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HYDRO- AND LITHODYNAMIC ASPECTS OF CONSTRUCTING A NAVIGABLE CANAL THROUGH THE VISTULA SPIT

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Key words: the Vistula Spit, the Vistula Lagoon, cutting, navigable canal, fairway, breakwater, sediment transport, silting up of fairways, changes in the shoreline, non-homogenous sediments.

Abstract

The paper presents hydro- and lithodynamic aspects of the intended construction of a navigable canal across the Vistula Spit. The discussion is based on the results of a study funded by a research and development grant carried out in 2007/2008 at the Institute of Hydro-Engineering of the Polish Academy of Sciences in Gdańsk in collaboration with the Chair of Civil Engineering and Building Constructions, Faculty of Technical Sciences, the University of Warmia and Mazury in Olsztyn. The paper also contains an analysis of the effect of planned breakwaters protecting the entrance to the canal from the Gulf of Gdańsk on the seaward shores of the Vistula Lagoon and the effect of their length on the silting up of the fairway. Some recommendations have been suggested regarding the optimal length of planned breakwaters.

HYDRO- I LITODYNAMICZNE ASPEKTY BUDOWY KANAŁU ŻEGLUGOWEGO PRZEZ MIERZEJĘ WIŚLANĄ

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Słowa kluczowe: Mierzeja Wiślana, Zalew Wiślany, przekop, kanał żeglugowy, tor wodny, falochrony, transport osadów, zapiaszczanie torów, zmiany linii brzegowej, osady niejednorodne granulometrycznie.

Abstrakt

W artykule przedstawiono aspekty hydro- i litodynamiczne planowanej budowy kanału żeglugowego przez Mierzeję Wiślaną. Dyskusję wyników przeprowadzono na podstawie rezultatów uzyskanych w ramach grantu badawczego rozwojowego realizowanego w latach 2007/2008 przez Instytut Budownictwa Wodnego PAN w Gdańsku we współpracy z Katedrą Budownictwa i Konstrukcji Budowlanych Wydziału Nauk Technicznych Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. Przedstawiono analizę dotyczącą oddziaływania projektowanych falochronów osłaniających wejście do przekopu od strony Zatoki Gdańskiej na odmorskie brzegi Mierzei Wiślanej oraz wpływu ich długości na zapiaszczanie toru wodnego. Analizę wykonano na podstawie autorskiej metody uwzględniającej zmienność uziarnienia osadów. Sformułowano zalecenia optymalizacyjne dotyczące długości projektowanych falochronów.

Introduction

Constructing a new fairway on the Vistula Lagoon and a canal across the Vistula Spit raises high emotions (cf. DUBRAWSKI, ZACHOWICZ 1997). Supporters emphasize the economic benefits to be gained by the Polish economy, should the canal and a new fairway be opened that would connect the Gulf of Gdańsk with the port in Elbląg. Those against the idea speak about catastrophic impact of the planned construction on environment and emphasize huge costs of maintaining a fairway across the Lagoon and an approach fairway from the Gulf of Gdańsk.

At this point, it is worth reminding the reader that the concept of cutting the Vistula Spit is not a new one. On the contrary, it goes back to the times of King Stefan Batory. In brief, the history of plans to dig a canal across the Vistula Spit is as follows:

– 1577 (a riot in Gdańsk), King Stefan Batory plans to dig up a canal across the Spit and build a seaport on the seaward coast. The plan fails due to a war with Moscow,
– the 17th century, following the Swedish Deluge, a plan to cut the Spit between the villages of Przebrno and Skowronki appeared. In order to protect the canal, two forts were planned to be raised – for land and water defence,
– 1695 (the time of King Jan III Sobieski), the Lord Castellan of Chełm, Kazimierz Rogala Zawadzki, proposed to build a town and a seaport on the Hel Spit or the Vistula Lagoon,
– 1766–68, Andrzej Stanisław Młodziejowski, the Chancellor of the Crown and a bishop, presented a plan to cut through the Vistula Spit,
– 1847, a concept of digging up a canal near the vilage of Kąty Rybackie appeared,
– after 1945, Eugeniusz Kwiatkowski, head of the government delegates for

the reconstruction of the Polish Seacoast, expressed his hope that the problem of the Vistula Lagoon narrows would be solved successfully,
– 1983, prof. T, Jednorał completed a plan for the construction of a navigable canal across the Vistula Lagoon,
– 1994–96, a three-volume report "Principles for activation of the Elbląg region in terms of sea and river transport, recreation and fisheries" was published,
– 2007/2008, the Sea Office in Gdynia commissioned *The Feasibility Study for the Construction of a Navigable Canal across the Vistula Lagoon*. The feasibility study was prepared by the consortium of Polbud Pomorze, GEOSYNTEX Ltd and Fundacja Naukowo-Techniczna Gdańsk.

Despite so many attempts to build a canal which would cut across the Vistula Spit, the actual hydrotechnical works performed up to this day are limited to two undertakings: a permanent cutting across the Spit near Piława (in 1497) and, in the 1960s, the broadening and deepening of the narrows leading to the war port Baltijsk to about 460 m in width and 12 m in depth.

However, it should be kept in mind that the Spit is a geologically young formation and back in the Middle Ages it was intersected by single cuttings, including one near Krynica Morska present before the year 1300 and the so-called Elbląg Depth near the village of Skowronki between 1426 and 1431.

The concept of constructing a navigable canal consists of the following works:
– construction of a canal across the Spit, 1100 m long, 60 m wide at the depth (locally 100 m at the depth along a 200-meter-long section), 150 m wide at the water level and 5 m deep including the embankments,
– construction of a lock, 200 m long, 25 m wide and 5 m deep, with gates on each end,
– construction of breakwaters protecting the port and the approach to the canal from the sea,
– construction of a fairway on the side of the Vistula Lagoon along the section from the canal to buoy ELB10, about 13 km long, 60 m wide and 4 m deep in the first stage of the construction,
– construction of two low draw bridges and access roads.

Objectives of the research and development work conducted in the area of the intended canal

The article is a summary of the papers (KACZMAREK L.M. et al. 2008, KACZMAREK J. et al. 2008) which presented the results of the research completed under R&D grant no R04 017 03, called "Analysis of hydro- and lithodynamic processes in the area of the planned cutting across the Vistula Spit and prediction of the effect of the cutting on the seashore, along with the evaluation of the intensity of silting up of the fairway from the cutting to the port in Elbląg”. At the same time, this paper is an extension of the presentation the Author gave during the ceremony of the 60th anniversary of the Olsztyn Branch of the Polish Association of Civil Engineers and Technologists (PZITB).

The outcome of the study, carried out at the Institute of Hydro-Engineering, Polish Academy of Sciences, in Gdańsk in collaboration with a subcontractor, the University of Warmia and Mazury in Olsztyn (Chair of Civil Engineering and Building Constructions), consisted of an evaluation of the effect produced by the intended cutting across the Vistula Spit in the village of Skowronki (3 km away from Kąty Rybackie, situated at the base of the Spit, cf. Fig. 1) on the seashore on each side of the cutting. Another, equally important aim of the project has been to evaluate (predict) sedimentation processes in the fairway from the planned cutting to the port in Elbląg and on the approach fairway to the cutting from the Gulf of Gdańsk. Additionally, recommendations have been proposed regarding optimum length of entrance breakwaters on the side of the Gulf as well as suggestions concerning neutralization of possible erosion processes occurring on the shore near the aforementioned breakwaters.

Fig. 1. Location of the planned navigable canal across the Vistula Lagoon

Numerical calculations as well as field and laboratory measurements have been performed in order to achieve the above aims. The calculations (theoretical modelling) comprised the following physical processes: wind waves, wave-generated currents and sediment motion in the Gulf of Gdańsk and Vistula Lagoon, wind and gradient currents on the Vistula Lagoon, the morphodynamics of the seashore near the planned cutting on each side of the Vistula Lagoon, with particular attention paid to the effect produced by the entrance breakwaters on the side of the Gulf of Gdańsk as well as the intensity of the silting up of the fairway. For the calculations concerning the wave field, a third generation spectral model WAM4 was applied, whereas the calculations of the parameters defining the sediment motion were performed using a Dutch numerical software package UNBEST-LT and a novel Polish method, which takes into account the non-uniform grain size structure of sediments. Finally, mathematical modelling of water flow velocities in the Vistula Lagoon was performed using a Dutch software package DELFT-3D.

The field testes included measurements of the concentration of suspended sediments in the Vistula Lagoon, analyses of ground samples taken from the seabed near the shores of the Gulf of Gdańsk and detailed tachymetric and bathymetric measurements on the waters and shores of the Gulf of Gdańsk and Vistula Lagoon. For the measurements of the concentration of sediments suspended in the Vistula Lagoon, a laser device LISST-100 (version C) was used, which can measure volume concentration of sediments in 32 diameter classes, from 2.5 to 500 μm. The measurements were conducted within the area of the planned Elbląg-Skowronki fairway, at the sites where core samples from the seabed were taken. The bathymetric measurements were accomplished with an aid of a single-beam echo sounder coupled with a GPS receiver. One of the subcontractors, the University of Warmia and Mazury in Olsztyn, performed the field studies comprising collection of surface ground samples from the seabed of the Gulf of Gdańsk and Vistula Lagoon in the area of the planned approach fairways. The other subcontractor, the UNIGEO Ltd., carried out the sampling and analysis of core ground samples from the seabed of the Vistula Lagoon.

The laboratory tests consisted of the measurements of the speed of "washing away" of a seabed composed of both sandy sediments and cohesive ones, characteristic of the seabed in the Vistula Lagoon. In addition, deploying a LISST-100C device, turbidity time, i.e. time required for sedimentation of the sediments from the bottom of the Vistula Lagoon, was measured. These tests enabled us to estimate the maximum time it takes for sediment particles raised up during the future dredging works to fall down.

The present article is limited to the presentation of the results concerning two aspects, i.e. estimated effect of the planned breakwaters protecting the approach to the cutting from the side of the Gulf of Gdańsk on the seaward shores of the Vistula Lagoon and determination of their influence on the silting up of the fairway. The rationale behind these research areas is the following principle: the longer the breakwaters (in this case, the ones protecting the entrance to the planned cutting), the lesser the problems caused by silting. However, when the breakwaters are longer, they are more expensive to construct and can generate more severe negative impact on the nearby stretches of seashores. When breakwaters are short, the costs incurred by their construction are reduced and their negative influence on the seashore is minimized. At the same time, however, it can become more difficult to enter and leave the canal due to the excessive silting up of the fairway.

For the purpose of our calculations, it has been assumed that the breakwaters will be perpendicular to the coast, which means the least positive solution regarding their effect on the shores. The breakwaters consisted of single, impenetrable, perpendicular groynes, measuring 100, 200, 300 and 400 m in length. Apart from the length of the breakwaters, the volume and rate of the silting up of the fairway has been analyzed depending on the assumed six variants of lengths of breakwaters protecting the entrance to the cutting. In the basic variant, recommended by KACZMAREK et al. (2008), the minimum distance between the heads of the breakwaters and the coast is 400 m, and the depth of the fairway, according to the Feasibility Study (1007/1008) is no less than 5.5 m. Five other variants have been analyzed, i.e. the distance between the breakwater heads and the shore is 150 m and the assumed depth is 6 and 5,5 m, or when the distance is 300 m and the depth is 6 and 5.5 m, and when the distance is 400 m and the depth is 6 m. The analysis of sedimentation processes within the fairway (in each of the six variants) leading from the Gulf of Gdańsk to the planned cutting was conducted for three types of grain size distribution, i.e. for sediments with a large amount of fine fractions, with a relatively small amount of such fractions and with homogenous distributions of a grain diameter $d = 0.22$ mm.

Hydrologic, bathymetric and ground conditions in the area of the planned canal

Measurements of wind waves on the Baltic Sea are conducted irregularly and only in a few places. For the water reservoir situated in the Gulf of Gdańsk near the Vistula Spit, no historic measurements are available. Thus, in order to re-create wind waves, a prognostic model was applied, which calculates wind wave parameters, such as height, period and angle (azimuth) of waves approaching the shore on the basis of speeds and directions of winds as well as the extent of their influence.

These computations have been done using the WAM4 model. In this model, the basic equation is the so-called equation of the wave effect balance, in which the following are included: energy transfer from wind to sea, formation of whitewater waves, i.e. whitecapping, bottom friction and mutual resonance interactions between wave components. The resolution of the computational space grid was 5’ × 5’ (about 9 × 9 km).

In order to determine the parameters of the wind waves occurring in an average statistical year in the forefield of the Vistula Lagoon near the planned cutting, the data obtained from a 44-year-long reconstruction of wind waves in the Baltic Sea based on wave sets from prognostic points situated in the eastern part of the Gulf of Gdańsk were analyzed. The point located closest to the analyzed region was found at the coordinates 54°25’ N and 19°18’ E and the depth $h \approx 45$ m, situated about 6 km off the shore. In order to establish periods of duration of certain wind wave heights for each direction, wave intervals at 0.5m were assumed, and for each interval the following were determined: significent wave heights H_s, peak times T_p, wave radius azimuths A_z and periods of duration.

The results of the calculations indicate that in an average statistical year wind waves approach the shores for a nearly identical time period from both sectors. The highest waves occur at winds blowing from NNW and N, when they reach the parameters: $\bar{H}_s = 4.72$ m, $T_p = 11.2$ s and duration time about 3 hours.

In 2007, bathymetric and tachymetric measurements were performed in the site of the planned cutting (KM 27, near Skowronki), on the side of the Gulf of Gdańsk. The field measurements included tachymetry of the beach (from the base of the dune) and bathymetry of the shore zone belt 800 m wide and 2 km long. The cutting was planned to be made in the centre of the analyzed area. The measurements were made in profiles located 100 m from one another and perpendicular to the averaged shoreline. Based on the results of these measurements, the seacoast near the planned cutting was classified as dissipative, that is the one whose near-shore profile favours gradual and gentle dispersion of energy generated by waves. The bathymetric profile of the seabed (Fig. 2) in this area is characterized by the presence of two bars (I – about 80 m and II about 250 m away from the shoreline). The average bed incline is about 1%.

In 2007, samples of sediments from the seabed of the Gulf of Gdańsk were taken in the analyzed area. Based on the grain size distribution analyses, it has been determined that the bottom in the analyzed area is composed of sandy sediments characterized by varied grain size along the crosswise profile of the shore (Fig. 3). The cumulative grain size distributions shown in Figure 3 indicate that further away from the shore (at depths of 4–9 m) the sediments

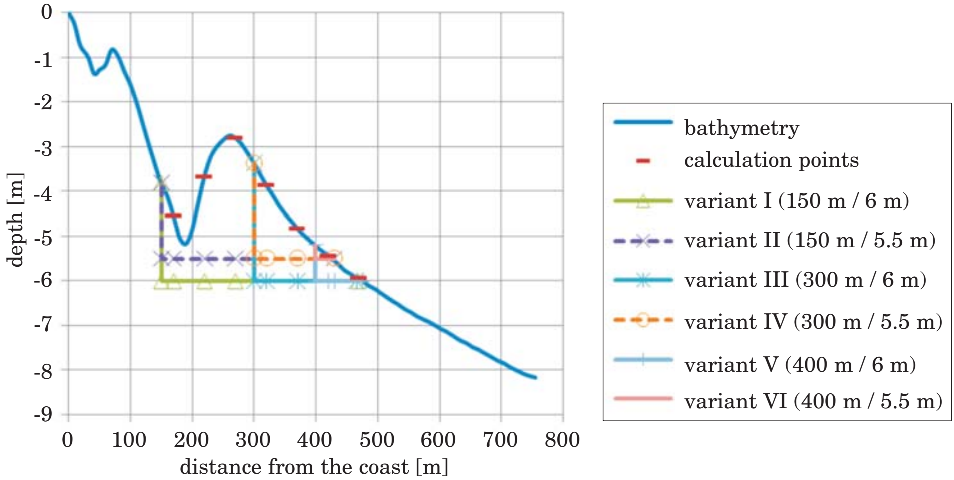

Fig. 2. The Gulf of Gdańsk – the bathymetry used for the calculations

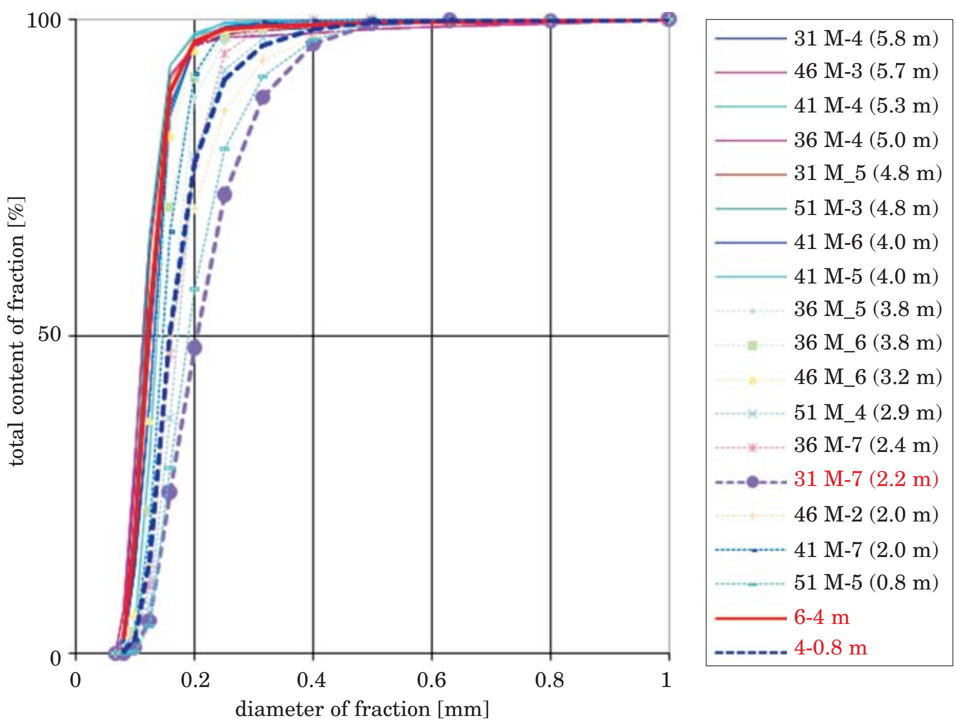

Fig. 3. Cumulative curves of grain size distributions of the seiment sampled from different depths near Skowronki

consist of fine sand of a median D_{50} = 0.12 to 0.15 mm and in the shore zone (at depths of 1-4 m) the sediments are slightly coarser of a median D_{50} = 0.17 to 0.25 mm. Closets to the shoreline and on the beach is sand of non-uniform grain size and a median in the interval from 0.21 to 0.38 mm.

The influence of the planned breakwaters on the seaside coasts of the Vistula Lagoon

The force responsible for transport of sediments and, consequently, the evolution of the see shore and bed consists of waves and currents, and in particular the so-called currents generated by waves breaking as they approach the coast. The volume of sediment transport depends on the intensity of hydrodynamic processes which occur, mainly during storms, in the shoreline zone and on the bathymetric conditions as much as on the type and supply of rubble lying on the sea bottom.

The calculations concerning the longshore sediment transport were performed using a licensed numerical programme from Holland *UNIBEST-LT* (version 4.0), which is part of the numerical package *UNIBEST*. The calculations in this programme were carried out on one, selected, representative bathymetric profile (cf. Fig. 2). The diameters of the sediments occurring in the shore zone were averaged for the calculations, by assuming in the numerical simulations the median D_{50} = 0.22 mm. In the *UNIBEST-LT* programme, the calculations regarding the volume of longshore sediment transported were performed using van Rijn's formula (1993). The results thus obtained were compared with the results generated by Kaczmarek's model (cf. KACZMAREK et al. 2004, KACZMAREK 2008) for homogenous sand (d = 0.22 mm) and very good agreement between the two sets of results was revealed.

The calculated distributions of the size of transported rubble as a function of the distance to the coast for particular directions of wind waves as well as the total resultant transport are presented in Figure 4. When comparing the calculated distributions of sediment transport intensity, as shown in Figure 4, with the shape of the bathymetric profile, illustrated in Figure 2, three streams of transport sediment are observable. The first one, relatively small, occurs very close to the coast, in a 50-m wide belt; the strongest one appears on the seaward slope of the first bar from the land; the third stream, a small one, occurs along the second bar on the seaward slope. The maximum width of the shore zone where sediment transport takes place is about 400 meters, but most of the sediment is transported within 160 meters from the coast.

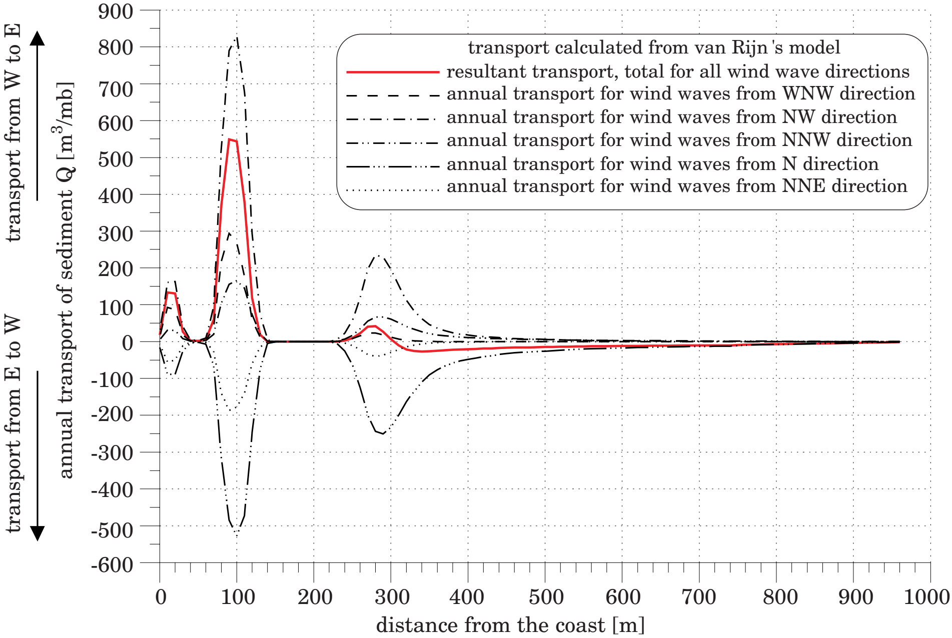

Fig. 4. Calculated distributions of sediment transport in an average statistical year on the seaward side of the Vistula Lagoon near Skowronki

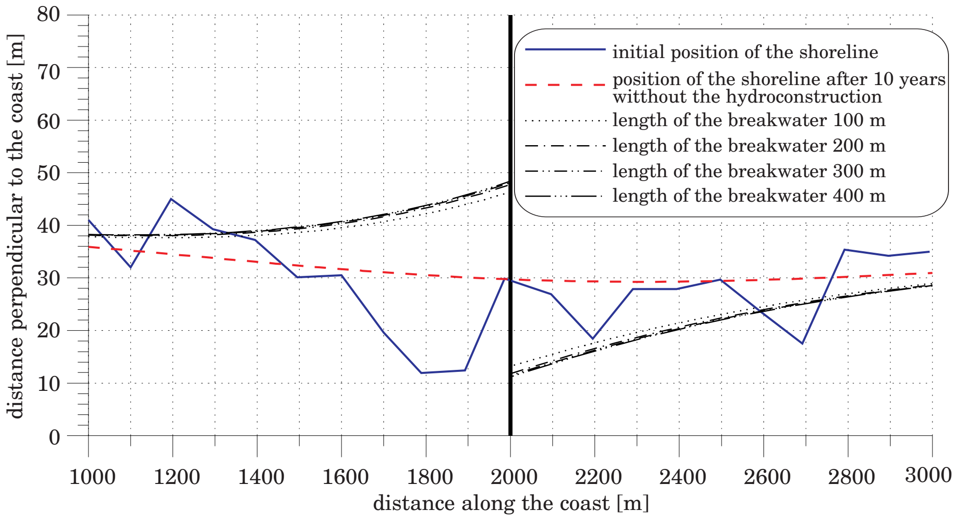

Fig. 5. Calculated changes in the position of the shoreline after 10 years, depending on the length of breakwaters near Skowronki on the seaward side of the Vistula Lagoon

Figure 5 shows the calculated changes in the position of the shoreline ten years after constructing the breakwaters provided that the breakwaters block all longshore sediment transport. In the simulations, the breakwaters are represented by a single, impenetrable groyne, situated perpendicularly to the coast and measuring 100, 200, 300 and 400 m in length. The starting point consisted of previously calculated resultant intensities of sediment transport in an average statistical year. This figure proves that, irrespective of the length of the breakwaters, both maximum changes in the position of the shoreline as well as the extent of such changes along the coast are nearly identical. This is due to the fact that most of the sediments transported along the coast travel very close to the shore.

Effect of the length of breakwaters on the silting up of the fairway from the Gulf of Gdańsk to the cutting

The calculations deployed a model for transport of non-uniform sediments that has been developed for a few years now (cf. KACZMAREK et al. 2004, KACZMREK 2008). This model enables one to calculate transport of sediments including all sandy fractions present in sediments since, as it turns out, it may be insufficient to know only one parameter, i.e. median D_{50}, to attain reliable evaluation of sediment transport and analysis of the silting up of fairways (cf. KACZMAREK, SAWCZYŃSKI 2007). Apart from the value of D_{50}, the shape of the grain size distribution is crucial. It becomes even more important when the amount of fine fractions in sediment is high.

This model distinguishes the bedload layer, the contact layer and the outside area where sediments are transported as suspension. The nature of interactions between water and sediments is different in each of the layers and therefore they are described using different equations, whereas at the contact area between these layers the solutions are “sewn” together, ensuring a complete description of the structure of transport of sandy sediments.

The mathematical modelling takes into account the fact that the most intensive vertical sorting out of grains occurs when they are raised up in the contact layer above the seabed. In the contact layer, pulse turbulences and chaotic collisions between grains cause very strong differentiation in the transport of particular size fractions of the sediment. Very close to the seabed – in the sub-layer where bedload flow features very strongly in the distributions of the velocity of i^{th} fraction of sediments – there is a very strong interaction between particular fractions, caused by mutual chaotic collisions. Further upwards from the bed, these interactions between the fractions weaken. However, the concentration of i^{th} fraction is big enough to cause suppression of turbulences, with the actual suppression depending on the grain diameter d_i. It can be, therefore, expected that each i^{th} fraction, due to mutual interactions, moves at its own speed and is characterized by its individual concentration.

The velocities and concentrations of coarser fractions calculated in the contact layer are larger than the values obtainable should the bed be uniform and consisted of one corresponding fraction. Such acceleration of speed in a mixture results from mutual interactions between fractions, where coarser fractions are accelerated by finer ones.

In the outside layer, above the contact one, it is assumed that grain size distribution of transported sediment remains unchanged. The vertical concentration distribution in this layer is described by a power function.

It has been assumed, for the purpose of the calculations, that each wave characterized by the parameters H_{rms} and T_p can be described via the Stokes second approximation, with the crest made steeper and the flattened trough. This assumption has limited the area for the calculations to the waters near the second bar (cf. Fig. 2).

It has also been assumed (cf. KACZMAREK 2008) that along the windward edge (away from the current) of the approach fairway, sediments are transported during the wave crest phase in the bedload and contact layers and in the outside layer under the effect of the resultant current. On the edge away from the wind (under the current), sediments are transported only during the wave trough phase in the bedload and contact layers.

As mentioned above, this model enables inclusion of the effect of all fractions on sediment transport. The calculations were completed for two grain size distributions, shown in Figure 3, i.e. for the distributions designated with the symbol 31M-7 (collected from the depth of 2.2 m) and an averaged distribution from samples taken from depths 6 ± 4 m or the depths 4–8 m.

It is worth noticing that the measured sediment grain size distribution marked as 31M-7 resembles in its shape the distributions collected from the edge of the approach fairway to the port in Łeba (cf. KACZMAREK, SAWCZYŃSKI 2007, DUBRAWSKI 2003). Thus, although at the moment the contribution of fine fractions in averaged grain size distributions in the crosswise profile of the shore near Skowronki is larger than the 31M-7 distribution, it can be expected that following the exploitation (dredging) of the planned entrance fairway the presence of fine fractions will stabilize at a level similar to the one found in the sediments on the edge of the approach fairway in Łeba.

The results of the calculations pertaining to the distribution along the crosswise profile of the average annual volumes (cubic capacities) of sediments retained annually at 50-m long sections of the fairway, for the three presupposed "entrance" grain size distributions (including one homogenous distribution characterized by the diameter d =0.22 mm) are shown in Figures 6, 7 and 8.

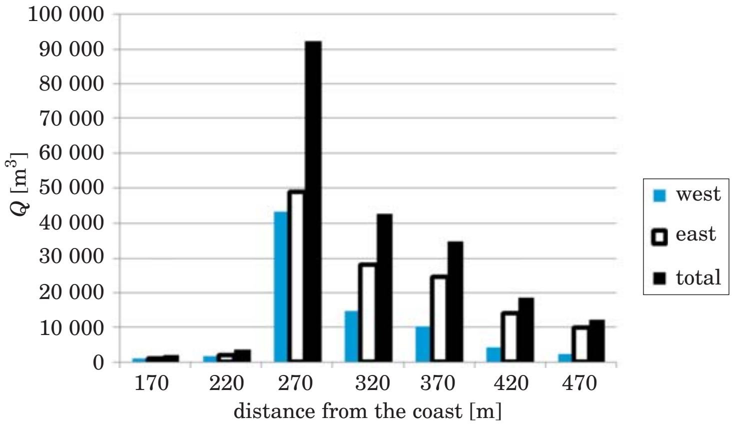

Fig. 6. Results of the calculations of the year average silting up along the fairway for the real grain size distribution, i.e. averaged from the depth 0.8–4 m or 4–6 m

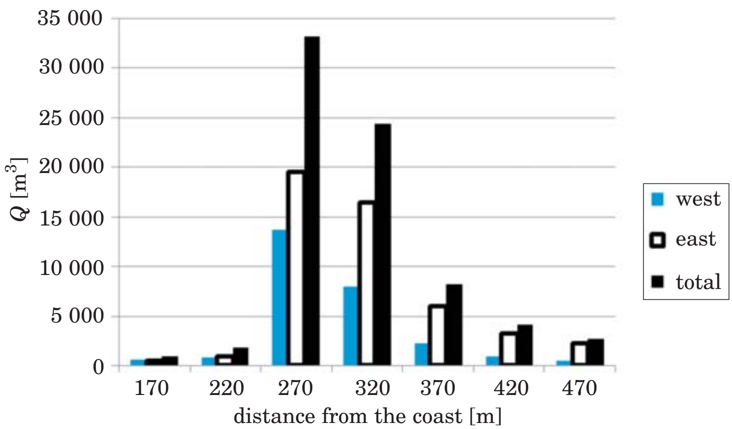

Fig. 7. Results of the calculations of the year average silting up along the fairway for the distribution 31M-7

It should be noticed here, however, that the contribution of wave situations to the silting up of the fairway is considerably large from both directions, i.e. from the west side as well as the eastern edge of the fairway. Nevertheless, it is evident that near the second bar, where the above calculations were made, the contribution of wind waves from the east to the silting up of the fairway is larger than the analogous influence from the western direction.

It needs to be emphasized that the largest intensity of silting up along the crosswise profile will occur at the top of the bar, i.e. at a calculation point distant about 270 m from the coast. This means that if we should decide to build shorter breakwaters, the future administrator of the fairway at the entrance to the canal from the Gulf of Gdańsk would be constantly in need of

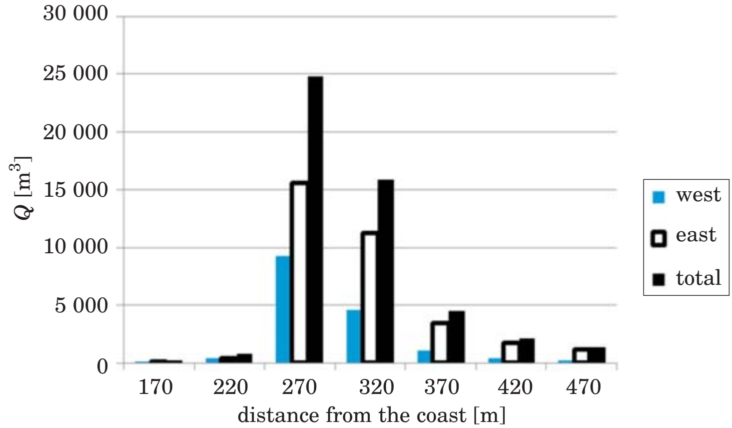

Fig. 8. Results of the calculations of the year average silting up along the fairway for homogenous distribution d = 0.22 mm

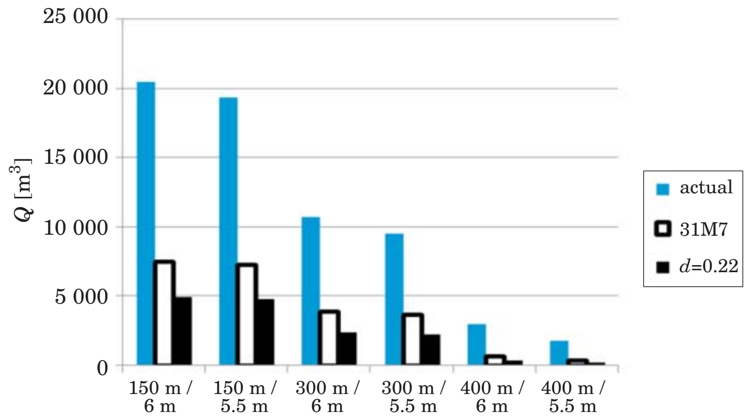

Fig. 9. Results of the calculations of the year average silting up along the fairway for different types of sediments and six variants of the fairway

using dredgers in order to maintain this entrance in good working order. The problems caused by accumulation of sand in this area will be graver when amounts of fine fractions in sediments lying on the edges of the future fairway increase.

The effect of grain size distribution on the total (sum) volume of sand built-up in the fairway is illustrated in Fig. 9. The calculations were performed for six variants of the fairway. It can be seen that the highest year average silting up will appear in the fairway in variant 1, i.e. where breakwater heads are 150 m away from the coastline and the intended depth is 6 meters. By extending the breakwaters, and consequently moving the fairway further away from the coast, we can decrease the rate of silting up. In the most optimum situation (variant VI), where the breakwater heads are 400 m away from the coast and the depth of the fairway is 5.5 m, the total amount of sand accumulated due to silting will be 18.5 thousand m^3/year provided the amount of fine fractions in sediments remains considerably large. Should less fine fractions be deposited on the edges of the fairway (distribution 31M-7 and uniform distribution d = 0.22 mm), it can be expected that the year average silting up will reach, respectively, 4.1 and 2.1 thousand m^3/year, which means that the entrance fairway will have to be cleaned every 1-3 years.

Summary

The article contains a discussion on the influence of planned breakwaters on the seaward shores of the Vistula Spit and the effect of the length of these breakwaters on sedimentation processes in the fairway from the Gulf of Gdańsk to the planned cutting across the Vistula Spit. The analysis of the hydro- and lithodynamic aspects was conducted using a licensed Dutch programme *UNIBEST* and an original, Polish method which includes varied grain size distribution of sediments. In our simulations, the breakwaters consisted of a single, impenetrable groyne, perpendicular to the coast, which was 100, 200, 300 and 400 m long. The volume and rate of the silting up of the fairway were analyzed depending on the six variants of the lengths of the breakwaters. In the basic variant, the minimum distance from the breakwater heads to the coast was 400 m and the depth of the fairway was no less than 5.5 m. Additionally, five other variants were considered, i.e. the distance from the heads of the breakwaters to the coast was 150 m and the assumed depth of the fairway was 6 and 5.5 m, the distance was 300 m and the depth was 6 and 5.5 m and, finally, the distance was 400 m and the depth 6 m. The results are discussed in terms of three grain size distributions of the sediments, i.e. sediments with a large amount of fine fractions, with a relatively small amount of such fractions and uniform sediments characterized by the diameter d = 0.22 mm.

Owing to the fact that most of the sediments transported along the coast travel very close to the shore, within a belt measuring 160 m from the coast, the calculated changes in the position of the shoreline 10 years after constructing the breakwaters, for the analyzed lengths of these constructions: 100, 200, 300 and 400 m, are nearly identical.

The maximum increments of the shoreline, appearing at the same time, immediately near the western side of the breakwaters and losses on the

eastern side are about 20 m. However, considering all the errors made while calculating parameters of waves, water flow rates, intensities of sediment transport, it has to be assumed that an error in the evaluation of changes to the shorelines can be as high as 100%. This means that the maximum changes in the position of the shoreline are within the range of 10 and 40 m.

The extent of the changes to the shoreline 10 years after constructing the breakwaters, calculated from the outside edges of the breakwaters along the shore in both directions is about 1000 meters.

The above analysis verified that the optimum variant of a length of the breakwaters is the basic variant, i.e. when the distance from the breakwater heads to the coast is 400 m and the depth of the fairway if 5.5 m. In that case, the maximum volume of silting up will reach about 18.5 thousand m^3/year provided that the contribution of fine fractions in the sediment will remain high. This volume means that the fairway will have to be dredged every year. Should less fine fractions persist in sediments on the edges of the fairway (distribution 31M-7 and homogenous distribution d = 0.22 mm), the average annual volume of silting up could be expected to reach, respectively, 4.1 and 2.1 thousand m^3/year, which means that the approach fairway would have to be cleaned just every 1-3 year.

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