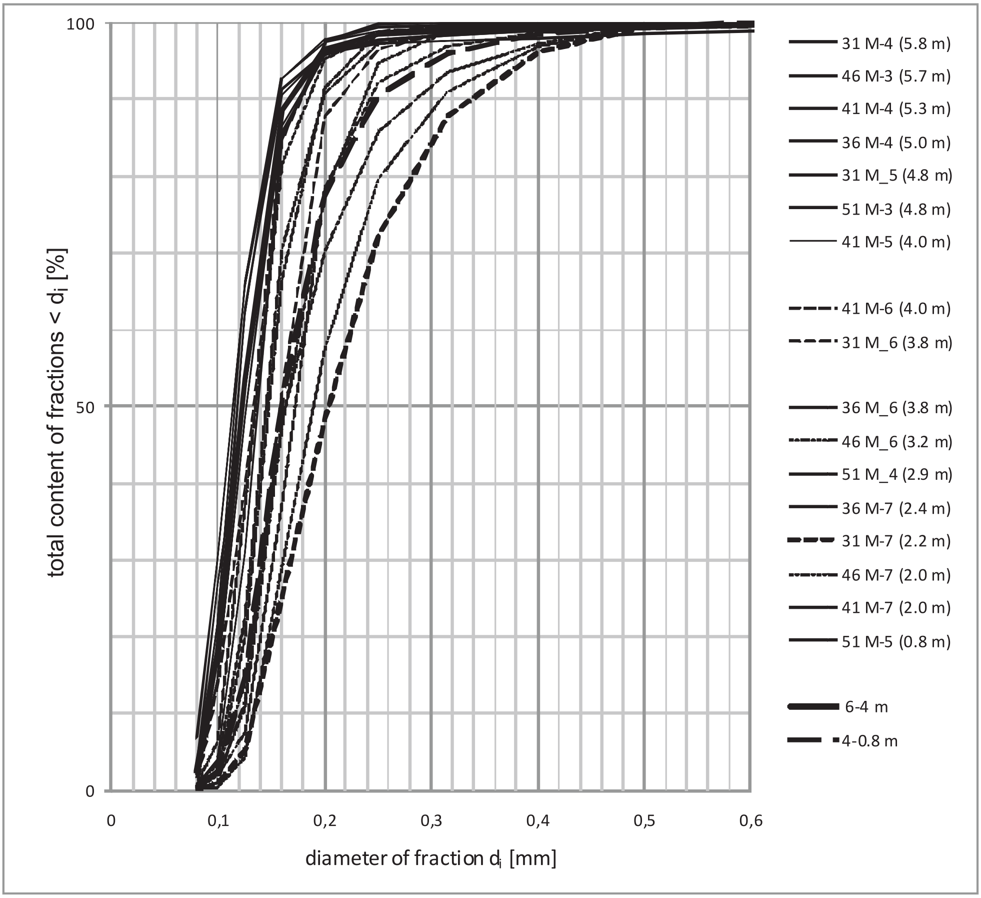

Fig. 3. Cumulative grain size distributions of sediment collected at various depths nearby Skowronki

4. Wave Parameters in the Coastal Zone of the Vistula Spit

There have been not many regular wave measurements carried out in the south Baltic Sea. No wave data are available for the eastern part of the Gulf of Gdańsk. In order to determine wave conditions in the coastal zone of the Vistula Spit, a numerical prognostic wave model has been used, based on meteorological (wind and air pressure) input.

The wave model WAM4 was previously used at IBW PAN for reconstruction of the long-term wave climate in the period from 1958 to 2001. The model is based on a so-called wave action balance equation and takes into account the energy transfer from wind to the sea, "white-capping" wave breaking, bottom friction and resonance interactions of wave components. The model resolution of the spatial grid was

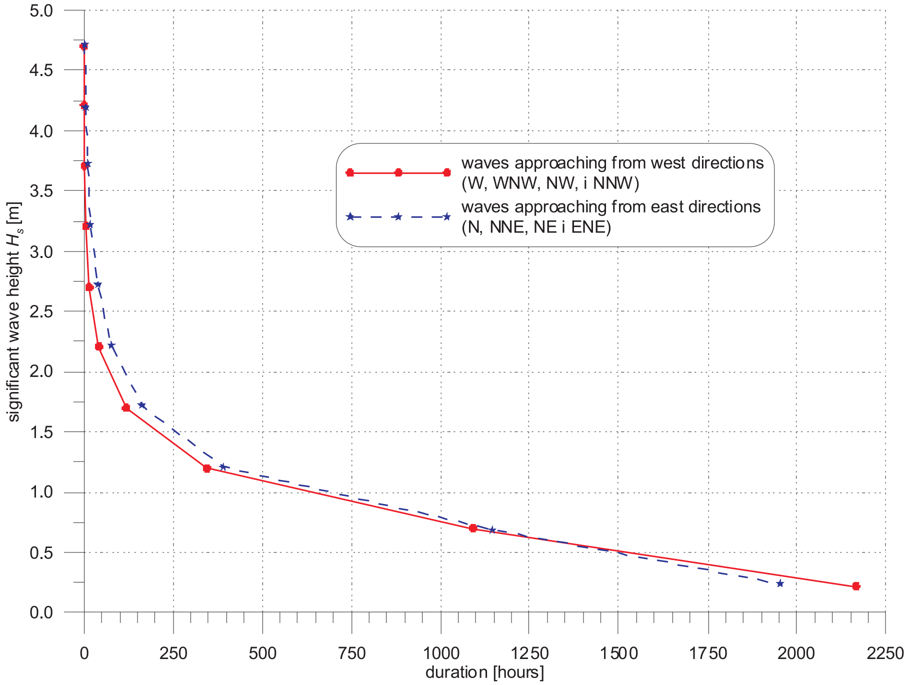

Fig. 4. Duration of significant wave heights for west and east directions nearby the location of the planned cross-cut in the mean statistical year

$5' \times 5'$ (about 9×9 km). The model time step of the input wind data amounted to 1 hour. This input was next interpolated, yielding computational resolution of 300 s. At each grid point, for each hour of the 44 year long reconstruction period, the computational results comprised the following representative wave parameters: significant wave height, wave period and wave ray direction.

Comparison of the above modelling results and field measurements of waves, as well as satellite observations, have shown that the model WAM4 approximates actual waves very well and can be useful in an analysis of wave climate in the Baltic Sea, see Cieślikiewicz & Paplińska-Swerpel (2008).

In order to determine wave parameters in the mean statistical year nearby the location of the planned cross-cut, the prognostic point has been chosen at geographical coordinates of 54°25′ N and 19°18′ E, at the water depth of $h \approx 45$ m, about 6 km from the shoreline. Wave heights in the wave climate have been determined with the resolution of 0.5 m. For each range of wave height, the analysis has yielded the significant wave height (H_s) and the wave period corresponding to the spectral peak of wave energy (T_p), azimuth of the wave propagation direction (A_z), and duration time. The distributions of wave heights and their durations, separately for waves coming from west and east sectors, are given in Fig. 4. At the location of the planned cross-cut, the waves coming from W, WNW, NW and NNW approach the shore from the west (left hand side), while the waves from N, NNE, NE and ENE approach the shore from the east (right hand side). The analysis carried out for the mean statistical year, results of which are depicted in Fig. 4, shows that the directional distribution of waves is well balanced – the duration of waves from the west is almost identical to the duration of waves from the east. The highest waves approach the site from NNW and N, having H_s = 4 m, T_p= 11.2 s and the duration of about 3 hours.

5. Lithodynamic and Morphodynamic Processes along the Vistula Spit

The south Baltic coast along the Vistula Spit in the Gulf of Gdańsk ranks among accumulative beach-dune shores. The zone of dunes is about 500 m wide. The dunes, covered by bushes and trees, attain a height of about 30 m. As reported by Zawadzka-Kahlau (1999), the shores of the Vistula Lagoon are stable, with the mean annual coastline displacements from the Polish-Russian border (KM 0.0) to Kąty Rybackie at the Vistula Spit root assessed as follows:

<u>Shoreline</u>
in 1911–1979 => accumulation of +0.15 m/year,
in 1960–1983 => erosion of –0.15 m/year,
in 1971–1983 => erosion of –0.37 m/year.
<u>Dune toe</u>
in 1960–1983 => erosion of –0.06 m/year,
in 1971–1983 => erosion of –0.26 m/year.

The other detailed analysis of shoreline evolution for the region of the planned cross-cut (KM 27.0) by Zawadzka-Kahlau (1999) implies that accumulative processes prevailed in the period from 1908 to 1978, with the mean shoreline advance of +0.6 m/year, while erosion predominated in the periods 1960–1982, and 1973–1982 with the mean rates of –0.7 and –1.8 m/year, respectively. In the same periods, the dune toe was eroded as well, however, with much less intensity, amounting to –0.1 and –0.2 in 1960–1982 and 1973–1982, respectively.

It can be generally concluded that lithodynamic processes at the Vistula Spit shores are rather weak and yield very slow evolution of the seabed. Further, according to Zawadzka-Kahlau (1999), the location of the planned cross-cut lies nearby a place of convergence of two longshore sediment fluxes. Hence, the local resultant longshore sediment motion is not intensive.

According to Musielak (1980), there are a few points of convergence of the longshore sediment fluxes in the Gulf of Gdańsk. In its east part, Musielak (1980) suggests on existence of two such points: in the vicinity of Baltiysk and nearby the root of the Vistula Spit. Places where the longshore sediment fluxes converge or diverge are certain singular points of discontinuity at which two-directional sand motion can take place at the same cross-shore profiles. Such a concept with respect to a number of locations on the Polish coast, including the shore of Vistula Spit, was presented by Cieślak (1985).

6. Sediment Transport Rates at the Location of the Planned Cross-cut

Coastal sediment transport is generated by hydrodynamic processes, namely waves and currents, especially the currents induced by waves breaking in the surf zone. The sediment transport rate depends on the intensity of nearshore hydrodynamic events and the bathymetric layout of the coastal zone, as well as on the amount of sandy sediments accumulated in the nearshore seabed.

Within the present study, computations of the longshore sediment transport rates have been carried out using the licensed software UNIBEST-LT ver. 4.0 (1993), produced by Delft Hydraulics, the Netherlands. This numerical package enables the user to run theoretical modelling of wave transformation by Battjes & Janssen's (1978) model and the longshore sand transport for chosen representative cross-shore transects. Such a representative cross-shore profile, located in the region of the planned cross-cut, has been selected from the bathymetric data of November 2007. The profile azimuth amounts to 350° and its shape is plotted in Fig. 2.

The numerical modelling of wave transformation, wave-driven currents and longshore sediment transport has been carried out for all input wave parameters shown in Fig. 4. The measured cross-shore profile, originally reaching the depth of only 8 m, has been elongated to the location of the offshore wave prognostic point, i.e. to the depth of 45 m. The missing data have been digitised from a navigational chart of the Gulf of Gdańsk. In the computations, the median grain diameter has been assumed as d_{50} = 0.22 mm.

In the UNIBEST-LT programme, the sediment transport rates can be calculated by use of 5 classical theoretical models, i.e. of Bailard, Bijker, CERC, Engelund-Hansen and van Rijn. It appears from the experience of the Authors of the present paper that for the south Baltic coastal conditions the model of van Rijn (1993) yields very reliable results. As an input wave height in the model, the significant wave height H_s is used. The simulated total net sand transport rate and the distributions of rates for individual wave directions are shown in Fig. 5. According to the Polish convention, the eastward directed sediment motion rates are denoted as positive while the westward directed rates are negative.

Analysing the sediment transport rates in Fig. 5 together with the cross-shore profile shape in Fig. 2, one can distinguish three sediment fluxes. The first one is relatively weak and takes place in the direct vicinity of the shoreline, having width of about 50 m. The second flux of sandy sediment is very strong and occurs on the seaward slope of the first (nearshore) bar. The third flux has moderate intensity and concentrates about the seaward slope of the second bar. It can be seen in Fig. 5 that the offshore range of sediment motion does not exceed 400 m and the main stream of sediment moves along the shore in the zone 160 m wide from the shoreline. It is also worthwhile noting that local sediment transport rates are very small, appearing as values close to zero in Fig. 5. This takes place at distances of 40–60 m and 150–230 m from the shoreline. This is justified by the cross-shore profile shape (cf. Fig. 2) which displays

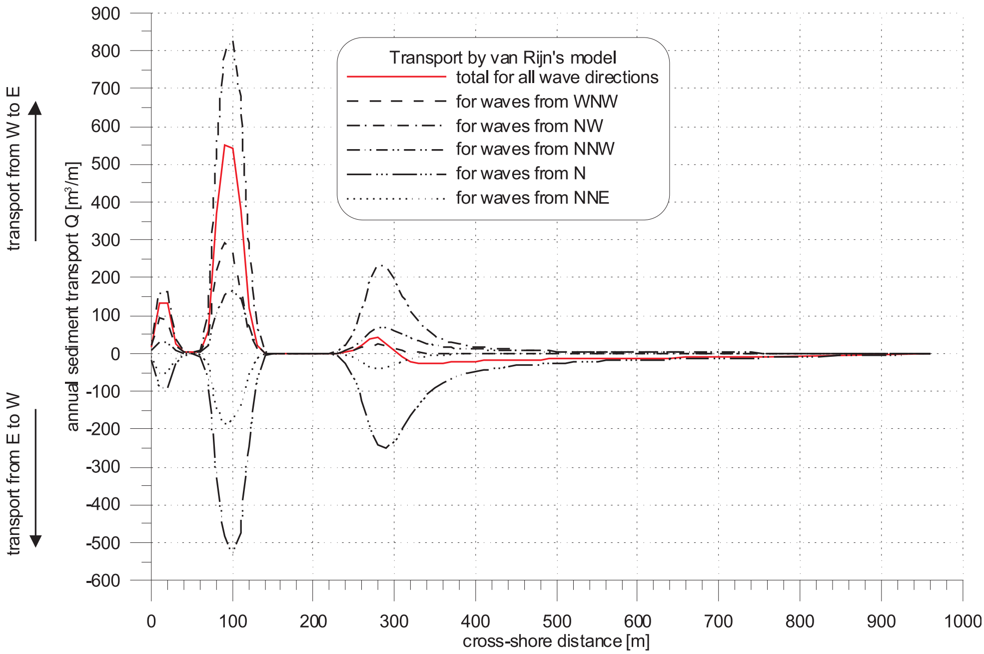

Fig. 5. Computed annual sediment transport rates for the cross-shore profile of the Vistula Spit at location of the planned cross-cut

bottom troughs at these locations. The wave height is subject to considerable decrease after wave breaking which takes place on the seaward slopes of the bars and on the bar crests. The wave conditions become much less intensive in the troughs and the modelled bed shear stresses are insufficient to cause any significant sediment motion. In actual coastal conditions, at a presence of the roller (rotating mass of water in front of the breaking wave), the longshore currents are observed also over bar troughs and interact with wave-induced near-bed orbital velocities. This effect gives rise to the existence of the longshore sand transport also over troughs between the bars, which unfortunately is not reproduced by the model.

The largest longshore sediment transport rate is generated by waves approaching the shore from NW and N, while a very small one is induced by waves from W, NE and ENE. The total sediment transport rate from the west to east amounts to about 84000 m^3/year, while the total rate of sediment transport in the opposite direction equals about – 68000 m^3/year. As a result, the net transport is directed eastwards and its rate is about 16000 m^3/year. The net transport is very specific because it is two-directional (see Fig. 5): the main sediment flux in the zone 0–300 m from the shoreline is directed eastwards, while the sediments in the offshore zone move westwards. The detailed quantities of these rates are as follows:

– resultant transport in the zone 0–300 m from the shoreline, directed eastwards => 25126 m^3/year,

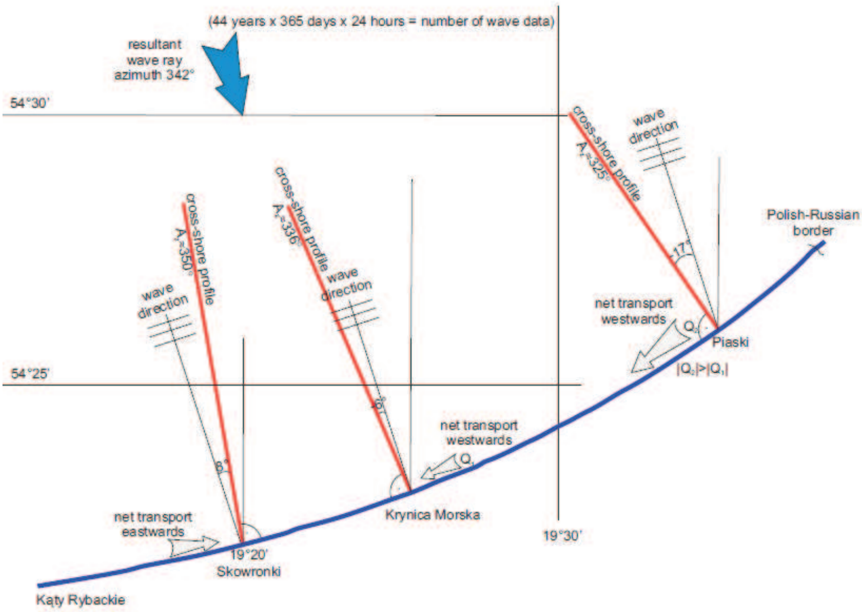

Fig. 6. Variability of the resultant wave approach angle in the mean statistical year along the Vistula Spit coast (the shoreline is copied from the navigational chart: "Gulf of Gdańsk – east part", scale 1:75000)

– resultant transport in the zone more than 300 m from the shore, directed westwards => –8765 m^3/year,
– net transport in the entire cross-shore profile, directed eastwards => 16361 m^3/year.

The obtained computational results are in agreement with the findings of Gajewski et al (1995), Jednorał (1996) and Zawadzka-Kahlau (1999) in which seabed dynamics is said to occur mainly nearby the first bar and the second bar. According to the above publications, at depths greater than 5 m the seabed changes are very small while for depths of 6 m and more no seabed evolution is observed. Further, eastward and westward sediment fluxes are almost the same and thus mutually balanced.

In the mean statistical year, the resultant azimuth of the wave approach, determined as a weighted mean of wave directions and durations of individual wave conditions, amounts to 342°40′. For the representative bathymetric cross-shore profile having the azimuth of 350°, this denotes that the resultant wave ray is deviated from this profile by less than 8°. The arched shape of the shoreline of the Vistula Spit causes that the cross-shore transects located eastwards from the analysed site have smaller azimuths. As a result, assuming similar offshore wave climate in the area, one can expect a decrease in the longshore sediment transport rate, and even a change in the direction of this transport, as depicted in Fig. 6. This conclusion agrees with hypotheses of Jednorał (1996) and Zawadzka-Kahlau (1999) who claimed that the region of Krynica Morska (middle of the Vistula Spit) is a place where two opposite longshore sand fluxes converge. This implies that the net annual longshore sediment transport westwards of Krynica Morska is directed eastwards, while the transport eastwards of Krynica Morska is directed westwards.

7. Influence of the Planned Breakwaters on the Shores of the Vistula Spit

The planned breakwaters, shielding the entrance to the cross-cut from sea waves, will constitute an obstacle to the sediment motion. Such a perturbation usually causes shore accretion on one side and erosion on the other. Intensity of these processes grows with the length of the structure.

Until now, no detailed design of the breakwaters has been elaborated. The Feasibility Study (2007/2008) presents only drawings of draft ideas. In order to design an ultimate layout of the breakwaters, constituting a small harbour at the cross-cut, the following criteria ought to be considered:

1. requirements concerning safe navigation of vessels at the entrance to the harbour,
2. limitations concerning the maximum wave height allowed in the harbour during an extreme storm,
3. purpose of the planned harbour – a shelter for fishery boats, marina for large yachts or only a wave-protection measure for vessels entering the cross-cut.

Independently of the above criteria, it can be assumed at the present stage of design that the minimum seaward stretch of the breakwaters should amount to 350 m at minimum. This quantity results from the regionally observed shore face shape, with the crest of the second bar located about 240–300 m from the shoreline and natural depth of 4 m occurring about 350 m from the shoreline. The approach channel to the planned cross-cut will have the depth of 5.5 m, and it will be inconvenient if the channel goes through the second bar, because it will be silted-up very quickly (the main longshore sediment flux takes place there, see Fig. 5). Thus, the designers will probably suggest breakwaters at least 350–400 m long.

As it has been mentioned before, the net longshore sediment motion at the site in the mean statistical year is directed eastwards. In such a situation, if the breakwaters are built, accretion of the shore will take place on the westward side of the harbour, compensated by erosion on its east side. The intensity of the above processes depend mainly on the net longshore sand transport rate and the length of the breakwaters. The layout (shape in plan) of these breakwaters is not so important. It should be expected, however, that the arched shape of the breakwaters will facilitate natural sediment bypassing around the harbour in comparison to straight breakwaters perpendicular to the shoreline.

The predictive computations of long-term shoreline evolution after the construction of the harbour have been carried out using the numerical programme

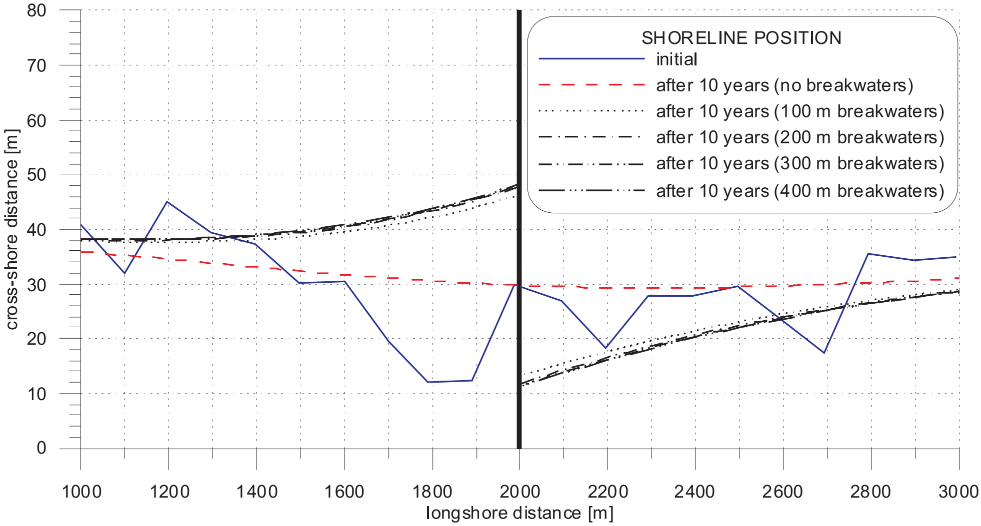

Fig. 7. Numerically simulated shoreline changes at the planned cross-cut after 10 years for various lengths of the breakwaters

UNIBEST-CL ver. 4.0 (1993). The influence of the breakwaters on the coastal morphodynamic processes has been represented in the model in the form of a single impermeable groin. The length of this groin was changed for individual model runs and amounted to 100, 200, 300 and 400 m.

The results of prognostic modelling for 10 years of the impact of the breakwaters are presented in Fig. 7. It has been assumed in the computations that the longshore sediment transport is driven by the wave conditions of the mean statistical year. For such a wave climate, the model has yielded accumulation of sediment westwards of the harbour and a lee-side effect in the form of shore erosion eastwards of the harbour. It can be seen in Fig. 7 that the changes in the shoreline position does not depend much on the breakwaters length, as most of the sand transport takes place close to the shore (cf. Fig. 5). The long-term shoreline displacements do not exceed 20 m and the range of coastal changes amounts to about 1000 m westwards and eastwards of the planned harbour structures.

8. Relation between the Planned Breakwaters and Silting-up of the Approach Channel

The length of the breakwaters will have a significant influence on the intensity of silting-up of the approach channel to the planned cross-cut through the Vistula Spit. The longer the breakwaters are, the shorter the required approach channel and consequently the smaller silting-up rates.

The prognostic computations were carried out using a size-graded sediment transport model which has been developed at IBW PAN for several years. The model ensures the determination of sediment transport rates taking into account all sandy fractions present in the seabed. This capability of the model is very important, since aside from the median grain diameter d_{50}, the entire grain size distribution should be known to simulate the sediment motion accurately, especially when larger amounts of fine sand are found in the sediment.

The model distinguishes three layers of motion, namely the bedload layer, the transitional (contact) load layer, and the outer region (freely suspended load layer). Interactions between sand grains are different in each of the layers and they are therefore modelled by use of different equations. The individual solutions match each other at interfaces between the layers. This provides a complete theoretical description of the transport of sandy sediments.

In the modelling, an assumption is made that all fractions of the bedload layer move with the same velocity as a dense water-soil mixture, and no sorting of grains takes place in this layer. It is also assumed that interactions between the fractions are very strong, causing an inhibition of fine particles by coarse grains.

In the contact load layer, an intensive vertical sorting of grains is taken into account. Turbulent pulsations and chaotic collisions of grains in this layer give rise to huge differences between the motion of the individual fractions. It can thus be expected that each fraction move with its specific velocity and has its specific concentration of grains. The velocities and concentrations of a coarse fraction in the contact load layer are higher than they would be if the seabed was size-uniform (non-graded), built of only this fraction. In the mixture of fractions, coarse grains are "driven" and accelerated by fine (more mobile) particles.

In the outer region of the sand motion, beyond the contact load layer, no changes of grain size distribution of transported sediments are assumed. The vertical profile of concentration is described by a power function.

In the predictive calculations of the silting-up rates, the wave motion characterised by the root-mean-square wave height H_{rms} and the wave energy peak period T_p has been approximated by second-order Stokes theory, which describes the water surface as narrow-crested high waves, with wide and shallow troughs between crests. The assumption of the root-mean-square wave height H_{rms} and the peak period T_p as the parameters representative for irregular (random) wave motion has been successfully verified for the present three-layer sediment transport model by use of numerical and laboratory experiments. Results of this verification were published by Kaczmarek & Ostrowski (1996) and Kaczmarek & Ostrowski (1998).

On the windward edge of the approach channel, the sediment is transported into the channel during the wave crest phase in the bedload and contact load layers, as well as due to a resultant (wave-driven) current in the outer layer. Close to the leeward side of the approach channel, the sediment is moved into the channel in the bedload, and the contact load layers only during the wave trough phase.

An influence of the grain size features on the silting-up rates is depicted in Fig. 8. The calculations have been carried out for 6 variants of the waterway, defined by var-

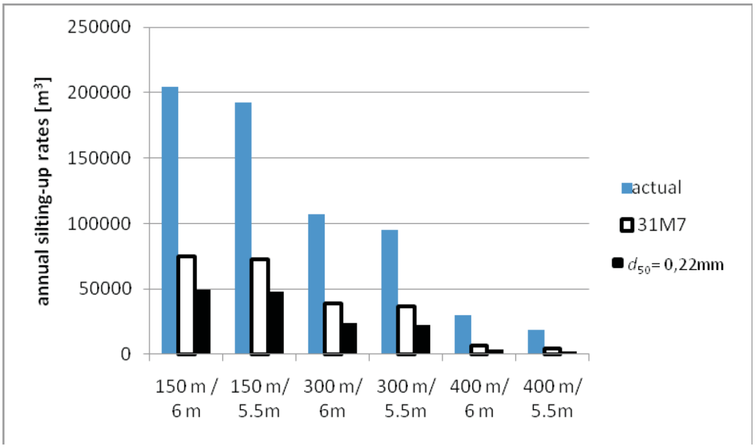

Fig. 8. Computational results of silting-up rates for various types of sediments, various lengths of the breakwaters, and various depths of the waterway

ious lengths of the planned breakwaters and various depths of the navigation channel. The smallest sedimentation in the approach channel has been obtained for the breakwaters 400 m long and the waterway 5.5 m deep. For this situation, the annual silting-up rate will amount to 18 500 m^3 if fine fractions dominate in the seabed (which actually takes place 400 m offshore and more). Such a quantity indicates a necessity of dredging works every year. If there are fewer fine fractions in the seabed, which is represented by the distribution 31M-7 and the non-graded sand with d_{50} = 0.22 mm, the sedimentation in the channel will attain about 4000 m^3/year and 2000 m^3/year, respectively. Such results suggest that occasional small dredging works will be needed.

It is worthwhile pointing out that the sediment sampled at the considered site (31M–7) resembles the soil collected close to the edge of another Polish navigation channel, namely at the approach channel to the harbour of Łeba (cf. Kaczmarek & Sawczyński 2007). Therefore, one can suppose that although actual sediments at Skowronki have now a considerable contribution of fine fractions, the long-term maintenance (dredging) of the waterway will lead to the set up of a similar content of fines as observed at the harbour of Łeba.

9. Summary and Conclusions

On the basis of the theoretical analysis and numerical modelling, the conclusions can be drawn, concerning the coastal hydro- and lithodynamic specificity of the Vistula Spit, as well as some technical issues related to the planned cross-cut through the Spit and the breakwaters on its seaward side. These conclusions are briefly listed below.

– The lithodynamic processes on the Vistula Spit coast are weak, which results in small seabed and seashore changes. The convergence of two opposite sediment fluxes takes place nearby the location of the planned cross-cut, and therefore the net annual longshore sand transport is small.

- Quantitative (rate) and qualitative (direction) variability of the net longshore sediment transport on the coast of the Vistula Spit is caused mainly by the arched shape of the shoreline and a spatially different shore exposure to the offshore wave climate.
- At the location of the planned cross-cut, the total longshore sediment transport rates amount to about 84 thousand m^3/year eastwards, and about 68 thousand m^3/year westwards, which yields the net rate of 16 thousand m^3/year only. The distribution of the net sediment transport displays two-directional features: the main sediment flux (ca. 25000 m^3/year) lies in the zone 0–300 m from the shoreline and is directed eastwards, while the secondary flux (ca. 9000 m^3/year) takes place further than 300 m from the shoreline and is directed westwards.
- In the distributions of the longshore transport rates, three major streams can be distinguished: the small one in the direct shoreline vicinity, the most intensive about the seaward slope of the first (nearshore) bar, and the third one on the seaward slope of the second bar. The sediment mostly moves in the zone 160 m from the shoreline. The longshore sediment transport does not occur at distances larger than 400 m from the shoreline.
- Due to the concentration of the longshore sediment motion close to the shore, the prognostic modelling of long-term (10 years) shoreline evolution yields almost identical results for breakwaters having the length of 100, 200, 300 and 400 m.
- The minimum breakwaters length should amount to 350 m. This quantity results from the regionally observed shore face shape, with the crest of the second bar located about 240–300 m from the shoreline, and a natural depth of 4 m occurring about 350 m from the shoreline. The approach channel to the planned cross-cut will have the depth of 5.5 m and it will be inconvenient if the channel goes through the second bar, because then it will be silted-up very quickly (the intensive longshore sediment flux takes place over the bars). Thus, the breakwaters ought to be designed with the length of about 400 m.
- The detailed numerical simulations of the silting-up rates for the breakwaters 400 m long and the waterway 5.5 m deep have shown that the sedimentation in the approach channel will amount to 18 500 m^3/year at maximum, if the sediment has a significant contribution of fine fractions. Such a rate implies the necessity of dredging at least once per year. If the content of fine fractions decreases, reaching a quasi-uniform sand with d_{50} = 0.22 mm or the grain-size distribution similar to 31M–7, which is probable during the long-term maintenance of the waterway, the annual silting-up intensity will drop to 2000–4000 m^3. Occasional small dredging works will be needed in such a situation.
- The numerically predicted changes of the shoreline position on both sides of the harbour equal about 20 m. Taking into account all errors and inaccuracies during the modelling of waves, currents and sediment transport, one can expect a total

error of about 100%. Thus, the expected shoreline displacements can lie in the range 10–40 m.
– The range of the shoreline changes after 10 years will amount to about 1000 m westwards and eastwards of the harbour.

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