

Założenia do numerycznego modelowania odkładu i rozprzestrzeniania się urobku pogłębiarskiego

Numerical modelling assumptions for deposition and spread of dumped material

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STRESZCZENIE: Prace pogłębiarskie związane z utrzymaniem odpowiednich głębokości nawigacyjnych torów podejściowych, basenów i kanałów portowych są konieczne do prawidłowej eksploatacji portów. Urobek pogłębiarski z basenów portowych (charakteryzujący się drobnymi frakcjami), często nie posiada parametrów pozwalających na wykorzystanie go w sposób użyteczny i musi być odkładany na morskich kłapowiskach. Deponowanie osadów w morzu jest działaniem o niekorzystnym wpływie na środowisko i w tym kontekście należy dążyć do minimalizacji negatywnych oddziaływań związanych z tego typu operacjami. Użyteczność modeli numerycznych stworzonych na bazie pakietu obliczeniowego MIKE 21, była sprawdzana w celu oceny oddziaływania kłapowisk w różnych fazach ich eksploatacji na środowisko morskie. Niniejszy artykuł przedstawia założenia i kolejne fazy budowy modelu numerycznego, który byłby przydatny do opisu rozprzestrzeniania się urobku pogłębiarskiego z obszaru kłapowiska, tak podczas samego deponowania jak i w okresie późniejszym. Uwagi zawarte w artykule dotyczą zasad doboru obszaru obliczeniowego, skali czasowej modelowanych zjawisk, problemów dotyczących definiowania warunków brzegowych na otwartych granicach modelu oraz optymalnego zakresu prowadzenia symulacji obliczeniowych. W artykule podkreślono również istotne znaczenie rozpoznania charakterystyk dna morskiego oraz materiału deponowanego na wiarygodność budowanego modelu numerycznego.

SŁOWA KLUCZOWE: Deponowanie urobku pogłębiarskiego • transport osadów zawieszonych • założenia do modelowania numerycznego • oprogramowanie MIKE 21.

ABSTRACT: Dredging is a necessary part of harbour operations, associated with the maintenance of the required navigable depths of approach channels and harbour basins. The fine dredged material obtained particularly from harbour basins often cannot be used in a beneficial way and must be disposed of at sea. Dumping dredged material at sea might have an adverse effect on the environment, so in this context one should seek to minimize the negative impacts associated with this type of operation. The potential of numerical models developed using the MIKE 21 package was tested, in order to assess the impact of disposal sites in different phases of their operation on the marine environment. The present paper examines the technical aspects of the construction phase of a numerical model which would be useful to describe the spillage of dredged material from the disposal site, both when the deposit operation takes place as well as in the subsequent period. Comments relate to the selection of a computing area, the model's time scale, issues associated with determining the boundary conditions on the model's open boundaries, and the optimal range for conducting computational simulation. The article also high-

lights the importance of identifying the relevant characteristics of the seabed and the material deposited on the reliability of the numerical model which is created.

KEYWORDS: Dumped material • suspended sediment transport • numerical modelling • MIKE 21.

INTRODUCTION

There are currently 66 harbours and marinas functioning along the Polish coast. One of the most crucial problems involved with them is maintaining the proper depth of harbour approach fairways, roadsteads and harbour basins, which amongst other things requires regular dredging. However, some problems related to the disposal of the material dredged may arise during dredging projects. If there is no possibility to use the dredged material in a beneficial way, (e.g. for the purpose of shore protection), then dumping is the only available alternative. However, the material originating from dredging can significantly differ from subsoil in its mineral content, as well as in terms of its chemical composition and properties. The state of demersal biocenosis (zoobenthos and phytobenthos), and the spawning grounds, feeding and migration grounds of fish and marine mammals can deteriorate during the deposition and settling of dredged material (Staniszewska et al., 2014).

At present there are 9 sea dumping sites along Polish shores, including 3 in the Gdansk Bay, where altogether about 21 million m³ of sediments have been deposited. The selection of new dumping sites is based on two factors: water depth (to prevent dilution caused by waves and sea currents) and location away from navigation routes (to ensure the proper implementation of the disposal operations).

Usually there is also a lack of supervision and monitoring of dumping sites, both before and after the dredging has been performed; and as a result, there are no reports of changes in the areas which are either near to or distant from the disposal sites.

The main objective of the current study was to develop comprehensive guidelines regarding the methodology of choosing where to deposit the sediment at sea, and the management of coastal dumping sites in the context of reducing the risks for the natural environment.

One of the tasks was to evaluate the usefulness of numerical modelling for surveying the behaviour of sediments at the dumping sites in different phases after disposal. This task is divided into two parts: model development and numerical simulations (Marcinkowski & Olszewski, 2014).

The model developed in this paper was based on the Danish MIKE 21 numerical Coupled Model FM software (2014). The paper presents the methodology for the numerical modelling of hydrodynamic processes during the deposition of the material dumped, and the assumptions regarding the operational

range of the model, the numerical mesh generation, the adoption of initial and boundary conditions, the characteristics of the dredged material and the bottom sediment, and the technology of the work performed. The focus points were the construction of the model, the source data collection, verification of the data sources, and the data for calibration. Moreover, some additional data which might influence the reliability of the model, e.g. the parameters of sediments at the bottom of the dumping sites, are also discussed in this paper.

Model layout

Two basic elements in the initial phase of constructing the numeric model should be determined:

- the size of the computation area, and
- the time scale of the computations.

The size of the computation area is difficult to define *a priori*. While the dumping site area is usually well-defined, the range of the deposited material's impact and its possible distribution strongly depends on the local environmental factors, such as sea currents, wave motion, impact of wind, water flows etc.

During the construction of the model, it is advised to introduce the minimal amount of open borders. Therefore it is necessary to define the boundary conditions that are essential for the validity of the computation results. In case of any uncertainty regarding the description of the model's boundaries, it is recommended to distance them from the area of the analysis.

The aim should be to build a so-called local model (spatially very limited), for which it would be possible to generate the necessary boundary conditions for the borders of the model operating on a much larger scale, i.e. a regional scale model. A hypothetical example of this would be to generate the boundary conditions for the local model of the Gdansk Bay, based on the regional model of the Baltic Sea. Another option is to assume the boundary conditions of the local surveys.

The time scales of the models may be very different. When the purpose of the computations is to define the environmental impact of the dumping, the computation time scales are short – days or weeks. But when the modelling is focused on the re-suspension of the material dumped, the modelling time horizon is long-term, covering a year, or even a number of years.

This report presents the structure of the model for the Gdynia dumping site located in the waters of the Gdansk Bay (Fig. 1a). Initially, the area of computing was limited to the western part of the Gdansk Bay (the red line on Fig. 1b). However, the

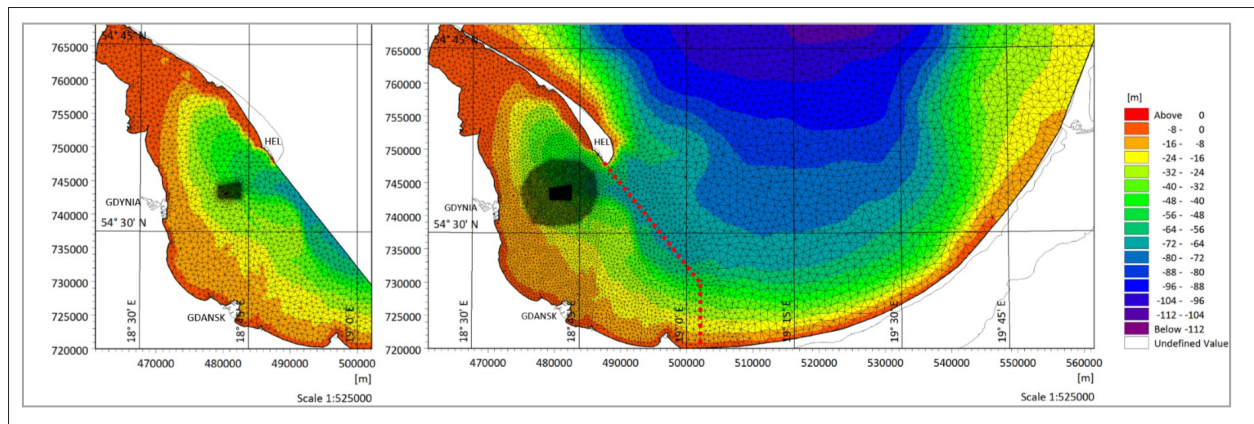


Fig. 1. Designation of the model area of the Gdynia dumping site
 a – initial size of the computation area
 b – final size of the computation area

numerical simulations showed that factors such as the overshadowing of the dumping site area by the Hel Peninsula, and the failure to consider the wind/wave motion approaching from NW to N (which, due to diffraction around a headland of the peninsula, can affect the deposited material significantly), leads to the underestimation of the transport range of the dumped material. As a result, an adjustment was made involving the extension of the model, so that the seaward border was on a line tracing the entire Gdansk Bay (Fig. 1b).

RULES FOR NUMERICAL MESH GENERATION

When generating numeric mesh of the Flexible MESH type, it is possible to choose triangular or rectangular elements. For geometrically simpler areas it is recommended to use rectangular elements, which are more effective due to the shorter computation times. For more complex area shapes, especially in the vicinity of a developed coastline, it is necessary to use triangular elements. However in this case, more accurate mapping requires longer computation times.

Usually in the initial phase, the numerical mesh is generated automatically with limited interference of the operator. Then, after the initial computation, the mesh is refined in the disposal places, in areas with varying depths or in areas where the correct representation of physical processes are important. The last feature involves avoiding sudden changes in the sizes of the mesh elements where the modelled processes play an important role. The plume exceeding the border from relatively small mesh elements to much larger ones, is diluted only in a numerical sense, which can lead to false interpretation of the actual process of mixing the suspension in the water column.

In general, the numerical mesh should be modified in such a way as to create effective models. This means establishing the improvement of detail accuracy in places subjected to analyses, as well as permission to perform faster computations (coarser structured mesh) for areas of lower priority.

BATHYMETRIC DATA

Proper mapping of the seabed morphology is one of the most important structural elements of the model. In practice, additional bathymetric measurements are often performed in high resolution for the area analysed in the vicinity of the planned disposal, while the same quality data is not available for the adjacent waters.

The process of using a variety of bathymetric data to build the model is shown based on the example of the computations performed for the Gdynia dumping site. For the area of the dredged material's dumping site, bathymetric data performed in a grid of 5×5 m was available. In turn, for the Puck Bay basin and the inner part of the Gdansk Bay data characterised by a resolution of 25×25 meters was available. However, for the outer parts of the Gdansk Bay, only the depths in a grid of 1000×1000 m were available. The assimilation of all available bathymetric data for the computation is shown in Fig. 2.

SELECTION OF COMPUTATION MODULES

The Coupled MIKE 21 FM model pack allows the linking of multiple computation modules and the mutual interaction of the results obtained therefrom. In the modelling of the physical processes occurring during the deposition and the subsequent spreading of the deposited dredged material, the user has a choice of the following modules:

- hydrodynamic (*Hydrodynamic Module*, 2013),
- sandy sediments transport, (*Sand Transport Module*, 2013)
- silty and clayey sediments transport (*Mud Transport Module*, 2013),
- wave (*Spectral Wave Module*, 2014).

However, one must bear in mind that linking too many computation modules together can lead to more potential errors, as well as a significant extension of the duration of computations. Therefore, it is advisable to make the optimal selection of modules appropriate to considering the physical issues for the construction of the model.

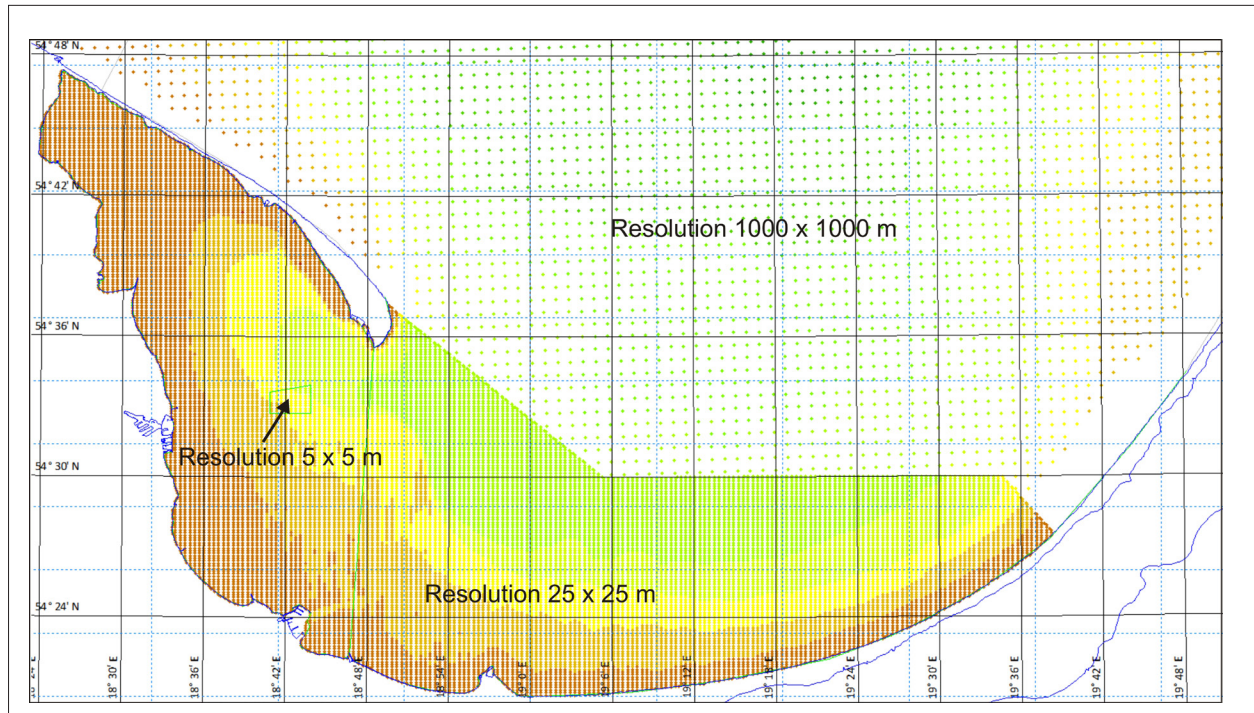


Fig. 2. Assimilation of bathymetric data for the purpose of constructing the model for the Gdynia dumping site

When analysing the spread of suspension during the deposition of the dumped material, the model can consist only of the hydrodynamic module and the silty and clayey sediment transport module. This is because this type of work can only be performed with little wave motion, and the impact of waves on the spreading of suspension may be omitted. In the case of Gdynia dumping site, the sand fraction will also settle to the bottom relatively quickly under the conditions specified for that site, and will not spread in the suspended form.

To analyse the potential movement of sediments already deposited in a dumping site (re-suspension), different modules should be selected. Re-suspension of sediment from the bottom is possible only with an appropriately higher velocity of water flow at the bottom. These currents can originate in wind, wave or gradient (salinity, density). As a result, the computation model must consist of the following modules: wave, hydrodynamic and sandy sediment transport. The sediment transport module should be substituted with the module of silty and clayey sediment transport for some cases.

BOUNDARY AND INITIAL CONDITIONS

Each of the computation modules included in the MIKE 21 Coupled pack requires the determination of its own boundary conditions on the borders of the modelled areas.

For the hydrodynamic model, one of the following boundary conditions can be chosen:

- determination of the flow velocity components and their variability,

- assumption of the flux components with changes in time and space,
- defining the water level fluctuation,
- characterisation of the discharge on the boundary of the area,
- determination of the complex condition (velocity components, variability of the water level, possibly with determining the discharge),
- adoption of a land boundary (closed).

For the wave module, the conditions on the borders of the area can be defined by:

- wave conditions defined by the wave spectral parameters, by wave energy spectrum or by spectral moments,
- the superposition of the energy spectra determined from the wave parameters for wind-sea and swell,
- the lateral boundary, where the information of the incoming waves in the start point and the end point of the line are obtained from the connected boundary lines,
- the reflective boundary,
- the closed boundary.

For the modules of sandy sediments transport and silty and clayey sediment transport, there are two options for defining the boundary conditions. These are:

- determining the suspension concentration level on the borders of the area (the Dirichlet boundary condition),
- determining the value of the suspension gradient on the borders of the area (the Neumann boundary condition),
- zero sediment transport on the land border.

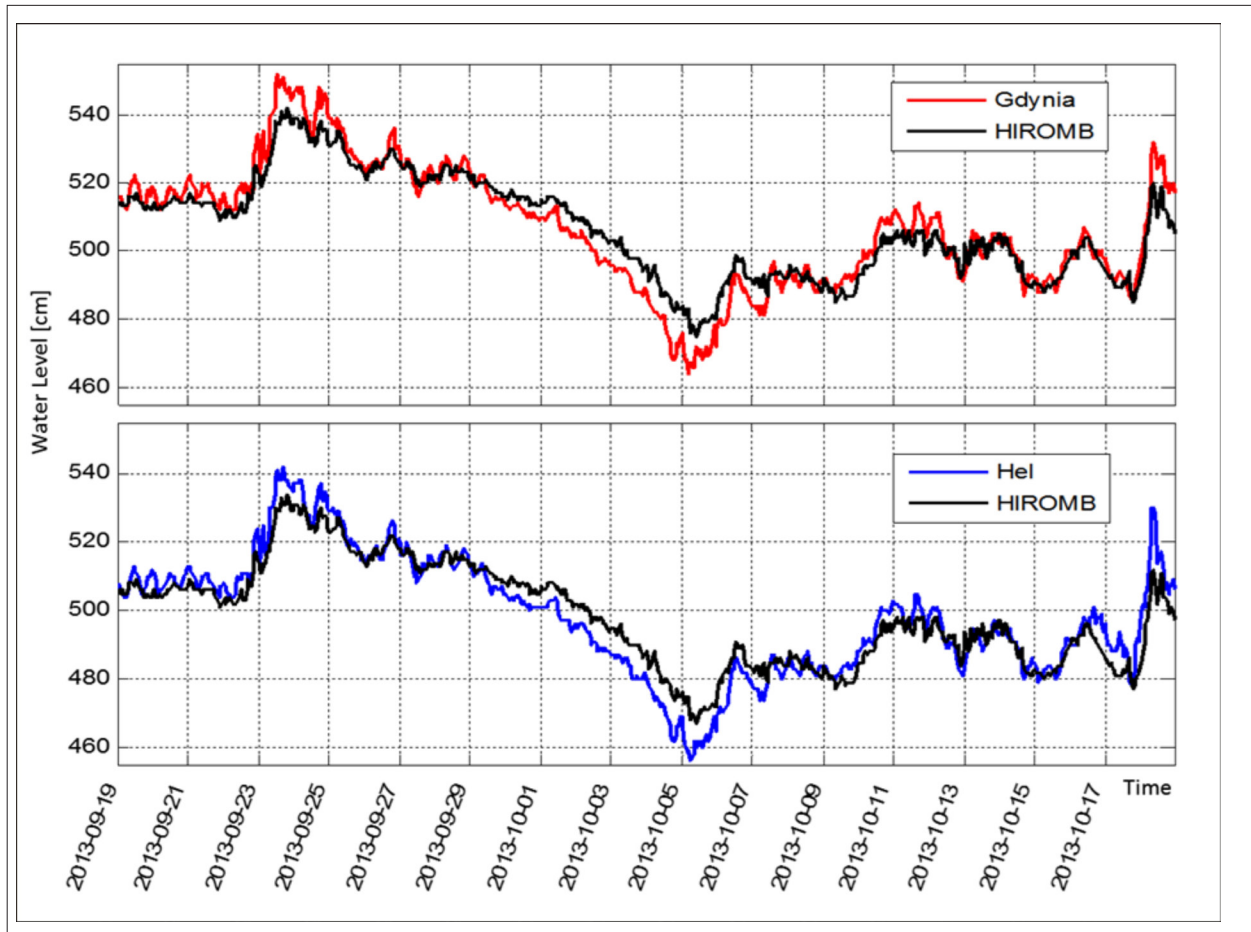


Fig. 3. Comparison of the measured water levels [cm] from Gdynia (the upper part of the figure) and Hel (the lower part of the figure) water gauge stations with the data obtained from the HIROMB model

The main problem in defining the boundary conditions in the various computing modules is the lack of actual measurement data. The operating results of calculations from the numerical models are used in engineering practice in such a case. Another common technique is to generate hypothetical boundary conditions. This technique is most frequently used to study extreme phenomena.

For the Baltic Sea, data can be used from regional models, such as UMPL, HIRLAM or COAMPS (pressure, wind parameters), HIROMB (variability of water level, sea currents), WAM (wave parameters), see Staniforth et al. 2006, Undén et al. 2002, the *COAMPS Model Description* 2003, Funkquist & Kleine 2007. Moreover, survey data for verification of the model can originate from specific points, for example from mareographic stations (water level), wave buoys (wave height, period and azimuth), acoustic current profilers, e.g. AWAC-type profilers (direction and speed of currents in depth function and wave parameters), from devices installed on drilling platforms, from data registered during survey cruises, etc.

There are also problems with making a correct definition of the initial condition in the computing area, i.e. the initial level of suspension concentration. In this case, the initial suspension concentration is usually assumed as equal to zero, and its growth in

time, which is caused by both environmental influences (waves, current, etc.) and the technology of depositing the dredged material, is analysed. This model is referred to as an excess model.

Meteorological conditions

In the case where the calculations require the adoption of actual forces (wind), the results of one of the atmospheric regional models (COAMPS, UMPL, HIRLAM, etc.) should be used. However, in a situation when the wind is to be given in the form of wind speed and direction with a specified return period, data should be taken from long-term statistical analysis. For such an analysis, data from a multi-year measuring period or data elaborated from the various statistical types, source materials are required.

Hydrological conditions

Data on the sea levels and the current field layouts should be based on the regional HIROMB model, in which the computational grid currently reaches the resolution of 1 nautical mile. In areas with a diverse coastline, it is recommended to verify the results of the calculated levels of water with in-situ measurements from the nearest mareographic stations. The

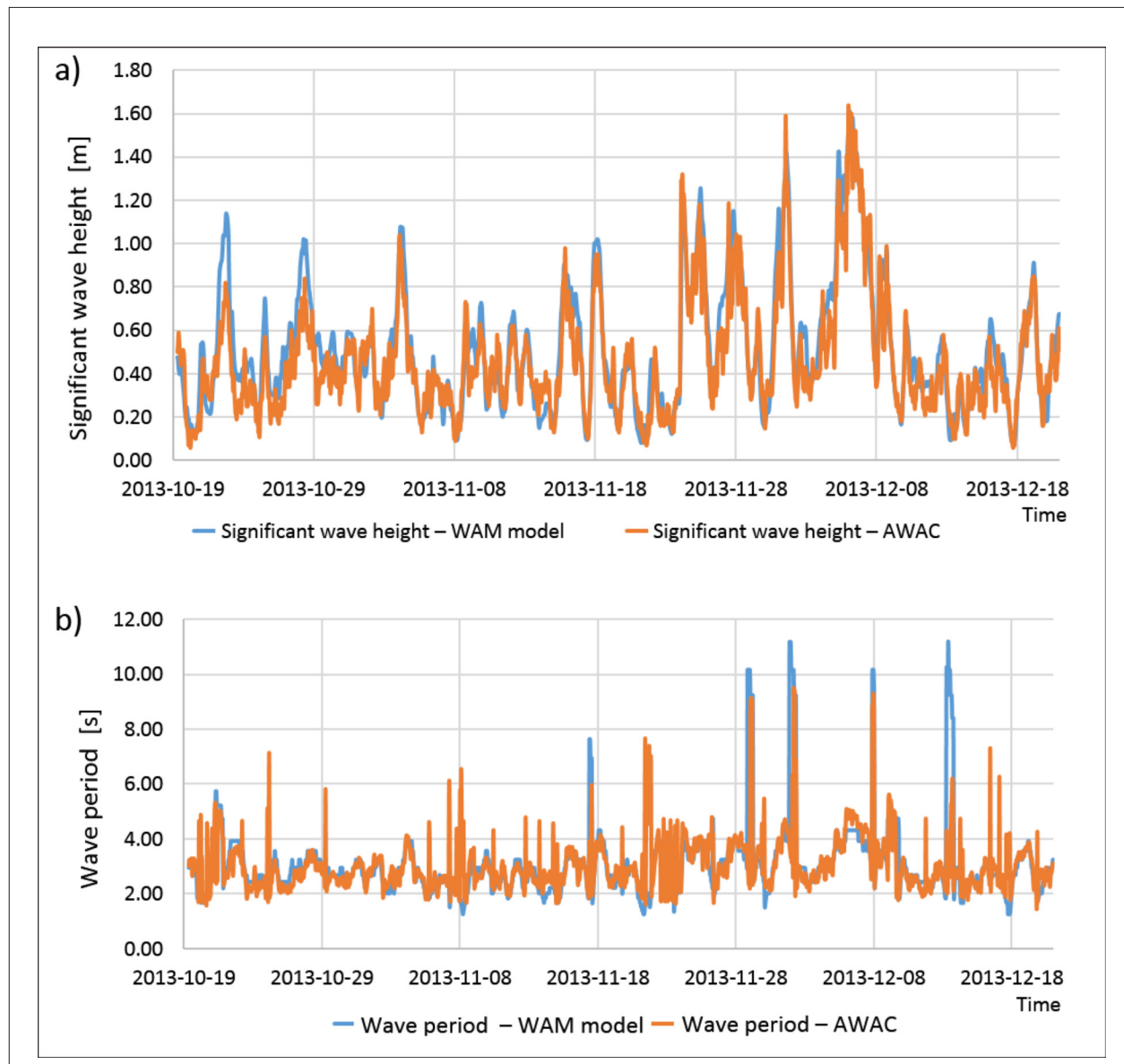


Fig. 4. Comparison of wave parameters (H_s [m], T_p [s]) measured with the AWAC and obtained from the regional WAM model

verification of the calculated velocities should, if possible, be done using the velocity measurements registered by profilers on nearby survey buoys, on drilling platforms and from research vessel cruises.

Wave conditions

Currently, for the Baltic Sea, there are several models operating on a regional scale. One of them is the spectral WAM model (Gunter, 2002), which describes the wave surface to a satisfactory level. The WAM model, which operationally functions at the Maritime Institute in Gdansk, has been repeatedly verified, showing its practical usefulness (Cieřlikiewicz & Paplińska-Swerpel 2005, Paplińska 1999). The analysis in which the modelled wave parameters were compared with the ones measured also proves that the thesis of the high conformity of the respective elements should be considered

legitimate. Only in the case of extremely strong storms was a slight overestimation of the significant wave height H_s observed in the WAM calculation model. The calculations show that when the perpendicular to the isobaths boundaries of the modelled area combine with the coastline and are shorter than the appropriate seaward boundary, it is recommended to define them as *lateral* type.

METHODS OF VERIFYING THE SOURCE DATA FOR BOUNDARY CONDITIONS

The verification of the values calculated within this work is shown below on the basis of the numerical tests on the dredged material deposited in the Gdynia dumping site. In the calculations performed, the parameters of wind, water levels, sea currents and waves from the HIRLAM, HIROMB and WAM regional models were assumed as boundary conditions and

forcings. The values calculated were verified by comparing them with the data obtained from the hydrological onshore stations, the acoustic current profiler (AWAC) and the survey buoy anchored in the area of the model calculations. The data from coastal stations were characterised by longer periods, while the data series from the profiler and the buoy were definitely shorter.

Water level

Water level fluctuations obtained from the HIROMB model, which were assumed along the open boundary, were tested against measurements. Fig. 3 shows a comparison of the measured water levels [cm] from the Gdynia (the upper part of the figure) and Hel (the lower part of the figure) water gauge stations with the data obtained from the HIROMB model.

The figure shows that the regional HIROMB model correctly maps the actual levels of water in the sea, especially in the ranges of the mean and higher levels. For lower levels, mostly in the range of 460 ÷ 490 cm, the calculated water levels are lower than measured. However, the maximum size of this error does not exceed 10%. Correlation coefficients between the calculated and the measured water conditions were as follows:

$$R_{Gdynia-HIROMB} = 0.96, R_{Hel-HIROMB} = 0.95.$$

The verification presented above shows a high conformity of the measured changes of sea level from the HIROMB model with the data observed from coastal stations (Gdynia, Hel). It justifies the assumption of the boundary condition describing the state of the sea from the regional HIROMB model.

Wave parameters

Measurement data from the selected point within the Gdynia dumping site was obtained based on the registration of current velocities and wave heights by an acoustic current profiler of AWAC (Acoustic Wave And Current) type.

The results of significant wave heights H_s [m] obtained from the measurements by AWAC, over a period of two months (19 October 2013 to 19 December 2013), were compared with the results obtained from the regional WAM model (the WAM grid point closest to the dumping site). The comparison of time series variation in H_s from measurements and from the model is shown in Fig. 4a.

The graph shows the high compatibility of the two data series, and the linear correlation coefficient is $r = 0.92$. Similarly, the results of wave period T_p [s] measurements for the same time with an AWAC were compared with the results obtained from the regional WAM model. The comparison of time series variations in T_p from the measurements and from the model is presented in Fig. 4b. The graph shows the high compatibility of the two data series, and the linear correlation coefficient is $r = 0.50$.

This analysis confirms the high compliance of the results of wave parameters from the WAM model with the observational data from the AWAC instrument, which justifies the acceptance of data from the WAM regional model for further numerical computations in the MIKE model.

CHARACTERISTICS OF THE SEABED AND DISPOSAL MATERIAL

Introduction

In the model modules which calculate the amount of the sandy and silty and clayey sediment transport, the physical characteristics of the subsoil and the deposited dredged material must be given. The definition of substrate parameters as precise as possible is important in modelling the processes of re-suspension and transport of sediments deposited in dumping sites. However, when modelling the dumping of dredged material, in turn, the leading issue is determining its physical properties as accurately as possible.

In general, initial information on the geological structure of the substrate is based on the data contained in geological atlases. But this is not accurate information, and it requires elaboration in the form of laboratory analysis of the surface and/or deeper core samples. The parameters determined in the laboratory, such as the grain size distribution curve or the amount of fractions < 0.063 mm, form the basis for the construction of the actual computational models. For the respective types of soil, building further layers of the bottom, geotechnical parameters are then identified which determine the potential for sediment movement. It is equally important, from the viewpoint of numerical modelling of the seabed deposited dredged material behaviour, to determine its thickness and the parametric characterisation of the changes which will occur in the sediments over time.

Discussion

We may assume that up to 12 layers of soil will compose the substratum in sediment transport calculation modules. From a practical point of view, it is recommended to limit its amount to the minimum, but in such a way that the adopted layer layout in the calculation sufficiently represents the geological variety of the seabed.

Immediately after the dumping of the dredged material, its loose top layer is susceptible to erosion. This layer, with very small thickness and extremely unfavourable geotechnical parameters, requires isolation and the introduction of at least two layers in the calculation model. The main parameters necessary for correct calculation of the transport amount of the deposited material are its dry density, the values of critical shear stresses beyond which the sediment starts to move, and the roughness of the seabed, most often described as a function of the height of the characteristic diameters of the sediment grains.

Dredged material can very rarely be treated as homogeneous, hence the need to define it for the purposes of modelling in the form of several types of fractions. Their number is limited to 8 in calculation modules. In this case, it is advisable to limit their amount with care, in order to characterise the deposited material with satisfactory accuracy. Determining each fraction forming the slurry requires the determination of:

- the velocity and method of settling of soil particles, and
- the sediment deposition criteria.

Depending on the concentration of suspension, the following is distinguished: freefall when the number of particles is small enough so that each particle falls independently, the increased concentration of particles forms flocculation and increases the rate of descent. A further increase in concentration leads to the so-called hindered settling process. A more detailed description of how the descent of the suspension and its sedimentation depending on the level of concentration can be found in the literature (van Leussen, 1988, the MIKE21 FM Manual, 2014). In the case of granular particles, freefall mainly occurs.

Sand and gravel almost immediately sink to the bottom and remain there. Another situation occurs in the case of single fine silty particles with a diameter of 0.063 to 0.002 mm, and clay particles with a diameter of less than 0.002 mm. These fine particles remain in the water column for a long time before finally descending to the bottom.

The criterion of sedimentation requires the determination of a shear stress threshold below which the process of sedimentation begins.

Each of the fine fractions can to different extents pass into a suspended state, wherein it is not always dependent on the particle diameter. For example, due to their significant cohesion, clay fractions are not easily defragmented and quickly descend to the bottom, remaining in a cluttered form. As a result, the percentage of such fractions passing into the state of suspension will be smaller than in the case of the silty fractions, the diameters of which are larger but less cohesive.

On the other hand, the percentage of sandy material passing into the suspended state depends not only on its diameters,

but also on the method of collecting the soil, its transportation and unloading. Most often, for fine-grained sand it is assumed that 3% of its mass passes into the suspended state (Hornsea Offshore Wind Farm, 2013). In contrast, depending on the method of unloading, up to 30% of the silty fraction's volume can be expected to pass into the suspended state.

When modelling the spread of the deposited dredged material, transport and material unloading technologies must also be presented. The routes of scows or dredgers should be thoroughly mapped, taking into account the speed of the transport and unloading. The method of unloading is characterised by the intensity of dumping expressed in kg/s, the duration of a single unloading of a scow or dredger, and the entire sequence of dumping work.

CONCLUSIONS

This elaboration has presented the principles for creating a numerical model, which would be useful for describing the spillage of the dredged material deposited on the seabed. Particular attention was paid to the following elements:

- correct determination of the calculation area's values and modelling the time scale phenomena,
- issues associated with the determination of the boundary conditions on open boundaries of the model,
- the relations between the local model, in which calculations are performed regarding the behaviour of the deposited sediments with regional models, the calculation results of which usually are used to generate boundary conditions in local models,
- the optimal selection of the number of calculation modules depending on the process surveyed and the dredged material deposited in various phases of exploiting dumping sites,
- the most accurate possible determination of physical characteristics, both of the subsoil and the deposited dredged material.

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