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MODELLING OF THE SILTING UP PROCESSES IN WATER ROUTES OF ŁEBA AND TOLKMICKO PORTS

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Key words: sediment transport, grain-size distribution, bathymetry, hydrodynamic parameters, silting.

Abstract

A theoretical three-layer model of non-uniformly graded sediment transport has been used to analyse the silting up of water routes in the port of Łeba and Tolkmicko. Comparison of the results derived from model calculations with the measurements and dredging work data has demonstrated that the model is useful for prediction of the silting up extent as well as the distribution of grain-size fractions in sediments captured in water routes of ports, which are different in bathymetric as well as hydrodynamic parameters, and where sea bottom deposits are different in nature.

MODELOWANIE ZAPIASZCZANIA TORÓW WODNYCH PORTÓW W ŁEBIE I TOLKMICKU

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Słowa kluczowe: transport osadów, rozkład granulometryczny, batymetria, parametry hydrodynamiczne, zapiaszczanie.

Abstrakt

Do analizy zapiaszczania torów wodnych portów w Łebie i Tolkmicku wykorzystano trójwarstwowy model teoretyczny transportu osadów niejednorodnych granulometrycznie. Porównanie wyników obliczeń z pomiarami i wielkościami robót czerpalnych wykazało przydatność modelu do predykcji zarówno wielkości zapiaszczania, jak i rozkładów uziarnienia osadów zatrzymywanych w torach portów o różnych reżimach batymetryczno-hydrodynamicznych oraz różnym charakterze osadów budujących dno morskie.

Introduction

Good prediction of the volume of sediments transported near various types of hydrotechnical facilities, both existing and planned ones, is essential to maintain the shoreline and man-made constructions. This paper presents a possibility of using a three-layer model of non-uniformly graded sediments, which for many years has been elaborated at the IBW PAN in Gdańsk by a team of researchers supervised by Leszek M. Kaczmarek, to solve specific engineering problems, using two ports, in Łeba and in Tolkmicko, as case studies. These issues have also been discussed in Master Degree theses (ZDUNEK 2006, BOŻOMAŃSKI 2007) written at the University of Warmia and Mazury in Olsztyn, under the supervison of L.M. Kaczmarek and J. Kaczmarek, respectively.

Methods

The three-layer model of non-uniformly graded sediment motion

The theoretical three-layer model has been used to analyse the silting up in water routes (KACZMAREK 1999, KACZMAREK, OSTROWSKI 2000, 2002). This model distinguishes the bedload layer, the transient (contact load) layer and the outer region, in which sediments are transported as suspension. The nature of interactions between water and sediments in each of these layers is different, which is why it is described with a different set of equations, folded at the contact between the layers so as to provide a complete theoretical description of the structure of sandy sediment transport.

For the mathematical modelling it has been assumed that all the fractions in the bedload layer move at identical velocity in the form of a dense water and ground mixture, and that sediments are not sorted out in this layer. Another assumption is that interactions between sediment fractions are so strong that finer fractions are retarded by coarser ones – as a result all fractions travel at the same speed. Thus, in this layer simple totalling of transport tensions of particular fractions, treated as uniform sediment, is not valid.

The mathematical model has also accounted for the fact that the most intensive vertical sorting occurs by picking up sand grains in the contact layer near the sea bed. In the contact load layer, turbulent pulsations as well as chaotic collisions among grains cause very strong diversity in transport of particular fractions. Very close to the sea bed – in the sub-layer, where the sliding friction features strongly in the distribution of velocity of i^{th} fraction – there is very strong interaction between particular fractions caused by their mutual chaotic collisions. Further away from the sea bed, these interactions between fractions weaken. However, the concentration of the i^{th} fraction is big enough to suppress the turbulence, with the actual suppression strength depending on the diameter of grains d_i. It can therefore be expected that each i^{th} fraction, because of the mutual interactions, moves at its own velocity and is characterised by its own concentration.

The velocities and concentrations of coarser fractions calculated in the contact load layer are larger than the values these fractions would obtain, should the sea bottom be uniform and built of one corresponding fraction.

In the outer layer, above the contact load layer, no change in the grain-size distribution of the transported sediment in expected. The vertical distribution of sediment concentration in this layer is described with a power function.

Calculation procedure

The transformation of surface waves and sea currents in the marine shoreline zone has been calculated using the programme CROSMOR, whereas the transport of sediments has been analysed with the programme KLEPSYDRA, which takes advantage of the three-layer model of non-uniformly graded sediments.

CROSMOR is a software application developed at Utrecht University by a team headed by professor Leo van Rijn and dr Bart Grasmeijer. It allows the user to determine the transformation of surface waves in a cross-shore transect. The surface wave and sea current parameters obtained with this programme are used in the application KLEPSYDRA, prepared at the Institute of Hydroengineering of the Polish Academy of Sciences (IBW PAN) in Gdańsk, by a team supervised by L.M. Kaczmarek. This software package runs calculations of the intensity transport for each sediment fraction in the three layers, i.e. bedload, contact load and outer layer. The calculations are performed along the two edges of a water route, i.e. on the windward and leeward sides. Along the windward (updrift) side of an approach route, sediments are transported during the wave crest phase in the bedload and contact load layers; along the leeward (downdrift) side, sediments are conveyed under the effect of the resultant current only during the trough wave phase in the bedload and contact load layers.

The data produced by the two programmes can be used to calculate the amount of sediment transported over a time period and to determine changes in the grain-size distribution of sediment captured in a water route. Knowing the figures, such as the values of transport itensity for each sediment fraction, in the bedload and contact load layers as well as in the outer region, where sediment is present as suspension, it is possible to determine the amounts of transported material along both edges of an approach route which is being silted up. The calculations must include the mutual location between the approach route, the cross-shore profile and the incident wave angle along the edges of the route.

Comparison of the calculations and measurements

The paper contains a comparison of the results of calculations of the mean annual grain-size distribution of sediments captured in the approach channels with the actual grain-size distributions of sediments sampled in these navigation channels near Łeba and Tolkmicko. In addition, the results of the modelling of mean annual volumes of silt deposited in the routes were compared with the actual size of dredging work completed in these routes. This means that a complex comparative analysis has been made, both in terms of grain-size distribution and the rate of silting up.

Such complex verification has been possible owing to the three-layer model of non-uniformly graded sediments.

Description of the analysed areas

Each of the ports (Łeba and Tolkmicko) has been selected for our analyses because of its unique location. The port in Łeba lies on the Middle Coast at the mouth of the Łeba River; the port in Tolkmicko is situated on the Vistula Lagoon. In general, both ports share the same problem, that is excessive silting up of their navigation channels. The approach routes to these ports are constantly silted up. Łeba port has a particularly difficult situation in this respect. Tolkmicko port is in a slightly different position, as it stands on a shallow closed water body, which adds to the difficult task of maintaining a sufficiently deep approach route.

Silting up analysis

Hydrodynamic parameters

The analyses included parameters of the seaward wind typical for each region. Next, the deep water wave parameters were added to these values as well as parameter of the shallow wave after transformation and sea currents. The wind conditions in Łeba were determined on the data for 1951-1978 (KACZMAREK et al., 1996, 1997).

The wind parameters necessary to calculate the wind wave on the Vistula Lagoon near Tolkmicko were found in the relevant references (ŁAZARENKO, MAJEWSKI 1975) and the data stored at the Port Office in Tolkmicko. The data were converted to mean annual values and then used for calculations (Krylov method) of the parameters of the wind wave.

The calculations were completed for four wind velocity classes (2.5 m/s, 7.5 m/s, 13 m/s and 18 m/s) blowing from five wind direction classes (N, NE, E, NW and W).

Bathymetry and sediments

Another set of the input data necessary for our analyses consisted in the bathymetric profile and grain-size composition of the sediments. The bathymetric data, illustrated in Figures 1 and 2, originated from the information provided by the Maritime Offices in Słupsk and Gydnia and the Maritime Institute in Gdańsk for two master degree theses (ZDUNEK 2006, BOŻOMAŃSKI 2007).

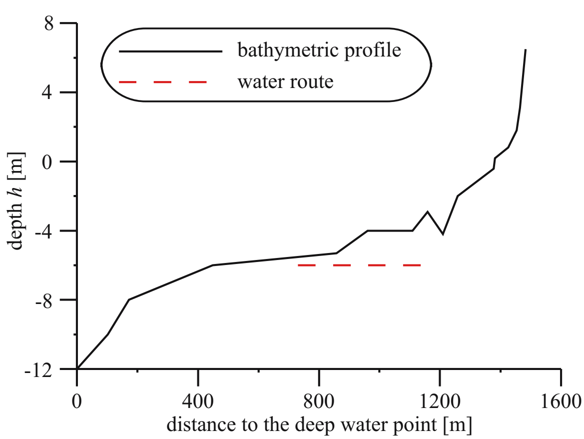

Fig. 1. Łeba – the bathymetric profile including the water route

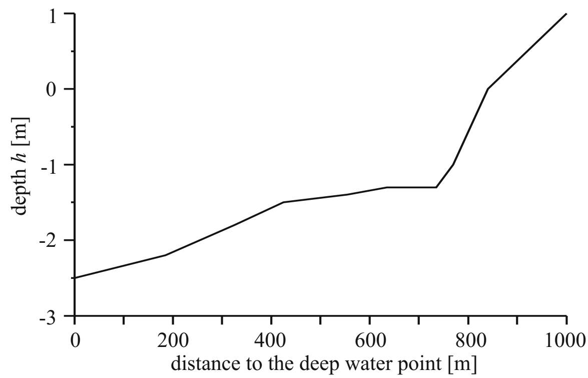

Fig. 2. Tolkmicko – bathymetric profile

The ground base of the approach route in Łeba port consists of unconsolidated deposits formed as fine-, medium- and coarse-grain sands, with dominant fine-grain sands. The Maritime Office in Słupsk provided us with 12 samples of surface sediments collected from the water route in Łeba. The results of the sieve analysis we performed are shown in Table 1. The grain-size composition of the sampled sediment includes fine-grain sands with a small contribution of medium-sized sand.

Table 1

Analysis of grain-size surface sediments in Łeba port (1998)

Range of grain size (d) [mm]	Sample number											
	r1	r2	r3	r4	r5	r6	r7	k8	k9	k10	k11	k12
0.08	0.13	0.04	0.07	0.19	0.14	0.08	0.07	0.02	0.07	0	0.02	0.06
0.1	6.53	0.11	0.69	0.96	0.46	0.45	0.33	0.2	0.31	0.05	0.18	0.45
0.125	74.15	20.2	23.8	25.5	15.39	18.21	15.16	8.645	11.07	3.15	6.3	16.24
0.16	13.4	21.37	39.36	38.16	30.42	41.52	43.99	32.10	30.89	11.45	23.64	35.05
0.2	2.04	33.36	22.92	23.28	25.79	28.2	26.12	30	23.42	17.82	28.91	21.13
0.25	1.11	12.57	8.34	8.34	15.41	9.42	9.28	20	16.81	28.21	26.65	12.2
0.315	0.76	7.37	2.85	2.3	6.95	1.35	2.95	7.205	10.74	24.35	10.46	8.36
0.4	0.78	3.29	1.19	0.8	3.33	0.3	1.31	1.4	4.87	12.15	3	5.26
0.5	0.46	0.92	0.33	0.22	1.16	0.16	0.45	0.23	0.76	2.11	0.57	0.94
0.63	0.64	0.77	0.45	0.25	0.95	0.31	0.34	0.195	1.06	0.71	0.27	0.31
Σ	100	100	100	100	100	100	100	100	100	100	100	100

For the calculations presented in this article, the grain-size distribution from a site designated as 'k10' was taken (Fig. 3). This is the distribution of the sediment sampled at the upper edge of the water route. Additionally, for comparison with the calculations, the results of sieve analysis of three sediment samples collected in 2003 inside the port channel, marked as no 1, 2 and 3, were used.

The grain-size distributions (Fig. 4) from Przebrno (nos 1 and 2) and Krynica Morska (nos 3 and 4) were used to calculate the mean annual grain-size distribution, which served as an input datum for the calculations run for Tolkmicko Port.

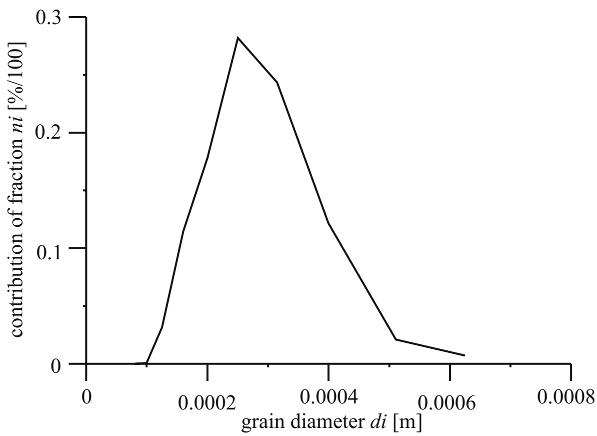

Fig. 3. Grain-size distribution of sediments in Łeba taken for the calculations

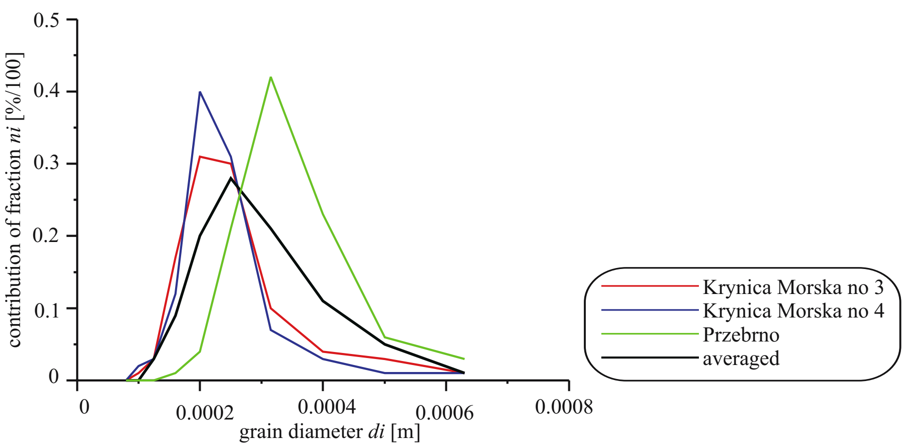

Fig. 4. Tolkmicko – grain-size distribution of sediments

Łeba

This sub-section presents results of the calculations of sediment transport intensity and changes in the grain-size distribution of the sediments captured in different sites along the approach route in Łeba, on each of its sides, for various wave formation conditions. Figures 5 and 6 illustrate the results obtained under storm conditions. In addition, Figures 5 and 6 contain the results of the calculations of transformation of waves (H_{rms}) and valued (averaged over depth) of longshore and cross-shore currents, produced by the programme CROSMOR.

It is evident that under intensive wave formation conditions, the transformation of waves starts at the deep water limit and consequently the whole shoreline zone experiences very intensive sediment transport. Figures 5 and 6 indicate that under intensive wave formation conditions, suspended sediment transport (q_0) prevails over the transport of sediments in the bedload (q_b) and contact load (q_c) layer. The symbols $q_{c,G}$, $q_{b,G}$ are assigned to the intensity of sediment transport during the crest wave phase in the contact load and bedload layers, respectively. The symbols $q_{c,D}$, $q_{b,D}$ designate the intensity of transport of sediments during the trough wave phase in the contact load and bedload layers, respectively.

Based on the information contained in Figures 5 and 6 it can be seen that the grain-size distributions of the sediment silting up the approach route depend on the position of the edge (windward or leeward) of the route as well as on the direction and height of the incident wave.

On the windward side of the route edge, i.e. facing approaching waves, grain-size distributions imply that the sedimentation material is much smaller in size, dominated by the fine fractions. This suggests that there is a large percentage of suspended sediments, transported by the longshore current.

On the leeward side, the silting up of the route is much weaker and caused only by the motion of bedload sediments and sediments suspended just above the seabed during the returning wave phase. The transport of bedload sediments does not modify the grain-size distribution of sediments. Thus, the grain-size distribution of sediments in the water route by the leeward side of the water route remains hardly changed versus the sediments found along the leeward edge of the route.

It should be emphasized that a considerable contribution of suspended sediment transport changes the grain-size distribution in the water route as only small fractions are transported in the form of suspension by the longshore current. Another interesting fact is that on the windward side the grain-size distributions of sediments are bimodal, with the fine-grain fractions being clearly dominant. In contrast, on the leeward side, the distributions are unimodal and dominated by coarser fractions.

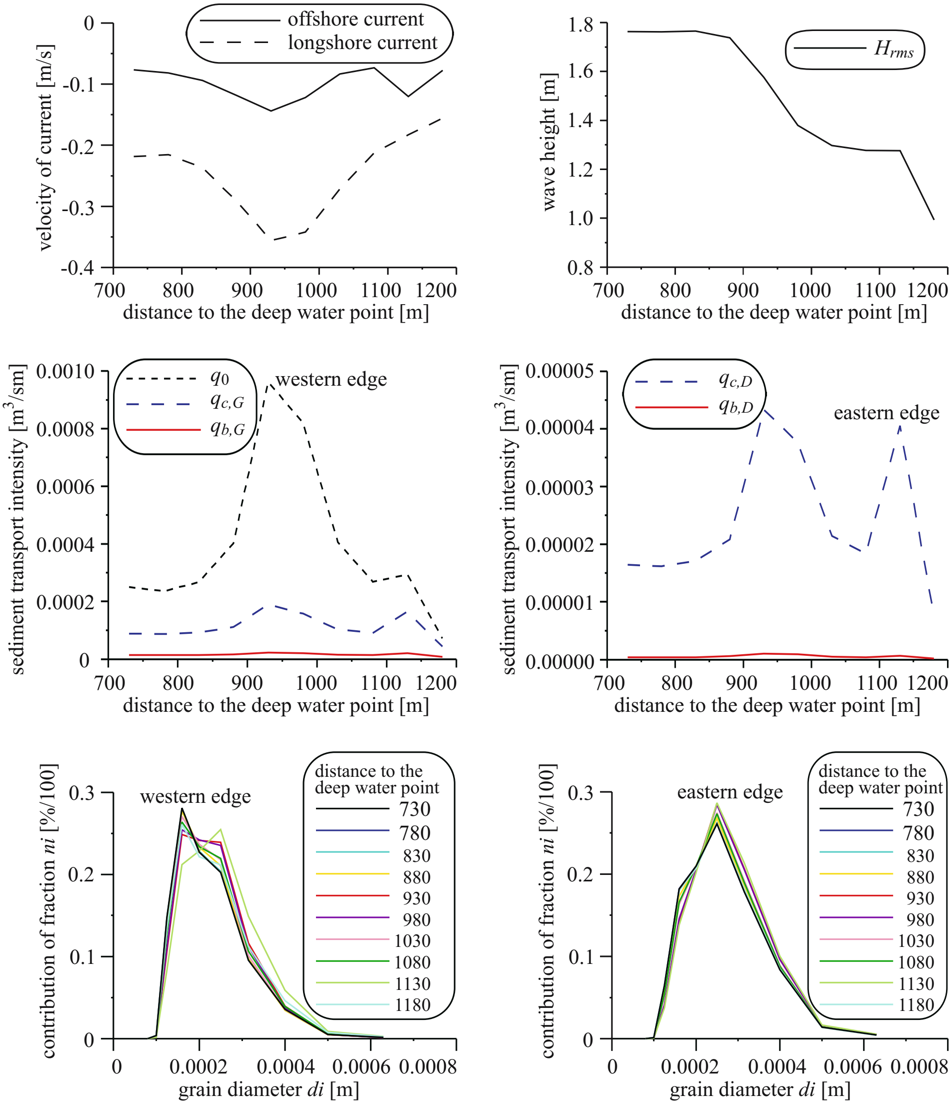

Fig. 5. Results of the calculations of wave formation, currents, sediment transport and grain-size distribution in the approach route in Łeba for the NW wind velocity of 17 m/s

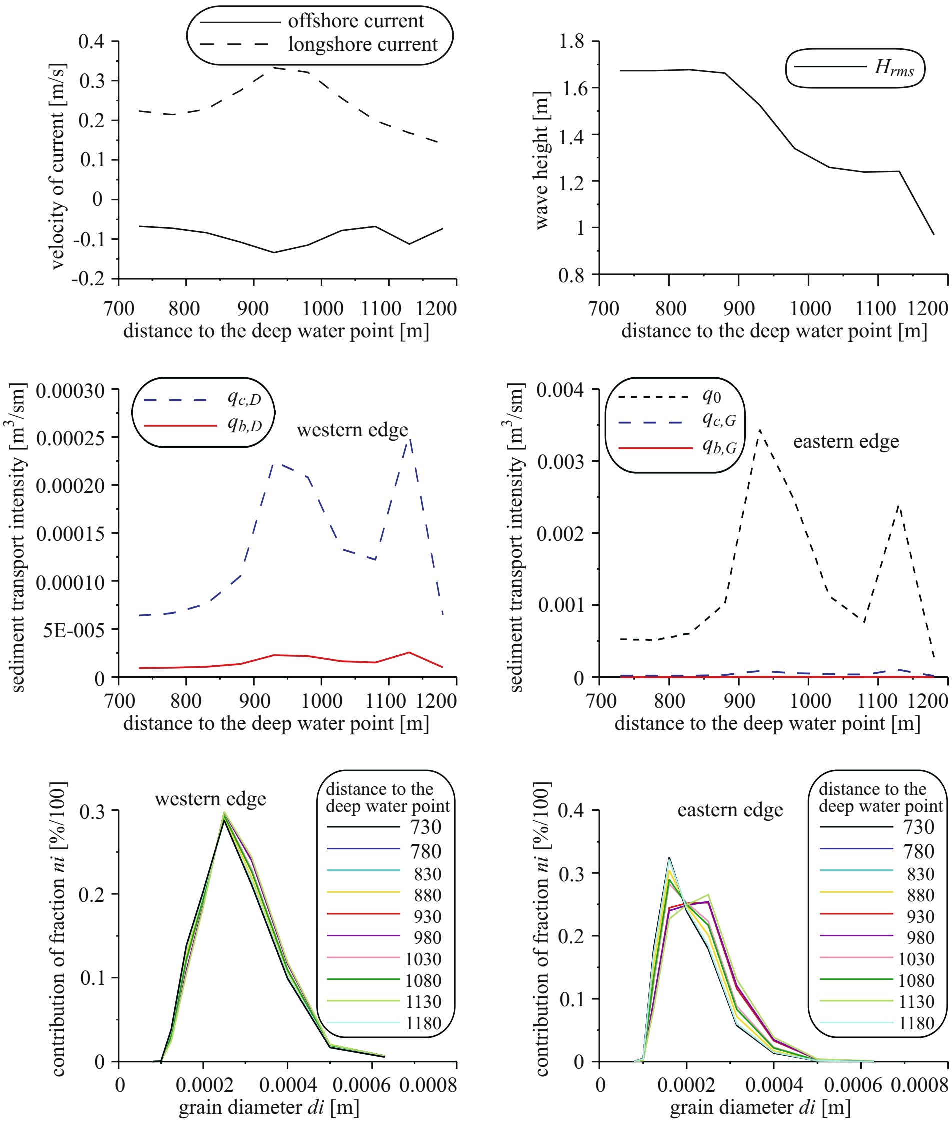

Fig. 6. Results of the calculations of wave formation, currents, sediment transport and grain-size distribution in the approach route in Łeba for the NE wind velocity of 17 m/s

Figure 7 shows the results of a comparison made between the calculations of the grain-size distributions of sediments silting up the water route in Łeba with the measurements carried out in 1998 and 2003. The agreement between these results is very good.

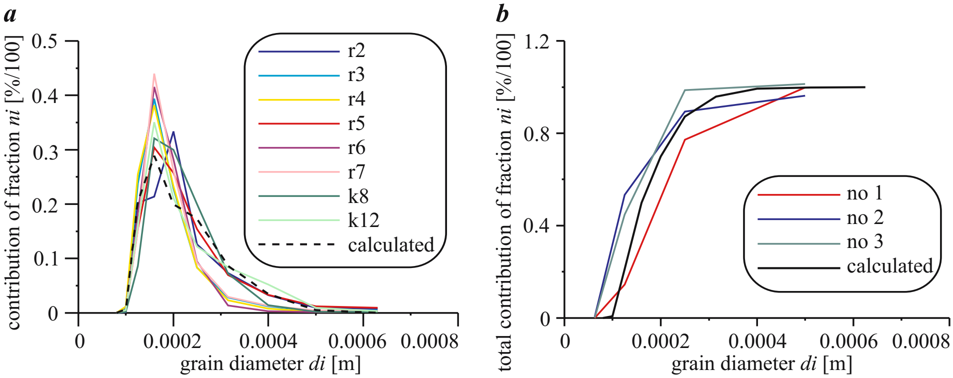

Fig. 7. Comparison of the results of modelling grain-size distribution of sediments silting up the water route in Łeba with the measurements of a) 1998, b) 2003

Tolkmicko

The results of the calculations of mean annual grain-size distributions along the length of the approach route and averaged over the transect of the route are shown in Figure 8.

In addition, Figure 8 presents the grain-size distribution averaged over the whole length of the route. It is evident that the calculated grain-size distributions are only slightly varied along the whole length of the channel. Figure 9 illustrates a comparison of the calculated mean annual grain-size distribution with the parameters obtained from Krynica Morska (Krynica 3 and 4). In addition, Fig. 9 shows the grain-size distribution which is an average distribution from the samples collected near Przebrno (1 and 2) and Krynica Morska (3 and 4). The average distribution was taken as an input distribution

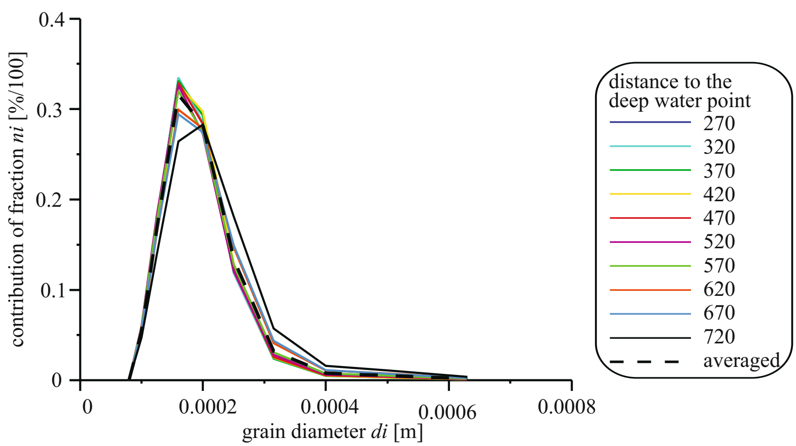

Fig. 8. Tolkmicko – calculated mean annual grain-size distributions in the approach route

for the calculations. The agreement between the calculations and measurements is good.

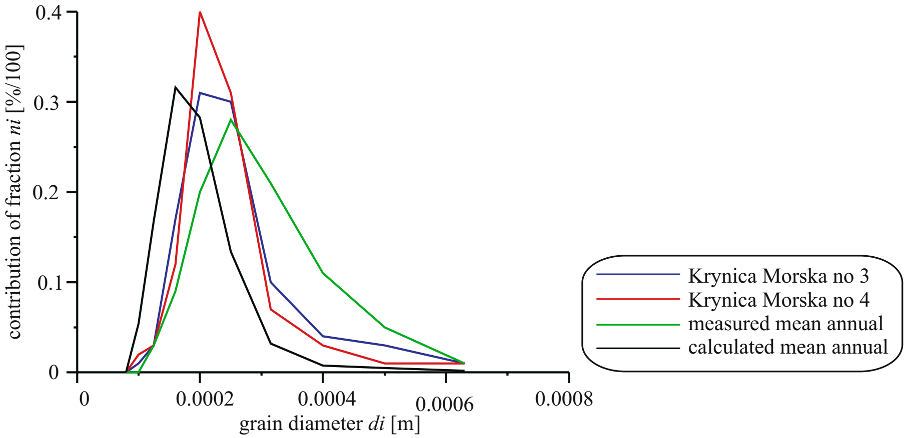

Fig. 9. Comparison of the calculated mean annual grain-size distribution with the measured grain-size distributions in Krynica Morska (nos 3 and 4)

Silting-up rate

Łeba

Figure 10 illustrates the extent of the dredging and silting works in the approach route of Łeba port. The data of 1915-1974 were found in the article by KACZMAREK et al. (1997), whereas the data of 2004-2005 were provided by the Maritime Office in Słupsk. The figure also contains the value of a mean annual silting-up of the approach route, which was calculated from the three-layer model of sediment transport. The agreement between the calculations and the empirical data seems to be very good.

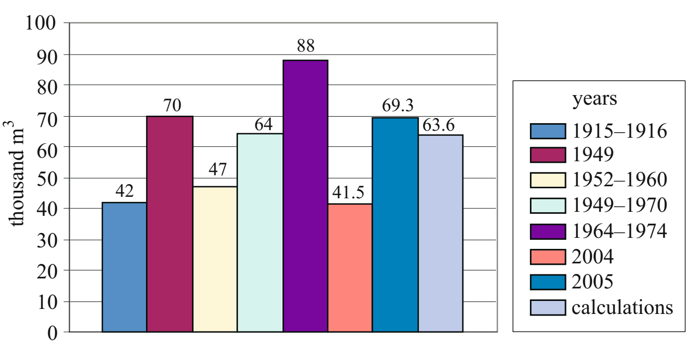

Fig. 10. Mean annual dredging work volume in the water route of Łeba port

Tolkmicko

Figure 11 contains a comparison of the results of calculations of a mean annual transport of debris halted in the approach route, depending on the grain-size distribution (e.g. for the distributions taken for the calculations from different sites in the Lagoon: Przebrno 1 and 2, Krynica Morska 3 and 4, and the averaged distribution for these sites) with the extent of the dredging works carried out in the approach route of Tolkmicko port in 2005.

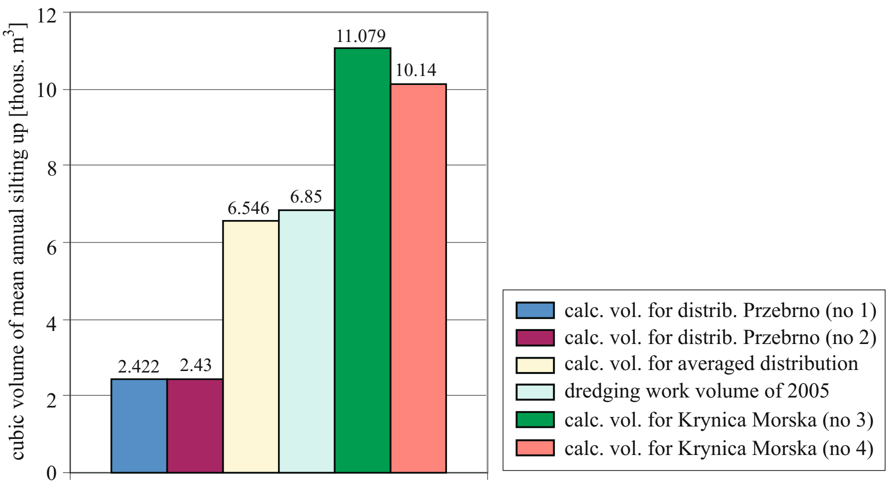

Fig. 11. Tolkmicko – comparison of the calculated mean annual cubic volumes of sediments and dredging work volume

The results shown in figures 9 and 11 demonstrate that the suggested theoretical model is good at depicting both grain-size distributions of sediments captured in the approach route of Tolkmicko port and the capacity of sediments silting up this navigation channel. Thus, the model can be recommended for use in engineering practice at closed shallow water bodies.

Summary

The paper deals with the hydrodynamic analysis of silting up of the approach routes in two ports: Łeba and Tolkmicko. For the purpose of such analysis, the three-layer model of non-uniformly graded sediment transport, developed for many years under the supervision of Leszek M. Kaczmarek at the IBW PAN in Gdańsk, has been applied. The article contains a comparison

of the calculations of mean annual grain-size distributions of sediments captured in the two water routes with the empirical data. Besides, the authors carried out a comparative analysis of the model determinations of mean annual silting up in these water routes with the actual extent of the dredging works carried out at Łeba and Tolkmicko. It has been demonstrated that the suggested three-layer model is suitable for prediction of both silting-up rate and grain-size distributions of sediments which settle down in water routes of ports different in bathymetric and hydrodynamic characteristics as well as seabed deposits.

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