TECHNICAL SCIENCES
Abbrev.: Techn. Sc., No 13, Y 2010

DOI 10.2478/v10022-010-0007-6

HYDRO- AND LITHODYNAMIC ASPECTS OF CONSTRUCTING A NAVIGABLE CANAL THROUGH THE VISTULA SPIT – PART 2

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Key words: the Vistula Spit, the Vistula Lagoon, cutting, navigable canal, fairway, breakwater, sediment transport, non-homogenous sediments, silting up of a fairway

Abstract

The paper discusses hydro- and lithodynamic aspects of a planned construction of a navigable canal across the Vistula Spit. The discussion is based on the results obtained under a research and development grant carried out in 2007–2008 by the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk in collaboration with the Chair of Civil Engineering and Building Structures, the Faculty of Technical Sciences, at the University of Warmia and Mazury in Olsztyn. The analysis presented in this paper regarding the effect of the length and position of planned breakwaters on the silting up of the fairway broadens the results of the research perfomed under the above grant by including such aspects as the position of the fairway's axis towards the shore. All analyses were performed employing an innovative method which takes into account the changeable grain size structure of deposists (cf. KACZMAREK L.M., SAWCZYŃSKI SZ. 2007 and KACZMAREK L.M. 2008). The recommendations regarding an optimum length of planned breakwaters and depth of an approach fairway, presented previously, have found further confirmation.

HYDRO- I LITODYNAMICZNE ASPEKTY BUDOWY KANAŁU ŻEGLUGOWEGO PRZEZ MIERZEJĘ WIŚLANĄ – CZĘŚĆ 2

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

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. Przedstawiona analiza, dotycząca wpływu długości oraz ustawienia projektowanych falochronów na zapiaszczanie toru wodnego, stanowi istotne rozszerzenie wyników badań uzyskanych w ramach grantu o aspekty związane z ustawieniem osi toru względem brzegu. Analizy wykonano, korzystając z nowatorskiej metody uwzględniającej zmienność uziarnienia osadów (por. KACZMAREK, SAWCZYŃSKI 2007 i KACZMAREK 2008). Potwierdzono zalecenia optymalizacyjne dotyczące długości projektowanych falochronów i głębokości toru podejściowego.

Introduction

This paper is a continuation of our previous article published in the last year's issue of the Technical Sciences (cf. KACZMAREK 2009), which contained the results of our studies completed as part of R&D grant no R04 017 03 called 'The analysis of hydro- and lithodynamic processes in the area of a planned cutting across the Vistula Spit and prediction of the effect of the cutting on the shore, along with the evaluation of the intensity of silting up of the fairway from the cutting to the port in Elbląg', conducted by the Institute of Hydroengineering, the Polish Academy of Sciences (KACZMAREK L.M. et al. 2008), in collaboration with the Chair of Civil Engineering and Building Structures of the University of Warmia and Mazury in Olsztyn (KACZMAREK J. et al. 2008). The concept of cutting through the Vistula Spit is not a new one and there have been many papers dealing with this idea, among which the most important ones are three expert opinions (KACZMAREK J. et al. 2008, KACZMAREK L.M. et al. 2008 and the Feasibility Study for the Construction of a Canal), which are now the basic source of information about the planned construction. In addition, other publications have appeared over the years, such as the earliest articles by GAJEWSKI et al. (1995), JEDNORAŁ (1996), DUBRAWSKI and ZACHOWICZ (1997), to the latest ones by KACZMAREK L. M. et al. (2009 a, b and c), which contain detailed results of studies and present the current state of the discussion on this construction project.

This article broadens the discussion about the planned cutting of the Vistula Spit by adding some aspects, which have been previously either neglected or taken for granted. These aspects have been analyzed as part of a master thesis (cf. SKILLANDAT 2010) completed at the Chair of Civil Engineering and Building Constructions at the UWM, under the supervision of L.M. Kaczmarek.

The article (KACZMARK L.M. 2009) contains an analysis of the influence produced by the planned breakwaters on the seaward shores of the Vistula Spit (cf. Fig. 1) and the effect of the length of these breakwaters on sedimentation processes in and around the fairway.

Fig. 1. Location of the planned cutting across the Vistula Spit
Source: www.google.maps.pl accessed on 4 May 2010 at 4.00 p.m.

Simulations of the volume and rate of the silting-up of a fairway, in which breakwaters consisted of a single, impermeable groyne of the tested lengths of 150, 300 and 400 m and depths of the fairway of 6 and 5.5 m (Fig. 2), have proven that the optimum results are achieved when the distance between the heads of the breakwater and the coast are 400 m and the approach fairway is 5.5 m deep.

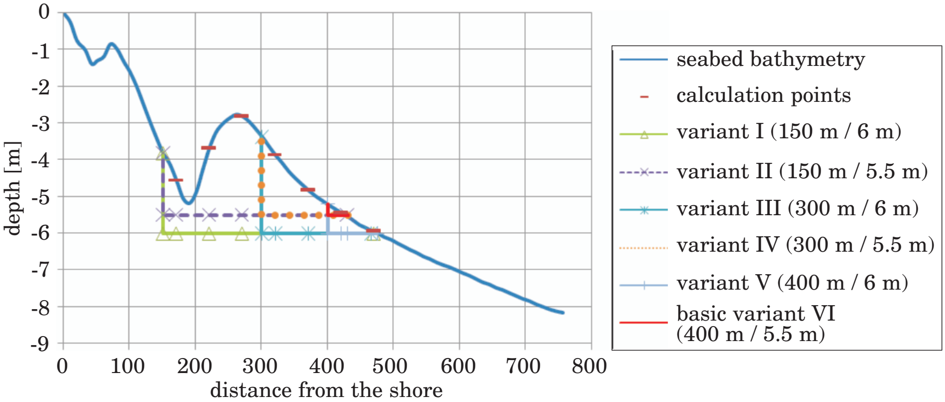

Fig. 2. Bathymetric profile in the area of the planned cutting across the Vistula Spit

All the analyses performed up to now have assumed that the fairway lies perpendicularly to the coastline. With this assumption, the forces causing the silting-up of the fairway were two of the three basic factors, i.e. wave generated sediment transport at the edges of the fairway and longshore sediment transport, in which the direction is parallel to the coastline. The volume of sediment carried by longshore transport is independent from the position of the approach fairway relative to the coastline because as the fairway diverges from the normal to the coastline, its length increases and the effective transport component, i.e. the perpendicular to its axis, decreases. The longshore transport is driven by a longshore current, generated by waves coming towards the shore which break obliquely (versus the shore). Grains of sediment are then transported in the water layers further from the bottom, where they form suspension. The wave-generated sediment transport at the edges of the fairway is the one caused by surface waves, whose direction agrees with the direction of the propagation of waves running towards the shore. This transport involves both rolling and dragging of sand grains, as well as the so-called saltation, i.e. short jumps of grains right above the bottom. Sediment grains are therefore in constant contact with one another and, in the form of a thick mixture, move in the surface layer of the bottom and a layer directly adjacent to the seabed, i.e. the contact layer (cf. KACZMAREK L.M. 2008). Silting up caused by this type of transport depends on an angle between the direction of wave propagation and the fairway, but along the winward edge of the fairway (away from the current) sediments are transported during the wave crest phase, while along the edge away from the wind (under the current), transport takes place during the wave trough phase. It is also assumed that surface wave can be described via Stokes second approximation with a steeper crest and flattened trough.

The third of the factors responsible for the silting up of a fairway, i.e. transport caused by a return current directed towards open sea, whose direction is perpendicular to the shore, does not have any influence on the volume of silting when the construction, i.e. a fairway, is situated along the normal to the shore, because the component of the transport perpendicular to the fairway's axis disappears. Analogously to the longshore transport, sediment grains are transported as suspension by the return current, generated by breaking waves.

The decision to locate the construction along the normal to the shore, which means that the estimation of potential sedimentation will only include the intensity of transport caused by waves at the edges of the fairway a longshore current, is based on the many years of experience gained by hydrotechnology engineers and the knolwedge of the terrain (Fig. 1) as well as the wave climate, according to which the mean annual resultant direction of wave-generated sediment transport at the edges at the fairway (accord. to the IBW PAN model), at a distance of 200 m and more from the shore, inclines eastward by no more than 10o from the normal to the coastline (cf. KACZMAREK et al. 2008). In this study, it has been decided to test the justifiability of the accepted assumption by performing additional analyses based on a changed location of the fairway relative to the coast and on measurements of the effect of the return current on the intensity of the silting up of the approach fairway.

Calculation procedure

Based on the results of bathymetric measurements and grain size composition of the sediments, as well as the calculations run according to the IBW PAN mathematical model, optimal parameters of the construction have been chosen. A model of non-homogenous sediment tranpsort, improved by the Instituite's researchers for many years, enables us today to account for the influence produced by all fractions on the transport of rubble. This is important because in addition to the value of a median d_{50}, the shape of the distribution of grain size fractions of sediments has a significant influence on the evaluation of the transport and analysis of the silting up of a fairway (KACZMAREK L.M., SAWCZYŃSKI Sz. 2007). The model distinguishes the bedload layer, the intermediate (contact) layer and the external area, in which sediments are transported as suspension.

Some modifications and additional components introduced to the calculation model, carried out in this study, have enabled us to present additional relationships illustrating the effect of the length of breakwaters as well as the depth and position of the fairway relative to the coastline on the silting up of the fairway. With this model, it was also possible to estimate the effect of the above factors on the silting up depending on the grain size distribution of sediments. Thus, thirteen different locations of the approach fairway relative to the coast and five different groups of sediments have been tested. The fairway profile is here understood as an appropriate positioning of its axis relative to the coastline. Therefore, the fairway's axis lying along the normal to the coast was marked as angle 0° and its successive westward and eastward inclinations by 10° from the normal to the shoreline were assigned respective values of negative and positive angles. The analyzed groups of sediments consisted of three uniform sandy sediments containing grains of the diameters $d = 0.1$ mm, $d = 0.22$ mm and $d = 0.4$ mm, a grain size sediment distribution sampled at a depth of 2.2 m and designated as 31 M-7, and another one, named the actual distribution, i.e. an averaged distribution, which – depending on the depth for which the calculations were performed – was an averaged distribution from samples taken at the depths $6 \div 4$, or $4 \div 0.8$ m. The uniform sediment characterized by the smallest grain diameter, i.e. d = 0.1 mm, was chosen for comparative analyses, since this size of sand grains is impossible to obtain in the natural conditions present in the Baltic Sea.

In the paper, the authors have limited the discussion to re-analyzing the volume of the silting up of the fairway, excluding the effect of the breakwaters on the seaward shores of the Vistula Lagoon, as this issue was directly addressed to in the previous article (cf. KACZMAREK 2009).

The effect of the length and position of breakwaters on silting up

Waves and sea currents have the strongest influence on the transport of sediments and, consequently, on the evolution of the shores and seabed. The actual parameters of litho- and morphodynamic processes depend on the type of rubble lying on the seabed and on the vulnerability of sand fractions to the effect produced by the flow of water in the near-bottom layer. Sand fractions are transported as bedload or suspended sediment due to the effects produced by near-bottom tensions. But above all, these processes depend on the wave climate, bathymetric relations in the seabed within the shore zone and the hydrotechnical facilities built along the shore.

The volumes of rubble transported near the planned canal, calculated from van Rijn's formula for each direction of shoreward waves and by totalling (the mean annual) volume of the resultant transport, have clearly demonstrated that there would be three streams of transported rubble (cf. KACZMAREK L.M. 2009), each characterized by a different intensity depending on the distance to the shore. The main sediment transport occurred in a belt 160 m in width whereas the maximum width of a shore zone with the transport of sediments reaches about 400 m from the shore at the seaward side of the submerged bar (cf. Fig. 2). Therefore, the breakwaters should be localized about 150 m or 400 m from the shore.

Figs. 3–5 show the total mean annual volumes of sediments, divided into three grain size distributions, brought into the fairway depending on the variants of the location of the breakwaters (cf. Fig. 2) and position of the axis of the appraoch fairway towards the shore. Considerable influence of the length of the breakwaters on the silting up of the fairway has been verified. In variants V–VI the annual silting up reaches a few thousand square meters, but the lengths of the breakwaters being successively shortened (variants III–IV and I–II) make the volume of deposited sediment tens of fold higher than when the length of the construction is optimal (400 m). These relations have been

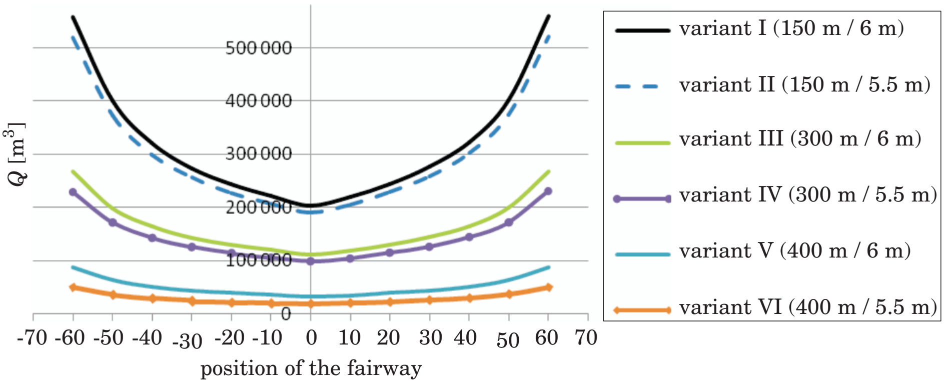

Fig. 3. The mean annual volume of the silting up of the approach fairway depending on the angle between the fairway and the normal to the shore – actual grain size distribution

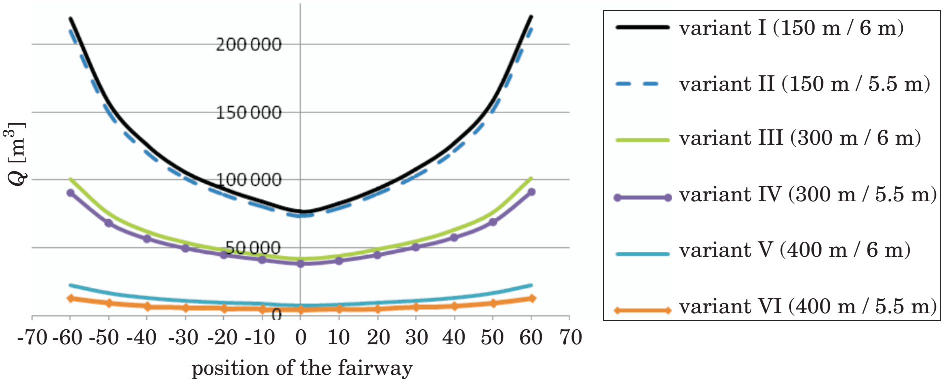

Fig. 4. The mean annual volume of the silting up of the approach fairway depending on the angle between the fairway and the normal to the shore – grain size distribution designated as 31 M-7

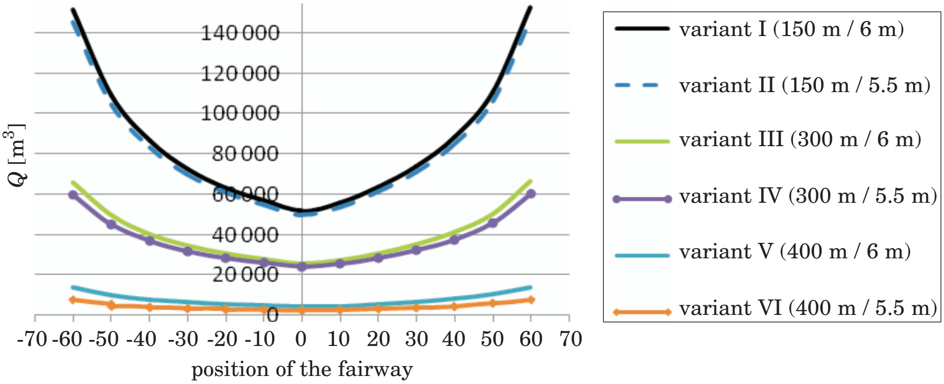

Fig. 5. The mean annual volume of the silting up of the approach fairway depending on the angle between the fairway and the normal to the shore – uniform sediment $d = 0.22$ mm

found out by totalling the mean annual volumes of the sediments deposited in the fairway due to three factors: sediment transport induced by surface waves at the edges of the fairway (Fig. 6), by longshore current (Fig. 7) and by return current (Fig. 8).

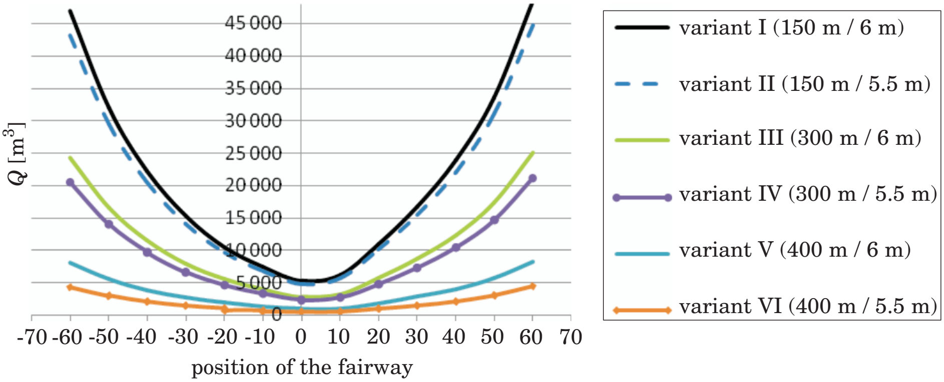

Fig. 6. Mean annual volume of the silting up of the approach fairway caused by surface waves at the edges of the fairway depending on the angle between the fairway and the normal to the shoreline – sediment designated as 31 M-7

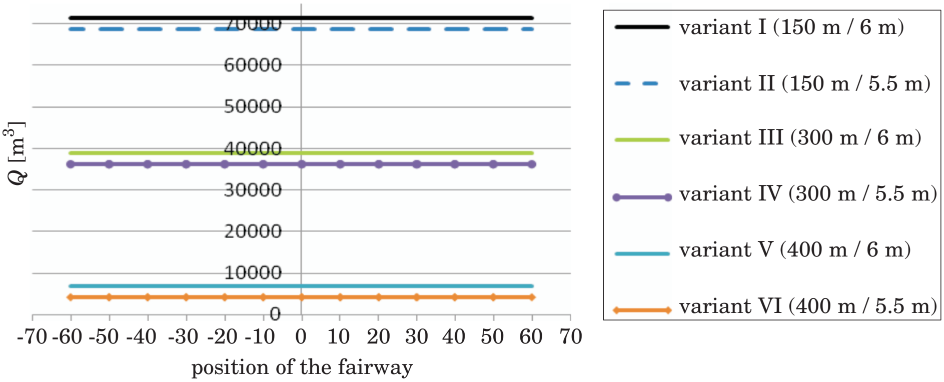

Fig. 7. Mean annual volume of the silting up of the approach fairway caused by the longshore current depending on the angle between the fairway and the normal to the shoreline – sediment designated as 31 M-7

The mean annual volume of sediments deposited in the fairway caused by the above factors have been presented for only one grain size distribution designated as 31 M-7. This grain size fraction draw our attention because it resembles in shape the fractions of sand sampled from the approach fairway to the port in Łeba (cf. KACZMAREK 2009). It can be suspected that although at present the share of small grain fractions in the averaged grain size distribu-

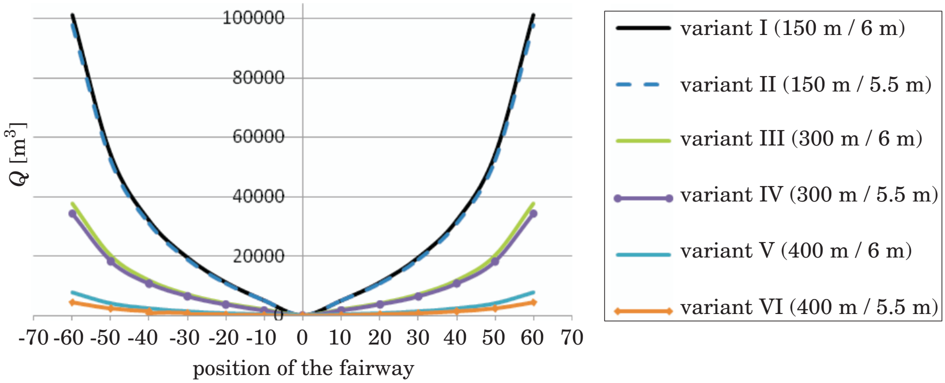

Fig. 8. Mean annual volume of the silting up of the approach fairway caused by the return current depending on the angle between the fairway and the normal to the shoreline – sediment designated as 31 M-7

tions in a transverse profile of the shore near Skowronki is larger than in the 31 M-7 distribution, once the canal is opened, the presence of fine grain fractions in the approach fairway will be stabilized after a few years on a level comparable to that in the sediments at the edges of the fairway in Łeba.

When analyzing the diagrams presented in Figs. 6–8, it can be noticed that the transport due to surface waves at the edges of the fairway (Fig. 6) is the largest for the two extreme angles of the position of the construction, whereas the smallest values are 'located' between the angles 0–10°. The minimum value of the mean annual silting up of the fairway shown in Fig. 6 is shifted away from the perpendicular profile by a few degrees. It is so due to the sediment transport induced by surface waves whose resultant direction, at about 200 m away from the shore (accord. to the IBW PAN model) is directed to the east and its deviation from the normal to the shore is about 10°. The volumes of the mean annual silting up caused by surface waves at the edges of the fairway, calculated for different angles between the fairway's axis and the normal to the shore, are nearly symetrical relative to the lower extreme value.

The silting up caused by the longshore current (Fig. 7), which moves parallel to the shoreline, is constant in each variant and independent from the position of the fairway relative to the shore. Our comparison of the orders of the volumes of sediments deposited in the fairway, shown in Figs. 6–8, proves that most of the sediment is carried by the longshore current.

The average annual volume of the sediment deposited in the fairway due to the return current, whose resultant is perpendicular to the shoreline, is symmetrical to the profile perpendicular to the shore. When the approach fairway is situated along the normal to the shore, the return transport does not cause any silting. As the fairway inclines westward (–10° to -60°) or eastward (10° to 60°), the role of the return current transport becomes more important, reaching the maximum values for the two extreme angles.

The figures shown above illustrating the total mean annual silting up (Figs. 3–5) and the components of the volume of deposited sediment (Figs 6–8) demonstrate that the calculated values depend on both the length of the fairway and its position towards the shore. The values obtained for the breakwaters measuring 150m and 300 m are a few or even tens of fold higher than the values calculated when the breakwaters are 400 m in length.

Our computations have confirmed that the optimum location of the breakwater, which will minimize the volume of sediments deposited in the fairway, is near the profile perpendicular to the shore. In addition, figs. 3–5 show that for the breakwaters 400 m in length, the smallest mean annual sitling up, independently from the particle size fractions in the sediments, occurs within the locations ±20°. The shorter the breakwaters, the stronger the relation between the volume of silting up and the angle of deviation from the normal to the shore.

The final decision about the position of a fairway versus the shore is usually conditioned by the predicted volume of deposited sediments in the planned fairway and the need to ensure navigation safety when ships enter and exit the canal. Thus, wave conditions which will be created in the canal as well as in the water basin within the breakwaters, also under stormy weather, are essential. Knowing that the deviation of the approach axis from the normal to the shore within ±20° does not cause any significant change in the volume of sediments deposited in the fairway, we now have more flexibility when determining the actual position of the planned construction.

The influx of sediments caused by surface waves at the edges of the fairway, the longshore current and the return current on the total mean annual volume of sedimentation of the fairway, for the selected paricle size distribution (31 M-7) and the basic variant (400 m/5.5 m) has been illustrated in figure 9. It can be seen that for the fairway whose axis is close to the normal to the shore, the largest contribution to the total mean annual silting up of the fairway is generated by the longshore transport. Any larger deviation of the fairway's axis from the profile perpendicular to the shore means that the wave – induced transport at the edges of the fairway and the return current will bring more sediments.

Noteworthy, apart from the location of the construction relative to the shore, the type of sediment lying on the seabed has a considerable effect on the contribution of particular component forces to the mean annual silting up of the fairway, as evidenced by the calculations gathered in Table 1.

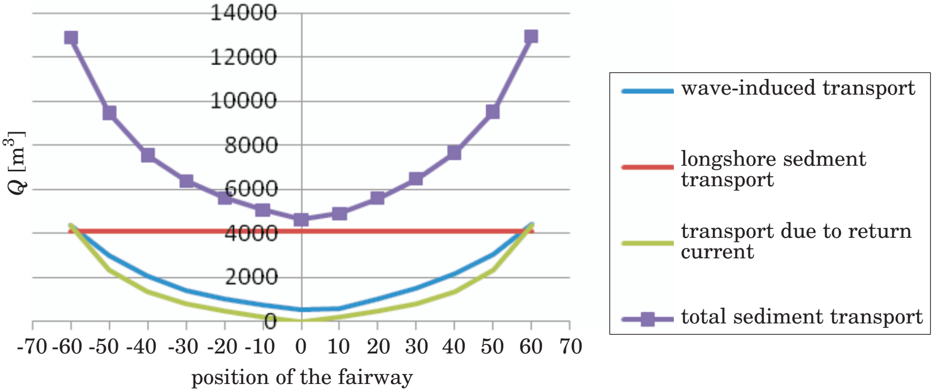

Fig. 9. Mean annual volume of the silting up of the fairway depending on the angle between the fairway and the shoreline, for variant VI – distribution 31 M-7

Table 1

Contribution of particular types of transport in the total mean annual silting up of the fairway depending on the type of sediment. Variant 400 m/5.5 m and the profile inclined by 20° from the perpendicular profile

Specification	Uniform sediment $d = 0.1$ mm [%]	Actual Sediment [%]	31 M-7 sediment [%]	Uniform sediment $d = 0.4$ mm [%]	Uniform sediment $d = 0.22$ mm [%]
Longshore sediment transport	81	80	73	66	20
Wave – induced sediment transport	6	8	18	27	78
Sediment transport due to return current	13	12	9	7	2

The information comprised in this table proves that if the sediment deposited on the seabed is mostly composed of fine grain fractions, then the most important factor generating the silting up of the fairway is the longshore current, whose contribution to the sedimentation process in the basic variant (400 m/5.5 m) and in a fariway deviating from the normal by 20° eastward can reach 80%. The larger the diameter of sediment particles, the lower the percentage. Likewise, the contribution to the total silting up of the return transport nearly disappears when the sediment is homogenous and particles measure 0.4 mm in diameter. It is so because both the longshore and return currents transport suspended load sediment. The transport at the edges of the fairway caused by surface waves, in contrast, involves a thick mixtrure of sand and water, in which grains are either dragged or more forward by making saltation jumps within the thin contact layer, right above the seabed.

The influence of grain size distribution on the total mean annual volume of sediments deposited in a fairway is shown graphically in Fig. 10. Six variants of the location of the fairway have been included in addition of five grain size distribution variants. It can be seen that the fairway in variant I, i.e. when the heads of the breakwater are 150 m away from the shoreline and the assumed depth is 6 m, will experience the most severe sedimentation during a year. By building a fairway further away from the shoreline and constructing longer breakwaters, the volume of sediments deposited in the fairway over a year decreases dramatically.

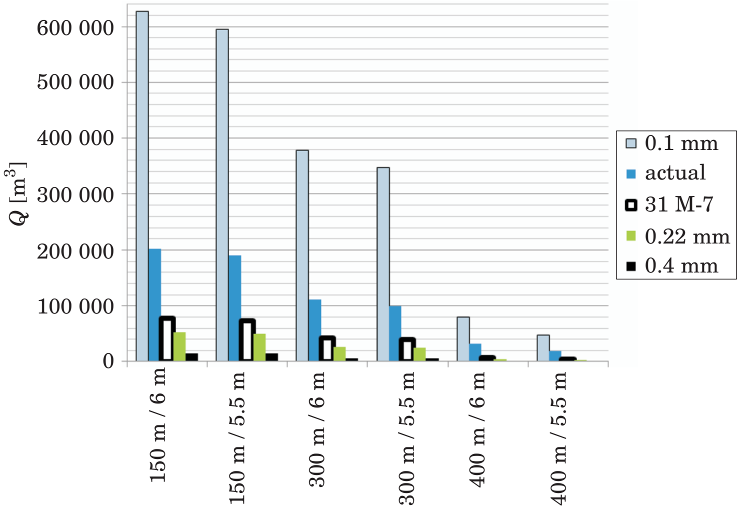

Fig. 10. Results of the calculations of sediment falling within a year into the fairway, for different types of sediment, six variants of the fairway and a profile perpendicular to the shoreline

The next diamgrams (Fig. 11 and Fig. 12) show, respectively, the amount of sediment deposited during a year per length unit (*L*) of the fairway and the mean annual loss of depth of the fairway analysed for each of the lengths (cf. Fig. 2) and for the 60-meter width (*D*). Additionally, it has been assumed that the sediment trapped by fairway is evenly distributed on its bottom. It should be noticed that when predicting the amount of sediment deposited during a year per fairway length unit (Fig. 11) and the mean annual loss of depth of the fairway (Fig. 12), we obtained lower values for the deeper (6 m) approach fairway than in the variants where the fairway was 5.5 m deep. This is an effect of the bathymetry of the seabed (Fig. 2). By making the approach fairway 0.5 m deeper, from 5.5 to 6.0 m, the fairway is lenghtened by 50 m (for a breakwater 400 m long, the approach fairway is 100% longer). Thus, despite

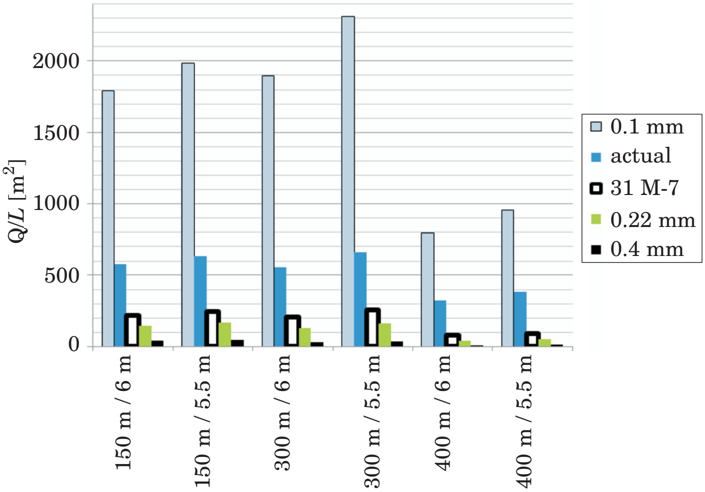

Fig. 11. Results of the calculations of the amounts of sediment deposited within a year per length unit of the fairway, for different types of sediment, six variants of the fairway and a profile perpendicular to the shoreline

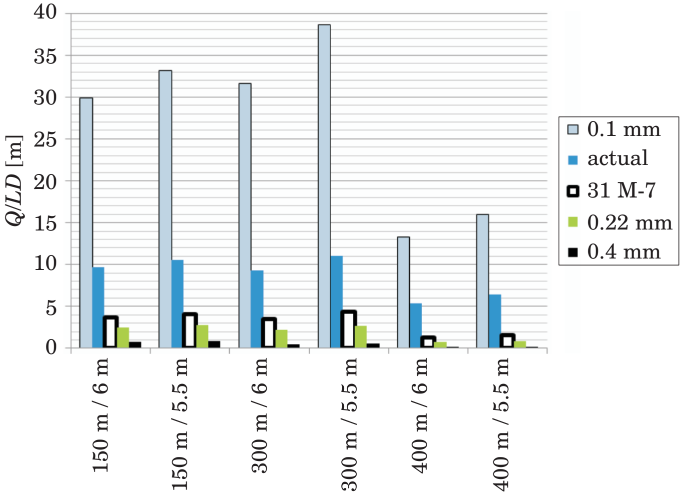

Fig. 12. Results of the calculations of the mean annual loss of depth of the fairway, for different types of sediment, six variants of the fairway and a profile perpendicular to the shoreline

the mean annual silting being almost twice as large for the deeper (6 m) fairway (Fig. 13), the loss of depth of the fairway will be nearly identical for both variants of the depth (Fig. 14).

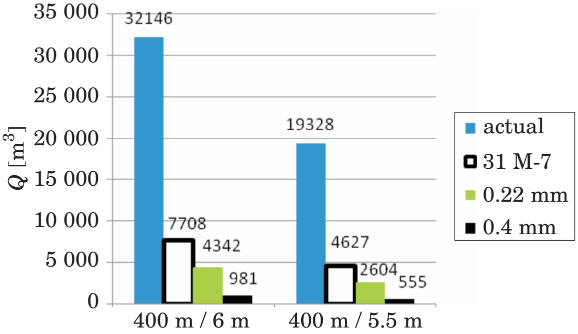

Fig. 13. Results of the calculations of the sediment falling into the fairway annually for different types of sediments – variants 400/6.0 and 400/5.5 as well as the profile perpendicular to the shoreline

A more thorough analysis of the solutions in which the heads of the breakwaters are 400 m away from the shore reveals that it is better to design a fairway that would be 5.5 m deep. In that case, the maximum amount of deposited sediment will reach about 19.5 thousand m^3 (Fig. 13) – for a considerably large fraction of small grain size in sediment – as compared to 32.1 thousand m^3 for a fairway 6 m deep. Should the amount of sediment brought into the fairway reach about 19.5 thousand m^3 annually, dredging would have to be carried out at least once a year. It is, however, highly possible that the sediment at the edges of the waterway will stabilize in time and remain at a level similar to the one found in the sediment samples taken from the edges of the fairway in Łeba. Then, if the percentage of fine grain fractions in the sediment was lower (distribution 31 M-7, homogenous sediment, d = 0.22 mm and d = 0.4 mm), the annual volume of deposited sediment would e 4.6, 2.6 and 0.6 thousand m^3 respectively. The above predictions would mean that the fairway would have o be cleaned up only every 1 to 3 years, which is a satisfactory economic result.

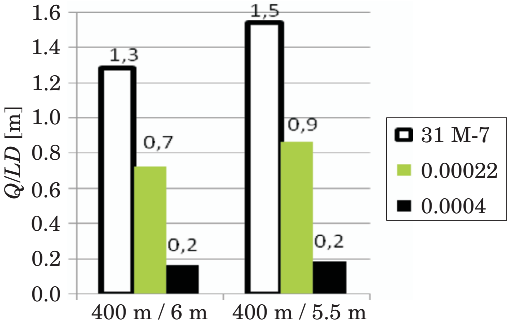

Fig. 14. Results of the calculations of the mean annual los sof depth of the fairway for different types of sediments – variants 400/6.0 and 400/5.5 as well as the profile perpendicular to the shoreline

Thus, the mean annual ranges of the fairway becoming shallower (Fig. 14) for variants V and VI, i.e. 400/6.0 and 400/5.5 (excluding the extreme value for d = 0.1 mm and actual distribution – with a large percentage of fine grain fractions), calculated on the assumption that the sediment in the fairway would be evenly distributed, are good prediction for the planned construction project. The values indicating the loss of depth of the fairway due to silting up confirm that the fairway would have to be cleaned up once a year at the most.

Summary

The article contains a presentation of the results of our analyses aiming at selecting the most suitable variant of the length of planned breakwaters and the depth of an approach fairway as well as its position relative to the shore so as to minimize the volume of sediment deposited in the fairway and thus reduce the frequency of dredging operations necessary in the future. The analyses included an innovative Polish calculation method called the IBW PAN, which takes into consideration the changeability of grain size distribution. For our calculations, three lengths of breakwaters (150 m, 300 m and 400 m) and two depths of an approach fairway (5.5 m and 6 m) were taken, which resulted in six different variants. Moreover, each of the variants was analyzed on the assumption involving five grain size distributions, which differed in the content of fine grain fractions. Finally, thirteen different positions of the fairway relative to the shore were examined, with the axis of the fairway situated along the normal to the shore being designated as 0°, while the successive deviations by 10° from this position, to the west and to the east, were designated as negative and positive angles.

The calculations have confirmed that the optimum solution is to situate the heads of the breakwaters 400 m from the shore and make an approach fairway that would be 5.5 m deep and to position the axis of the fairway along the normal to the shore. Then, the volume of deposited sediment shall remain on a level that will enable to reduce dredging operations to at least one-year intervals. More thorough calculations conducted for this optimum variant showed that a deviation of the water fairway from the profile perpendicular to the shore by about 15–20° to either direction (westward or eastward) would not modify the volume of deposited sediment. However, the shorter the breakwaters, the stronger the correlation between the rate of silting up of the fairway and the angle at which the fairway's axis is positioned towards the shore.

The paper also demonstrates that when the approach fairway is deeper, from 5.5 to 6 m, it is also longer and, consequently, although the mean annual amount of deposited sediment in the deeper fairway (6 m) is almost twice as large, the loss of depth will be nearly the same for both depth variants.

However, it seems safer to design a fairway which would be 5.5 m deep (for a breakwater 400 m long) because if large amounts of fine grain fractions persisted in the sediments, the predicted volume of deposited sediments would be so large that dredging operations would have to be conducted more often than once a year.

Accepted for print 9.07.2010

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