REPORT ON THE ENVIRONMENTAL IMPACT ASSESSMENT OF THE BALTICA-1 OFFSHORE WIND FARM

APPENDIX 2

THE MODELLING OF SUSPENDED SOLIDS DISPERSION

AUTHORS:

Tomasz Marcinkowski, Tomasz Olszewski

CONTRACTORS:

Justyna Edut, Kamila Gałka, Natalia Kaczmarek, Mateusz Kunicki, Teresa Moroz-Kunicka, Dominika Górnowicz

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ABBREVIATIONS AND DEFINITIONS

AWAC	Acoustic Wave and Current (Profiler) by Nortek
Baltica-1 OWF area	The area of the planned Baltica-1 Offshore Wind Farm
CMEMS	*Copernicus Marine Environment Monitoring Service*
DHI	Danish Hydraulic Institute
Forcing	Forcing (impact) applied in numerical models
HBM	*HIROMB-BOOS Model, i.e. High-Resolution Operational Model for the Baltic–Baltic Operational Oceanographic System Model*
HD	The hydrodynamic module of the Mike model
Investor	Baltica-1 Wind Farm LLC (*Elektrownia Wiatrowa Baltica-2 Sp. z o.o.)*
MT	The Mud Transport module of the MIKE model
OWF	Offshore Wind Farm
SW	Spectral wave module of the Mike model
UM	Unified Model – a numerical model of the atmosphere used for weather forecast
UMPL	Unified Model for Poland – a model used for forecasting the weather for Poland

1 NON-SPECIALIST SYNOPSIS

The study concerns the Baltica-1 Offshore Wind Farm with a maximum total capacity of 900 MW. The planned Baltica-1 OWF is located in the Polish Exclusive Economic Zone in the Baltic Sea, east of the Southern Middle Bank. The depth of water in the area of the wind farm is varied and ranges from 16 m to 50 m. The distance from the offshore wind farm to the coastline is approx. 75 km and it is located at the level of the Smołdzino and Łeba municipalities (Pomeranian Voivodeship).

This Report addresses the issue of suspended solids dispersion in the water depth and their deposition on the seabed in relation to the Investment implementation. It presents a concise description of numerical models used for calculation purposes and a set of calculation results obtained based on these models, including their interpretation.

The presented results illustrate the dispersion of suspended solids, their concentration in the water depth and sedimentation on the seabed. The sources of suspended solids include underwater work, which is connected with the installation of offshore WTGs and substations and the embedding of power and telecom cables. The analysis included both works related to preparing the seabed for the installation of gravity-based structures and methods much less invasive in terms of suspended solids agitation related to the foundation of support structures with the use of piles (monopiles and jack-ups). Work related to cable-laying, which includes clearing stones and boulders from the seabed on cable routes, as well as embedding cables into the seabed itself also generates suspended solids and that is why numerical simulations were also carried out for these works to determine the parameters of disturbance of the marine environment. In addition, work related to soil reinforcement in places where the spud cans of the installation vessel are placed, especially in the case of cohesive soils with low bearing capacity, where the soil will have to be replaced (by making excavations and replacing weak soils with crushed stone), is responsible for the agitation of suspended solids. This type of work was also examined using a numerical model.

The concentration of suspended solids depends, among other things, on the water depth, type of subsoil, type of underwater work, and the speed with which it is performed.

A numerical model was developed to represent suspended solids transport in the dynamic marine environment during the performance of underwater and dredging works at the seabed in the area intended for the implementation of the Baltica-1 OWF.

The results of numerical calculations allowed for analysing the maximum impact ranges of suspended solids with specific concentrations (formed during the long-lasting works conducted in the seabed), and the thickness and spatial distribution of seabed sediments formed in the process of suspended solids sedimentation. The performed calculations took account of the differences resulting from the variety of underwater works carried out when constructing the OWF, as well as the types of soil in which seabed works are carried out and the depths at which the works are performed.

Environmental forcings adopted in the modelling were the impacts of winds blowing over the entire sea area surveyed, wave motion, time-varying levels of the water table, and sea currents, which are a natural factor generating water movement, and thus, the movement of suspended solids in the water depth.

Previous calculations performed by different teams unambiguously indicate that works carried out in seabed with cohesive soils cause a greater impact of suspended solids on the marine environment than works conducted in non-cohesive soils (it should be highlighted that cohesive soils were identified in the surface layers of the seabed in a majority of the Baltica-1 OWF area). In the numerical models developed, the surface layers (in which the underwater works are conducted) under the seabed are represented by both cohesive and non-cohesive soils based on the geological survey. In the envelope method, analyses should consider scenarios providing for the greatest impact of suspended solids on the marine environment, with conservative assumptions being followed and with the aim of determining the highest values of environmental disturbance parameters.

The scope of the studied calculation scenarios also includes the implementation of works related to the preparation/replacement of soil in the location of two gravity-based structures performed at the same time. The purpose of calculating such a scenario is to examine the effect of the cumulative impact of suspended solids. Also, works related to the replacement of non-bearing soils under the spuds of the installation vessel are of a cumulative, stationary nature. On the one hand, an excavation is made in the cohesive non-bearing soil intended for replacement, and on the other hand, the excavated soil is deposited on the seabed nearby (approx. several hundred meters away) with a suction dredger. The impact during sediment replacement is significantly higher than the one recorded during excavations.

The conducted analyses show, among other things, that the greatest impact ranges of suspended solids occurred in the case of moderate winds with constant directions, while the highest concentrations of suspended solids were generated when currents of the lowest velocity (of several $cm \cdot s^{-1}$) and circular nature were recorded. An equally important conclusion drawn from the calculations is the fact that in the least favourable scenario, suspended solids with a concentration of over 5 $mg \cdot l^{-1}$ locally do not remain in the marine environment for more than 21 hours from the moment of starting the works with a movable source of suspended solids, and no longer than 24 hours from the moment of completing the works with a non-movable source of suspended solids. When considering two works performed simultaneously at a small distance from each other, as a result of cumulative impacts, these periods are extended and take the value of 31 hours (for a moving source) and 72 hours for quasi-stationary works, respectively.

2 INTRODUCTION

This study has been commenced by the Elektrownia Wiatrowa Baltica-1 Sp. z o.o. company. The main task was to determine the concentrations of suspended solids in the water depth and the manner of their dispersion and deposition on the seabed when performing underwater works agitating suspended solids as part of the Baltica-1 Offshore Wind Farm implementation. The Investor assumes the following types of support structures for wind turbine generators and offshore substations to be possible: gravity-based structures; monopiles, and jacket foundations. The foundation of a gravity-based structure requires levelling the substrate or partial replacement of the soil. In such works, the largest volume of soil is disturbed and therefore, they are responsible for generating the largest amount of suspended solids. The other two solutions are similar when it comes to soil-structure interaction, as they involve the driving of steel foundation piles into the soil. The fundamental difference is the pile diameter. In the case of monopiles, pile diameters of 12 m/11 m are considered. The assumed lengths of monopiles are 110 m for larger turbines and 90 m for smaller turbines, while the effective time of driving the monopile is estimated at 3–5 hours. When using WTG jacket support structures, it is planned to use foundation piles of up to Ø 4.2 m with a length of 70 m for larger WTGs and Ø 4.0 m with a length of 60 m for smaller WTGs. The effective time of driving the foundation pile into the soil is estimated at 6–8 hours. The base diameters of the gravity-based structures are Ø 55 m or Ø 45 m, depending on the selected WTG sizes. The effective time of preparing the excavation and levelling the ground for a gravity-based structure is estimated at 12 hours.

Both presented options involve the laying of inter-array cables within the wind farm area. Such operations cover both the preparation of cable routes related to boulder clearance and the embedding of cables into the seabed. The expected depth of cable laying will be up to 3 m, with local, unique places exceeding this value, but no more than 6 m, depending on the encountered soil conditions related to the seabed structure. Depending on the soil conditions prevailing in the area of the offshore connection infrastructure, it is assumed that the cables can be embedded using the water jetting technology. In addition, cable-laying methods that include the use of chain-cutting or ploughing devices are being considered. The experience gained during the implementation of this type of project indicates that, from the viewpoint of suspended solids impact, hydraulic methods of cable embedding have a greater effect on the marine environment than mechanical ones.

The primary goal of this study was to develop a numerical model which would make it possible to conduct simulation-based calculations to assess the impact of suspended solids during the performance of installation works, i.e. at the construction stage. An impact of this type, caused by anthropogenic factors, will occur at its greatest intensity during the construction stage but it will not occur at the operation stage. Also, it is expected to be negligible at the decommissioning stage.

As part of the work performance, the following was carried out:

- an analysis of hydrological and hydrodynamic conditions;
- a preliminary analysis of soil conditions, which is necessary for the development of a numerical model, in the Baltica-1 OWF area based on the available test results;
- a construction of a numerical model using the MIKE 21 software;
- simulation-based calculations for the scenarios assumed;
- an analysis of calculation results, including their summarization.

The numerical model developed allows for analysing the hydrodynamic processes taking place during the performance of underwater works generating suspended solids, which are related to seabed preparation and clearance, and installation of support structure foundations, and during the performance of works related to the laying and embedding of power and telecom cables in the seabed. The basic issue surveyed was the process of dispersion of fine-grained sediments suspended in the water depth; they are crucial both in terms of the assessment of suspended solids concentration as well as its range. Another important aspect is the assessment of the suspended solids sedimentation impact on the benthic habitats and benthic fauna. The modelling takes account of diverse meteorological and hydrological conditions which represent the actual impact of the marine environment. As a result of this impact, the current field, which is the cause of suspended solids transport, is also characterised by high variability (velocities and directions) in the periods adopted for the simulations. In the numerical modelling performed, a two-dimensional model developed by the Danish Hydraulic Institute (DHI) – MIKE 21 – was used. In the Report, the results of calculations regarding hydrodynamic issues and the transport of fine sediments, such as current velocities and suspended solids concentrations, take into account their depth-averaged spatial variability within the sea area analysed. All the figures included in the Report, which refer to the results of the numerical simulation-based calculations, such as current velocities, suspended solids concentrations etc., present depth-averaged values.

3 METHODOLOGY

3.1 NUMERICAL MODEL

The numerical calculations were carried out using a licensed, Danish software package MIKE 21 Coupled Model FM. This computational package has been developed at the Danish Hydraulic Institute (DHI) for years to calculate water flows, wave motion, and sediment transport within the coastal zone as well as in the open sea. The Coupled version enables the dynamic simulation of hydraulic aspects with the reciprocal interaction of all the modules used. This software is widely used all around the world (e.g. Burcharth et al., 2007; Lambkin et al., 2008).

For the purposes of calculations related to the transport of suspended solids generated during underwater works involving the installation of WTG support structures, and pre-lay clearance works along the cable routes, as well as during works that accompany the embedding of power and telecom cables in the seabed, and possible works associated with soil replacement to reinforce the subsoil under the installation vessel spud cans, the following modules were used:

- hydrodynamic module (HD);
- spectral wave module (SW);
- mud transport module (MT).

The hydrodynamic module (HD) makes it possible to simulate the changeability of the current field and the water table level depending on various forcing functions in sea basins. This module will make it possible to include the following hydraulic effects in the calculations (MIKE 21 HD Flow Model FM, 2013):

- friction at the water–seabed boundary (seabed roughness) and water–atmosphere boundary (wind impact);
- discontinuities in the form of sources and spillways;
- the impact of the water table level changeability;
- radiation strains caused by wave motion.

The spectral wave module (SW) enables the calculation of the wave field parameters (wave heights and periods as well as directions) generated by the wind, with the direction and velocity changing in time. In the initial phase of the performed calculations, the direct impact of wave motion on the dispersion of suspended solids generated by the works performed in the marine environment was tested. Although the findings of such tests prove an insignificant impact of wave motion on the suspended solids dispersion for moderate wave motion (limited to $H_S \approx 1.5 \div 2.0$ m), which is when the analysed underwater works can be performed, the model developed takes account of the spectral wave module (SW).

The mud transport module (MT) describes the seabed erosion, sediment (suspended solids) transport, and sedimentation of the finest soil fractions, caused by the sea currents and wave motion impact. The MT module may be used both for silty and loamy sediments and for a mixture of these sediments with sand, with fine fractions prevailing, and cohesion is a significant feature that characterises such a mixture (MIKE 21 MT Flow Model FM, 2013).

The following was taken into account and defined in the simulations:

- sea currents – as the main factor forcing suspended solids movement in the water depth;

- the impact of free sea surface motion on the modification of suspended solids dispersion in the marine environment;
- the process of sedimentation due to the physical structure of sediments – settling of single particles and settling of flocculant particles.

3.2 GENERAL ISSUES

In methodological terms, the creation of a numerical model consists of determining the boundaries of the computational region and constructing a numerical grid that is fit for the analysed issue. On the boundaries of the model, physical conditions for each of the issues under consideration need to be defined (boundary conditions). However, it should be highlighted that the measurement results obtained from the hydrological monitoring apply to several selected points within the OWF area, and the model requires to be based on a larger space and that the conditions defined for all of its open boundaries are entered. These conditions may originate from other models and actual measurements or may be formulated using theoretical mathematical models to analyse time variable forcings and the ones that actually appear in the marine environment. When entering the conditions obtained from the regional numerical models on the model boundaries, it is recommended to verify the values obtained from the model developed against the measurement data, if such data exist. The results of preliminary *in situ* surveys carried out in the area for which the numerical model was developed allowed for reconstructing the features of the environment in more detail. This applies to both hydrodynamic conditions and the characteristics of the marine sediments in which underwater works are to be carried out.

3.3 COMPUTATIONAL ASSUMPTIONS

3.3.1 General

For the purposes of the implemented Baltica-1 project, the dense numerical grid covers an area with sides of approximately 30 km × 20 km in length, enveloping the location of the Baltica-1 OWF. In the assumed region, all the soil conditions identified as part of the monitoring, and the measured bathymetric conditions are represented. The assumed area of the calculation model, including the dense numerical grid against the Baltica-1 OWF area, is presented in the figure below [Figure 3.1].

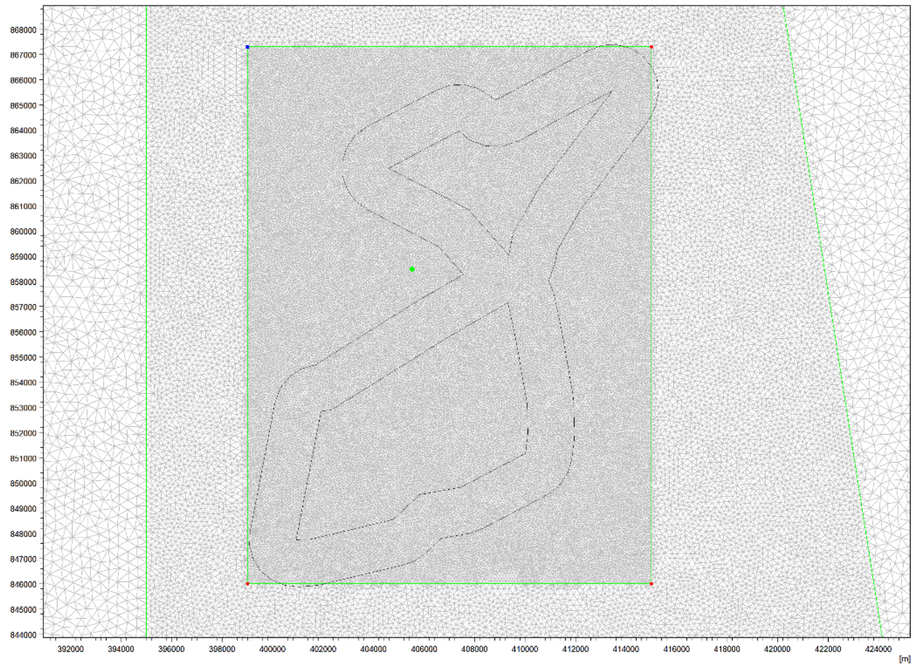


Figure 3.1. The location of the calculation model, including the assumed dense numerical grid, against the Baltica-1 OWF area

In the adopted numerical grid, the surface areas of triangular elements do not exceed 7000 m^2. The calculation area consists of 107,492 triangular elements based on 54,661 nodes. To conduct numerical simulations based on the pre-defined calculation scenarios, 5696 time steps were applied with a resolution of 900 s, i.e. 60 days. In the event of no numerical coincidence, intermediate time steps may be decreased with the Courant number of not more than 0.9 being maintained.

Bathymetric surveys in the analysed Baltica-1 OWF area were conducted by MEWO S.A., and after digital processing, presented as a numerical model. The depths are varied and in the area of the entire wind farm, they fall between 16.0 m to 50.0 m. The bathymetric surveys were carried out with a multibeam echosounder depicting seabed formations accurately with a resolution of 4 pts/m^2. For the purposes of the numerical model, this extensive data set was expanded and, in practice, sets with a spatial resolution of 5–10 m were used. It should be emphasised that the local seabed level differences of up to 0.2 m have practically no impact on the average speed calculated for the currents at the depths from 16 m to 50 m occurring within the Baltica-1 OWF area. The depth levels measured were assigned to the calculation grid of the model. The wind farm extends over an area much varied in terms of depth. However, assigning the measured depths and identified soil conditions to the appropriate grid elements allows for the calculations and analysis of results taking into account the diversity of both of these impacts.

Direct measurements of meteorological, hydrodynamic, and physicochemical parameters in the area of the Baltica-1 OWF were conducted by the Consortium of the Gdynia Maritime University and MEWO S.A. from December 2022 to the end of November 2023 at the B_MFW_3 measurement station at position y 410540.00; x 857679.00 (ETRF2000-PL/CS92 coordinate system), at a water depth of approx. 34 m. The measurement buoy deployed at this position was equipped with:

- a LUFFT WS500-UMB meteorological station, which was equipped with separate sensors for measuring individual meteorological parameters: relative humidity of the air, air temperature, wind velocity and direction;

- a Vaisala PTB210 barometer for measuring atmospheric pressure;
- a set of CTD probes for measuring hydro-physical parameters: temperature, electrolytic conductivity, and water pressure (depth) at five depths in the water depth: 1 m, 4 m, 8 m, 16 m, and above the seabed;
- a current profiler with a CTD probe and sensors for measuring water flow (speed and direction) throughout the water depth, waves on the free sea surface (height, period, and direction of waves), water temperature above the seabed, and the current water depth and turbidity.

The changeability of wind speed from the UM regional model for long (12 years) periods has been presented in the figure below [Figure 3.2], while the height of significant waves measured in 2023 using an acoustic wave and current profiler AWAC (at the measurement buoy, station B-MFW_3) in the Baltica-1 OWF Area has been shown in the next figure [Figure 3.3]. The recorded significant wave heights refer to a period when these parameters were subject to *in situ* measurements, with the period adopted for the numerical model being marked (blue-framed). The locations of the survey points are presented in the following figure [Figure 3.4]. Figure 3.2 clearly shows the cyclical nature of strong wind periods (autumn and winter periods) and periods characterised by lower wind forcings (spring and summer periods), when the performance of works related to the installation of support structure foundations, boulder clearance, a local soil replacement, and cable laying should be expected. The differences in mean wind velocities for the spring-summer periods and the autumn–winter periods in individual years of the 2009–2022 timespan are distinct, indicating an increase in the mean velocity in the autumn and winter period by approximately 30%.

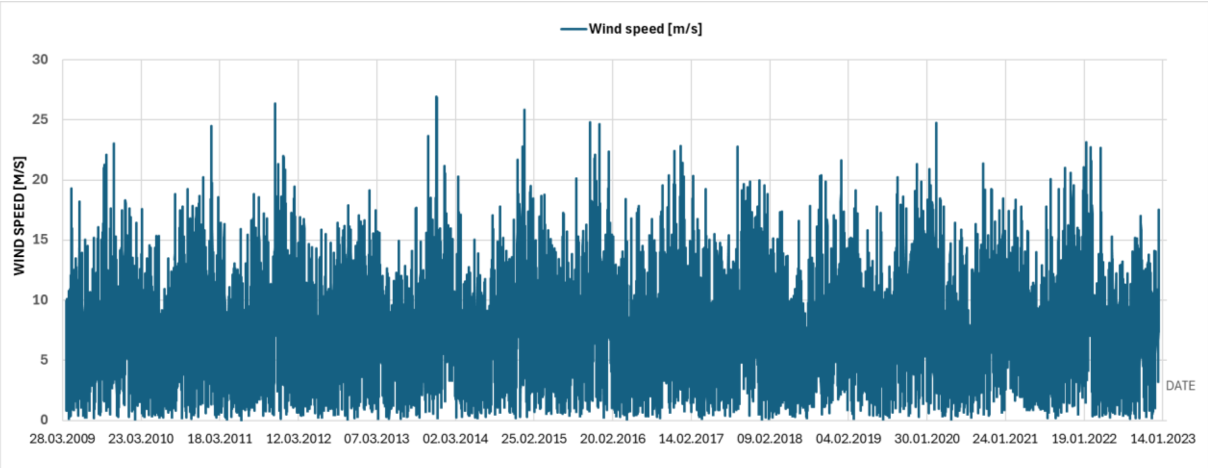


Figure 3.2. The wind velocity distribution in a 14-year period (2009–2022) in the Baltica-1 area based on the UMPL model

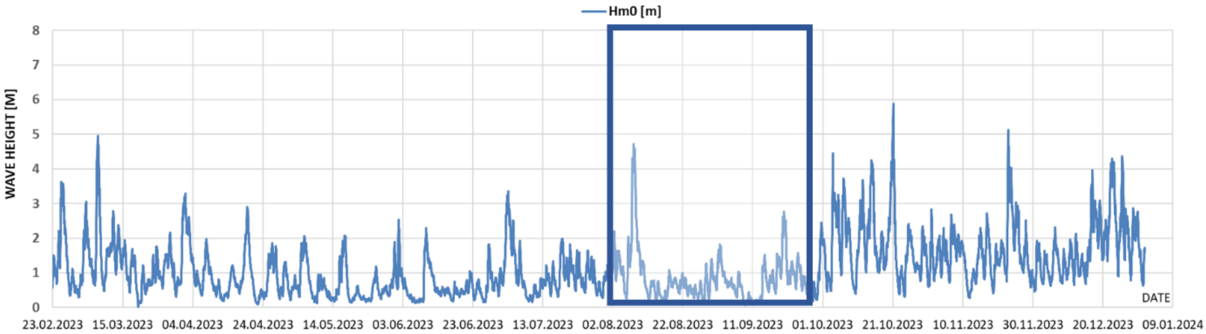


Figure 3.3. The wave motion measured at the measurement point B-MFW_3 (AWAC) in the Baltica-1 OWF area in 2023 with the period adopted for the numerical model marked (blue-framed)

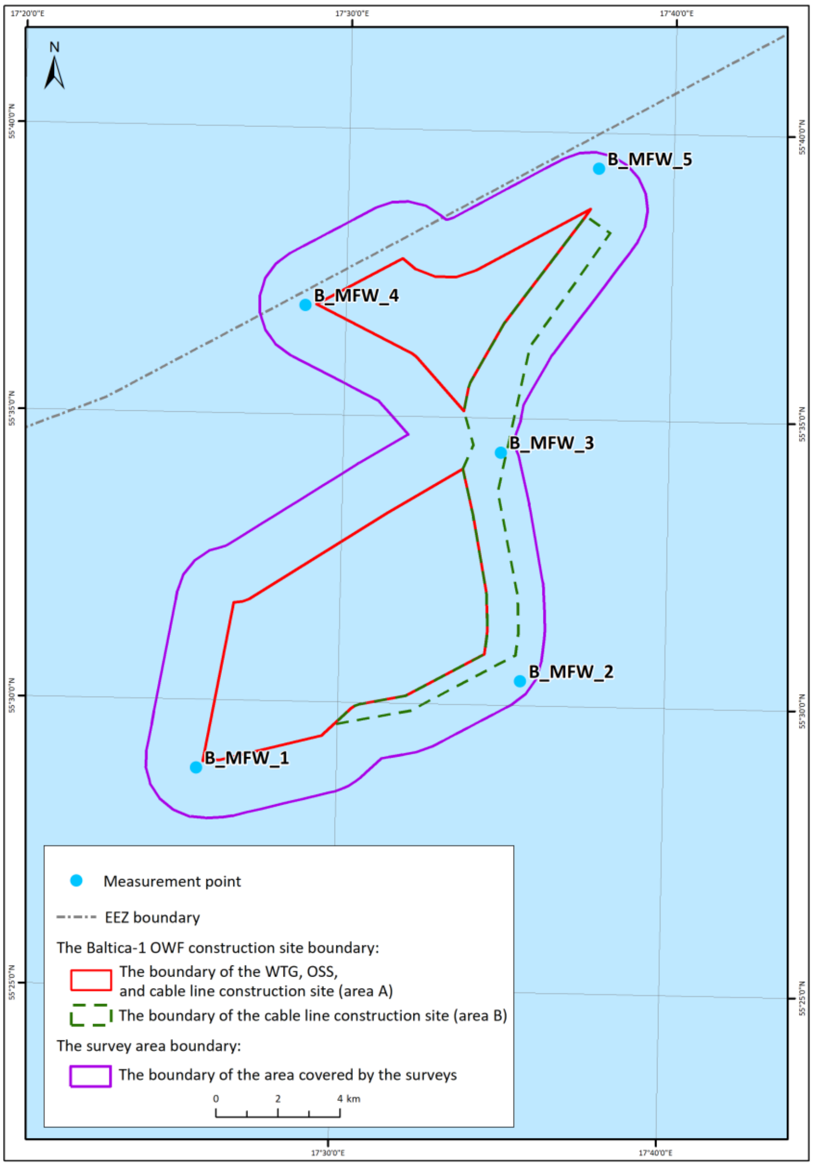


Figure 3.4. The location of the measurement points within the sea basin intended for the construction of the Baltica-1 OWF

As dredging works can be conducted only in moderate wave motion (H_S < 1.5 ÷2.0 m) (Grundlehner et.al., 2023), model calculations were carried out in the months with the highest probability of recording longer periods of small to moderate wind forcings (August–September). Statistically, the lowest values of wave motion are recorded in the spring–summer period. There is no sensible justification for modelling taking account of winter months, as there are too many days with excessively intense wave motion in these months, which prevent the operation of vessels engaged in the project implementation (significantly more frequent breaks in work, use of weather windows). By all means, in real conditions, it is possible to conduct dredging works in any season of the year provided that the boundary conditions for the equipment involved and the work performance techniques are not exceeded.

Taking into account that the possibility of carrying out the works is limited by weather conditions, the adopted calculation period gives fully representative results regarding the ranges of concentration and amount of sediment deposition for the entire possible period of work implementation.

3.3.2 Boundary conditions and forcings in the numerical model

The boundary conditions on the model's boundaries define the forcings causing suspended solids to move in the water depth. In the case of the issue under consideration, these are sea currents, the water table level fluctuations and wind-generated wave motion. The model also takes account of another forcing, which is different in nature and covers the entire computational region, i.e. the wind impact. The first two conditions were introduced on the boundaries of the model as Flather-type boundary conditions, taking into account the sea level and the current velocity components (*u, v*) as time variables. The hydrodynamic conditions (current parameters, water table level changeability and wave motion parameters) for the construction of a local model were obtained from the COPERNICUS marine service, i.e. the EU Copernicus Marine Environment Monitoring Service (CMEMS). The regional hydrodynamic model (HBM) of this service, which covers the Baltic Sea, is arranged on a grid with a spatial resolution of 1 NM, thus providing data with a one-hour resolution. This model has been operational since 2013. The arrangement of the required Flather-type input data set for each point on the model's boundaries is an example presented in the table below [Table 3.1]. The data for all the nodes on the model's boundaries are obtained in the process of linear interpolation between the pre-defined points. The MIKE model grid is characterised by a higher density (subsection 3.3.1) in comparison with the grid under the regional model based on CMEMS, which provides data for the determination of boundary conditions. However, it should be highlighted that along the boundary sections of the adopted MIKE 21 computational model, under open sea conditions, the changeability of the current kinematic parameters taken from the HBM regional model is rather low, and, consequently, this procedure is error-free.

Table 3.1. An example layout of the data set entered for the points selected on the numerical model boundaries, representing the Flather-type boundary condition [source: internal data based on the CMEMS]

Date and time	Water level [m]	U [$m \cdot s^{-1}$]	V [$m \cdot s^{-1}$]
2023.01.01, 01:00:00	-0.09	-0.03	-0.13
2023.01.01, 02:00:00	-0.09	-0.05	-0.12
2023.01.01, 03:00:00	-0.08	-0.08	-0.10
2023.01.01, 04:00:00	-0.07	-0.09	-0.06
2023.01.01, 05:00:00	-0.06	-0.08	-0.02
2023.01.01, 06:00:00	-0.04	-0.04	0.02
2023.01.01, 07:00:00	-0.02	0.02	0.05

Date and time	Water level [m]	U [m·s^{-1}]	V [m·s^{-1}]
2023.01.01, 08:00:00	-0.01	0.09	0.05
2023.01.01, 09:00:00	0.01	0.15	0.03
2023.01.01, 10:00:00	0.02	0.18	-0.01
2023.01.01, 11:00:00	0.03	0.20	-0.06
2023.01.01, 12:00:00	0.03	0.18	-0.11
2023.01.01, 13:00:00	0.02	0.13	-0.15
2023.01.01, 14:00:00	0.02	0.08	-0.17
2023.01.01, 15:00:00	-0.01	0.03	-0.16
2023.01.01, 16:00:00	-0.02	-0.03	-0.14
2023.01.01, 17:00:00	-0.01	-0.07	-0.11
2023.01.01, 18:00:00	-0.03	-0.10	-0.07
2023.01.01, 19:00:00	-0.03	-0.10	-0.01
2023.01.01, 20:00:00	-0.04	-0.08	0.04
2023.01.01, 21:00:00	-0.05	-0.03	0.07
2023.01.01, 22:00:00	-0.07	0.03	0.07
2023.01.01, 23:00:00	-0.07	0.08	0.04
2023.01.02, 00:00:00	-0.06	0.11	0.00
2023.01.02, 01:00:00	-0.05	0.12	-0.04
2023.01.02, 02:00:00	-0.03	0.11	-0.07
2023.01.02, 03:00:00	-0.02	0.09	-0.10
2023.01.02, 04:00:00	-0.01	0.06	-0.12
2023.01.02, 05:00:00	-0.01	0.02	-0.13
2023.01.02, 06:00:00	0.00	-0.02	-0.12
2023.01.02, 07:00:00	0.00	-0.06	-0.09
2023.01.02, 08:00:00	0.00	-0.09	-0.06
2023.01.02, 09:00:00	0.01	-0.09	-0.02
2023.01.02, 10:00:00	0.01	-0.07	0.03
2023.01.02, 11:00:00	0.01	-0.04	0.07
2023.01.02, 12:00:00	0.01	0.00	0.08
2023.01.02, 13:00:00	0.01	0.07	0.08
2023.01.02, 14:00:00	0.01	0.14	0.05
2023.01.02, 15:00:00	0.02	0.17	0.01
2023.01.02, 16:00:00	0.03	0.17	-0.03
2023.01.02, 17:00:00	0.04	0.16	-0.06
2023.01.02, 18:00:00	0.05	0.14	-0.09
2023.01.02, 19:00:00	0.07	0.13	-0.11
2023.01.02, 20:00:00	0.06	0.11	-0.11
2023.01.02, 21:00:00	0.05	0.09	-0.11
2023.01.02, 22:00:00	0.05	0.05	-0.10
2023.01.02, 23:00:00	0.06	0.01	-0.07

The wind blowing over the Baltica-1 area, which modifies the sea current field, was assumed to be a forcing in the numerical model. Wind parameters (direction and speed) for the assumed simulation time were determined using the regional UMPL model. Wind parameters measured using the LUFFT WS500-UMB meteorological station at the B_MFW_3 station location for the period assumed in the numerical model (August–September) are presented in the following figure [Figure 3.5].

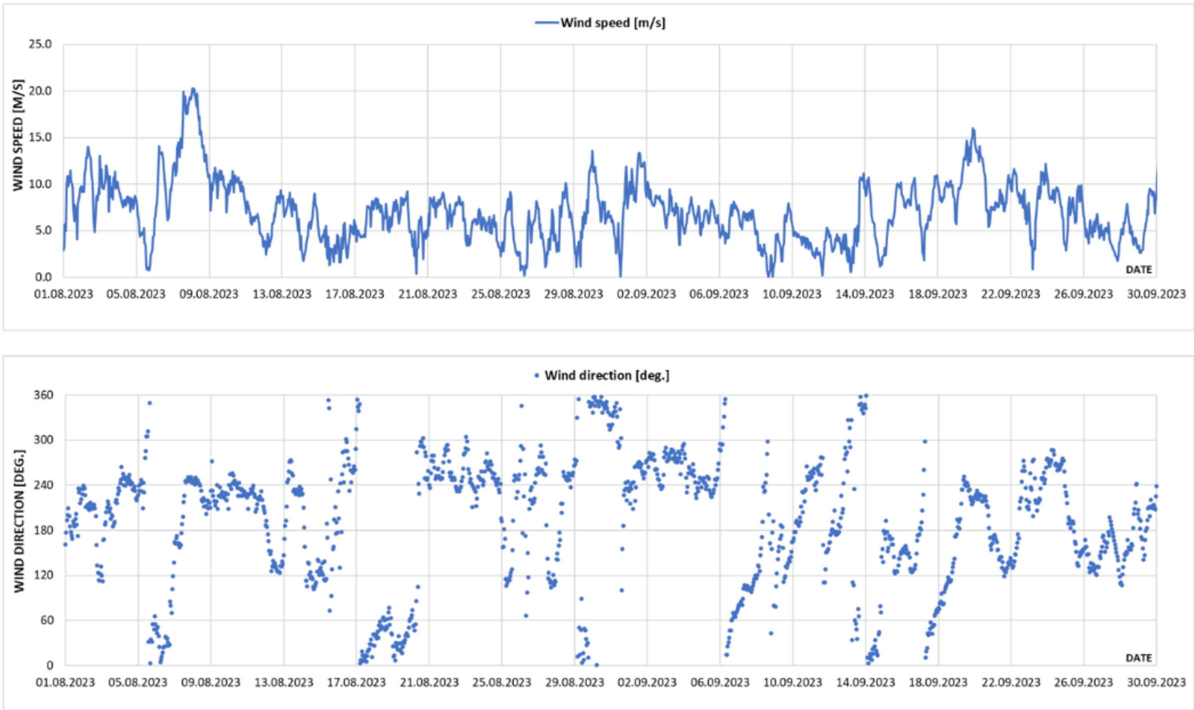


Figure 3.5. *The wind velocity and direction over the Baltica-1 area based on the measurements conducted in August–September 2023*

The model includes a restriction that the underwater work related to the seabed preparation and clearance and power cable laying takes place under permissible conditions (with significant wave height not exceeding 2.0 m).

3.3.3 Numerical model verification

The measurement results obtained from the meteorological, hydrological, and hydrodynamic monitoring were used to verify the numerical model developed. The time courses of the hydrodynamic and hydrodynamical data accounting for suspended solids dispersion, which occur in the constructed model, were compared with the data recorded in the Baltica-1 OWF area during the survey campaign. The cross-correlation function was used for the comparisons and analyses of the similarity of the two time series. By definition, the cross-correlation function shows the similarity of two discrete time series *x* and *y* – of the first series and a time-shifted (delayed) copy of the second series as an *m* shift function. Generally, the cross-correlation function of two random stationary processes with sample lengths *n* is expressed as:

$$c_{xy}(m) = E\{(x_{n+m} - \mu_x)(y_n - \mu_y)^*\}$$

where:
μ_x and μ_y – the average values of the two random stationary processes analysed,
asterisk (*) – the complex conjugate;
E – the value expected.

The consistency of the results obtained from the MIKE 21 model developed, which is used for computational simulations, was verified against the survey results obtained at the location of the measurement buoy in the Baltica-1 OWF area.

The analysis of the consistency of water levels recorded with an AWAC device manufactured by the Nortek company equipped with an external pressure sensor and the levels obtained based on the MIKE 21 local model developed is covered by the scope of its direct verification. The levels of pressure recorded at the seabed allow for determining the depth of water above the sensor and thus the variation of sea level during the measurement. However, the water pressure measured at the seabed is also influenced by changes in atmospheric pressure. Therefore, the variation of sea level determined from the measurement must be corrected for the atmospheric pressure. The course of the water level changes measured (taking account of atmospheric pressure) and modelled for the adopted simulation period is presented in the figure below [Figure 3.6] (left side). The maximum value of the cross-correlation function for the two analysed signals [Figure 3.6] (right side) is 0.85, which proves a strong correlation.

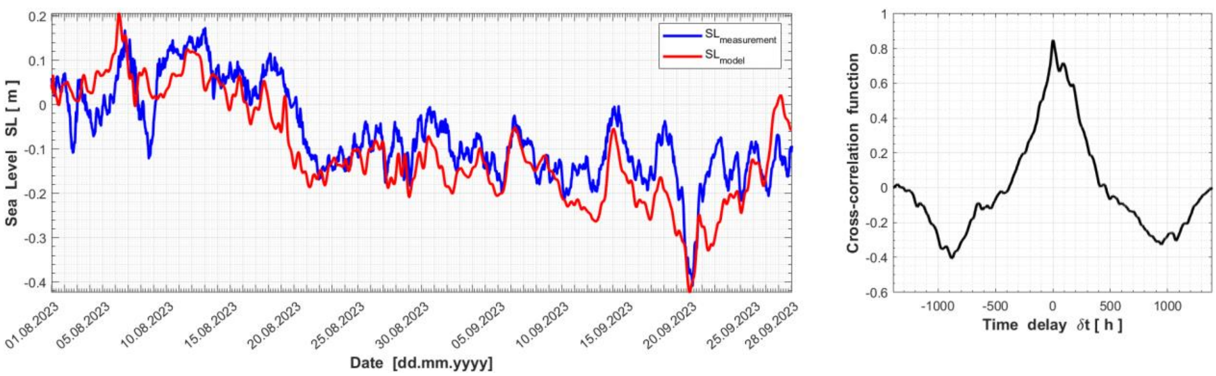


Figure 3.6. The waveforms of the water table level variability based on the measurements using a pressure sensor (blue) and calculated under the MIKE 21 model (red) for the period adopted for the numerical simulations (left side). The cross-correlation function for the measured and modelled water table level variability at station B_MFW_3 (AWAC) (right side)

During the measurement campaign in the area of the Baltica-1 OWF, wind-generated wave motion was measured, among others, at a measurement station operated by a buoy connected to an acoustic profiling current meter with an additional vertical beam echosounder for measuring waves. The numerical analyses of the measurements taken provided a spectral description of wind-generated wave motion. The wind-generated wave motion was another physical process that allowed for the verification of the constructed numerical model. The time series of the variability of wave motion parameters (H_S – significant wave height; A_Z – mean wave propagation direction; T_P – peak wave period) obtained under numerical modelling were compared with the measured analogous wave motion parameters for the entire simulation period [Figure 3.7]. This figure shows the high consistency of all the analysed pairs of stochastic signals. The maximum value of the cross-correlation function was respectively 0.95 for the significant wave height, 0.55 for the mean wave propagation direction and 0.80 for the peak wave period, which analytically proves an almost perfect correlation for H_S, good correlation for A_Z, and a very strong correlation for T_P. As part of the verification process, this statement makes the developed model distinctly reliable.

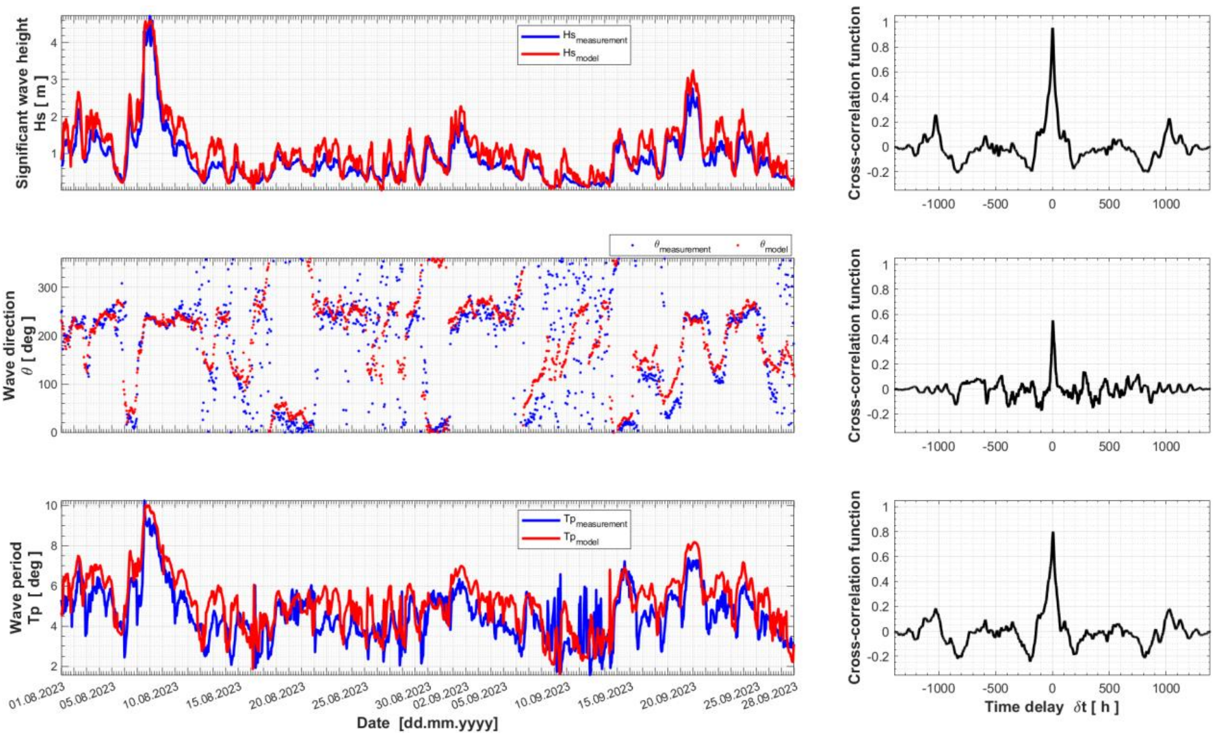


Figure 3.7. The comparison of variability waveforms for the basic wave motion parameters for the period analysed at the survey station (left side): a) significant wave heights (top), b) mean wave propagation directions (middle), c) peak wave periods (bottom). The values measured by the AWAC acoustic sensor (blue) and calculated under the MIKE 21 model (red). The cross-correlation function for the variability waveforms for the measured and calculated wave motion parameters analysed (right side)

The main factors causing the movement of sediments in the water depth and suspended solids dispersion are sea currents. The compared time variability of sea current velocities obtained as a result of measurements (blue) and based on model calculations (red) is presented in the figure below [Figure 3.8]. In the period analysed (August–September), sea current velocities did not exceed the value of 0.2 $m \cdot s^{-1}$, only occasionally, during a storm occurrence, going above this level to approx. 0.3 $m \cdot s^{-1}$. Velocity amplitudes in the MIKE 21 model are of the same order. The sea current directions are illustrated in the form of current roses [Figure 3.9]. A characteristic feature of both roses is the occurrence of all directions with a smaller number of events, in which the sea currents follow the directions from WNW to NE. The possibility of occurrence of all current directions with speeds not exceeding 0.3 $m \cdot s^{-1}$ during the underwater works demonstrated in the results of the created model and confirmed by the measurement results proves that the characteristics of the current field reproduced in the model are similar to the conditions occurring in nature. This is appropriate from the point of view of modelling, because it allows for including in the assessment a representative spectrum of all possible directions of suspension flow in the range of current speeds that are most often expected during the works carried out.

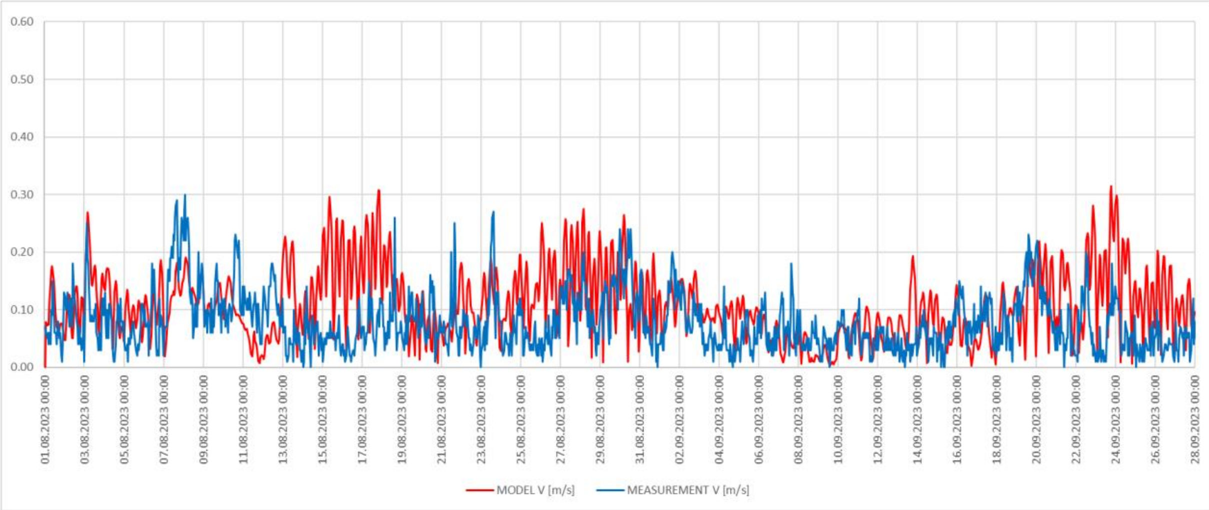


Figure 3.8. A comparison of the sea current velocity variations recorded in the analysed period at the location of the B_MFW_3 measurement station. The values measured by the Nortek AWAC device (blue) and calculated using the MIKE 21 model (red)

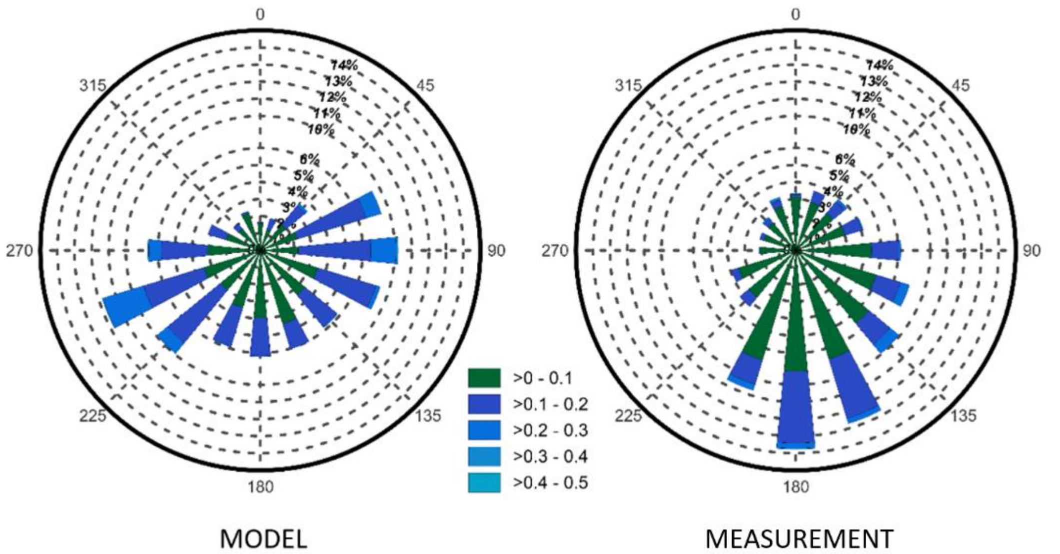


Figure 3.9. A comparison of the sea current directions recorded in the analysed period at the location of the B_MFW_3 measurement station. Values calculated using the MIKE 21 model (left side) and measured by the Nortek AWAC device (right side)

The comparative analyses which were conducted for the values measured during the survey campaign in the Baltica-1 OWF area and those calculated under the numerical model developed allow for positive verification of the constructed model and stating that the results obtained under this model show satisfactory consistency with the *in-situ* measurement results.

3.3.4 Soil data

The Baltica-1 OWF area is located in the Polish exclusive economic zone of the Baltic Sea, east of the Southern Middle Bank, where the depth ranges from 16 m to approximately 50 m. In this area, bathymetric measurements were taken to allow for a detailed survey of the seabed relief, sonar measurements were conducted to assess the nature of the seabed surface, and geological surveys were carried out to assess the shallow soil layers beneath the sea floor. The sediment layers identified on the seabed of the area designated for the construction of the Baltica-1 OWF [Figure 3.10] are mostly non-cohesive soils. However, in the north-eastern part, there are also places with cohesive soils. Based on the sonar and bathymetric data analysis, the character of the sediments forming the seabed of the area analysed was identified. Two main groups of sediments forming the seabed were distinguished: fine- and medium-grained sands and cohesive sands with a thin layer of sand and an erosive pavement on the surface.

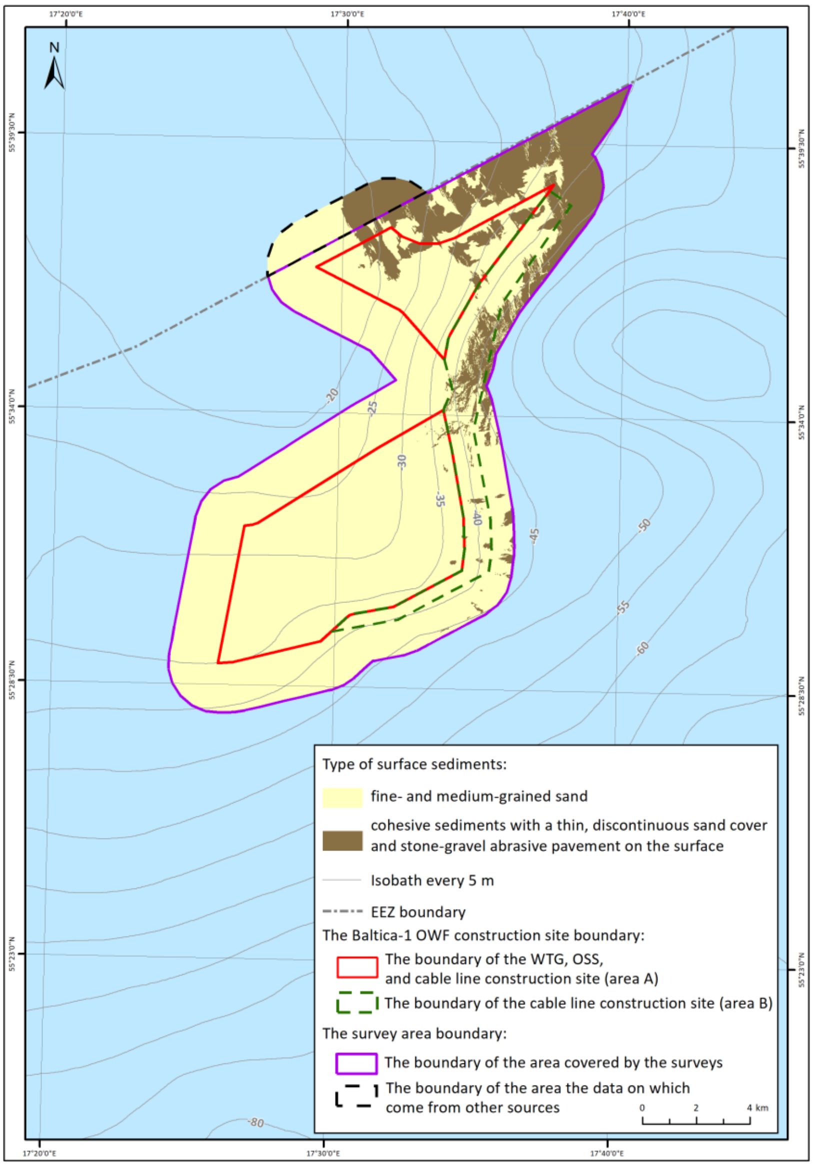


Figure 3.10. The map of seabed surface types in the Baltica-1 OWF area

From the point of view of numerical modelling of suspended solids dispersion, information on the occurrence of both types of soil in the seabed is important, because work conducted in these types of soil related to preparing the substrate for the installation of support structures or embedding of power cables will generate different amounts of fine fractions becoming suspended solids. For numerical modelling purposes, it was assumed that during the work carried out in the seabed in sandy soil, the share of finer fractions becoming suspended in the water column is 3% of the volume of soil disturbed. However, during the implementation of underwater works in cohesive soils, the proportion of fine fractions (silty and clayey) becoming suspended may be much higher, reaching 15%. A larger share of fine fractions becoming agitated will occur in soils with a higher degree of plasticity. The computational simulations of this type (Technical Project Description for Offshore Wind Farm, 2015) show that these are rather conservative assumptions.

3.3.5 Technological assumptions

The information on the assumed construction solutions, technologies selected or permissible for use in the foundation of WTGs and in the implementation of inter-array cable connections within the wind farm has been provided by the Investor. The Investor also presented data on the volumes of underwater works and the assumed, effective times of completion of individual works.

At the current stage, two variants of the implementation of the Baltica-1 OWF with a maximum capacity of 900 MW are being considered. The adopted concept assumes the use of the latest, rationally justified solutions available at the time of preparation of the construction design in the Applicant Proposed Variant (APV). The Reasonable Alternative Variant (RAV) is based on the existing technologies currently used and available on the market. In the APV, the possibility of using WTGs with specific rated capacities ranging from 15 MW to 25 MW (future solutions) was assumed, which means building from 60 to 36 WTGs in the farm area. In the RAV, on the other hand, the power of a single WTG was assumed to be 14 MW, which means the construction of 64 WTGs. The choice of support structures for both variants remains an open question, assuming that a WTG will be placed on a gravity-based structure, monopile or jacket foundation. For simulation calculations, as part of considering the worst-case scenarios, it was assumed that the most unfavourable method is the use of a gravity-based structure due to the amount of suspended solids introduced into the marine environment during installation works. Support structures such as jackets and monopiles are fixed to the ground using the piling technology, which turns soil fractions into suspended solids minimally (basically negligible impact on the environment). For a monopile structure, it has been assumed that in places where the pile is inserted into the ground, compact or rocky soils may occur, for which it will be necessary to use supporting methods, consisting of drilling of these soils inside the monopile. The material from drilling is usually extracted onto a barge. After the foundation installation is completed, most of the material will go inside the monopile, and its excess will be spread over a place agreed with the Maritime Office. If possible, some of the excess material will be used to protect the foundation against scouring. It is also possible to spread the material from inside the pile in the immediate vicinity of the foundation without extracting it onto a barge. Even if unfavourable ground conditions are encountered that require the use of technology involving drilling of the ground during the installation of the monopile, this action will not cause a greater amount of suspended solids than works related to the installation of a gravity-based structure. In the case of a jacket structure, founded on caissons, the suspended solids interfere with the marine environment to an even lesser extent, because the generation of negative pressure in the caissons, which makes them sink into the ground, takes place in the closed volumes of the caissons. Due to different water depths and the various generator capacities considered, two diameters of the support structure base were taken into account, respectively Ø 55 m and Ø 45 m, which can be located in the area of both cohesive and sandy soils.

Dredging works related to the preparation of the seabed for the foundation of support structures (seabed levelling, possible soil replacement) will be carried out with a trailing suction hopper dredger with a drag head or an additional grab dredger. A continuous working mode (12 hours) was assumed for the preparatory works in the area of each support structure. For larger-diameter structures, it was estimated that the volume of work related to the replacement/levelling of the seabed material could reach 22,000 m^3 of soil per structure or 16,500 m^3 for structures with a smaller diameter. The basic parameters influencing the scope of dredging work are presented in the following table [Table 3.2], where the values for 25 MW WTGs apply only to the APV option, while those for 14/15 MW WTGs apply to both APV and RAV.

Table 3.2. Assumptions for dredging works for gravity-based structure for 25 MW and 14/15 MW WTGs

Parameter	Value for a 25 MW WTG	Value for a 14/ 15 MW WTG
Foundation base shape	Round	Round
Number of foundations	36	64/60
Base diameter (max.)	55 m	45 m
The diameter of the area covered by the dredging works (max.)	75 m	65 m
Dredging depth (max.)	5 m	5 m
The volume of material excavated for a single foundation (max.)	22,000 m^3	16,500 m^3
Dredging method	Suction dredger, grab dredger	Suction dredger, grab dredger
The width of the scour protection layer measured from the edge of the foundation (average)	40 m	37.5 m
The thickness of the scour protection layer (average)	3 m	3 m
The maximum area of the seabed occupied by a foundation (max.)	2400 m^2	1600 m^2
The maximum area of the seabed occupied by a foundation, including scour protection	14,300 m^2	11,300 m^2
The amount of material becoming suspended solids (fine fractions: silt and clay) – sandy seabed [%]	3	3
The amount of material becoming suspended solids [%] (fine fractions: silt and clay) – a cohesive seabed, suction dredger [%]	5	5
The total volume of suspended solids – sandy seabed [m^3]	19,800	31,680/29,700
The total volume of suspended solids – cohesive soil [m^3]	33,000	52,800/49,500
Solids agitation intensity – sandy seabed [kg·s^{-1}]	23.7	17.8
Solids agitation intensity – seabed consisting of cohesive soils [kg·s^{-1}]	39.5	29.6
The duration of dredging works for a single foundation (average)	12 h	12 h
The time for installation of a single WTG (average)	30–40 h	30–40 h
The assumed number of foundations for which the seabed dredging works will be conducted simultaneously	1–2 pcs	1–2 pcs

The works considered optionally, concern the places where the bases of the installation vessel spud cans will rest. In the case of soils with low bearing capacity, it will be necessary to use soil reinforcement methods in the places where the spud cans of the installation vessel will be placed. Soil reinforcement can be performed using crushed stone ballast, however, in the case of soils with very low bearing capacity, it may be necessary to replace the weak soil altogether. Such replacement would consist of making an excavation and filling it with crushed stone. Performing underwater excavations in cohesive soils characterised by low bearing capacities would generate the formation of suspended solids, the dispersion of which is subject to assessment in terms of the impact on the marine environment.

It is assumed that excavations could be conducted using trailing suction hopper dredgers (TSHD) with greater draughts or using cutter suction dredgers (CSD) with smaller draughts. As for the former, the excavated soil goes to the dredger's own hold and is next transported to designated dumping sites and unloaded there, without causing a significant impact of the suspended solids within the wind farm area. In the case of the latter type of dredger, the excavated soil can be transported by a suction pipe and deposited a short distance away, within the wind farm area. However, the soil pulp transported by the suction pipe is in a liquid state, and all the soil fractions contained in it are mixed to a large extent. Therefore, when using suction pipes, significantly higher parameters of disturbance of the marine environment with suspended solids are recorded, because the largest volume of the excavated material becomes suspended.

Excavations conducted for the spud cans of the legs of a jack-up installation vessel have smaller cubic capacities than excavations made for gravity-based structures of WTGs. Therefore, the interference with the environment during their execution, assuming the deposition of excavated material outside the farm area, will be smaller than during work related to the preparation of the substrate for gravity-based structures.

In work related to the preparation of the soil for spud cans using a cutter suction dredger, two underwater works conducted at the same time and at a small distance from each other (in the order of several hundred meters) cause the agitation of suspended solids. In the first location, at the place of soil collection, insignificant amounts of fine soil fractions become suspended, while in the second, at a distance of not less than 350 m from the edge of the excavation works, during the discharge of liquefied soil (pulp) from the suction pipe, significantly larger amounts of fine soil fractions become suspended solids. The results of the calculations performed on the numerical model indicate that the scenario presented above, which is also related to the cumulative impact of two sources of suspended solids, is responsible for the highest levels of the parameters of the natural environment disturbance with suspension. It is assumed that the maximum volume of the excavation made for soil replacement under one spud does not exceed 19,000 m^3, and the time of its execution is estimated at 8 hours for 4 legs, with technological breaks of approx. 38 hours.

In the model, the lifting of sediments that become suspended solids was identified in places where dredgers work at the future foundations. The sediments that become suspended solids are distributed evenly throughout the water column.

The calculations estimate the way the suspended solids, the appearance of which in the water column is caused by underwater works related to the installation of support structures, disperse (their concentration and range) and deposit on the seabed. The variant method of numerical calculations for a gravity-based structure is derived from the following criteria: soil (cohesive and non-cohesive surface layer, subchapter 3.1) and dimensions of the support structures (2 dimensions). As a result, the calculation combinations produce 4 calculation sets.

The use of large-diameter piles for wind farm foundations applies to both monopiles and jackets. It was assumed that the maximum diameter of a monopile can be Ø 12 m, while the foundation piles of the jackets will not exceed Ø 4.2 m. For the purposes of modelling the suspended solids propagation, it was assumed that the volume of soil disturbed is equal to the volume of a cylinder with a diameter equal to the large-diameter pile base and a height of 2.0 m. According to the Investor's data, the effective time of driving a monopile was estimated at 3–5 hours, while the insertion of a jacket foundation pile takes approximately 6–8 hours. These numbers show that a greater load of suspended solids will be generated in the case of installing one monopile than when installing 3–4 jacket foundation piles. It should also be clearly emphasised that the suspended solids load introduced into the marine environment when using both of the technologies under consideration will be significantly lower than during underwater work associated with the installation of a gravity-based structure. The qualitative and quantitative differences in the calculation results will be presented for the gravity-based structure and the monopile. Power substations are founded on the same support structures. If it is necessary to transfer loads from a substation through several foundations, they are installed sequentially one after another, introducing the same unit loads of suspended solids into the marine environment.

The second type of operation carried out during the implementation of wind farms which has a direct impact on the formation and dispersion of suspended solids is the laying and embedding of inter-array power cables connecting individual wind turbine generators or interlinks between power substations. The technologies of embedding these cables in the seabed are analogical. The basic assumption regarding the work schedules (resulting from the experience gained with the wind farms already completed) is an interval between the completion of works related to the setting of foundations for the offshore wind turbine generators and the commencement of underwater works involving the burying of a cable for a specific wind power turbine. It was assumed that the cable embedding begins so much time after the foundation dredging works that there is no accumulation of the impact of suspended solids from both of these activities. As a result, the two actions analysed in the model (foundation installation works and cable laying) cannot be possibly carried out simultaneously for a single wind power station. Consequently, the suspended solids agitated in the course of works on the foundations will sediment on the seabed before cable laying starts in the vicinity of the analysed wind power station in any case.

The calculation model assumes that the maximum depth of internal cables buried in the seabed is 3 m, although, under the PSzW permit, it is possible to locally embed cables in the bottom at a greater depth of up to 6 m, if such a need arises, due to local conditions resulting from the structure of the seabed. The choice of cable line installation methods will be possible after a thorough study of the geological conditions prevailing on the seabed in the investment area, taking into account the most effective technologies for specific conditions. Frequently used methods such as ploughing, both in cohesive and non-cohesive soils, or the use of mechanical cutting devices in hard cohesive soils, only cause the agitation of suspended solids to a small extent. In turn, the water jetting method, which involves the use of devices based on the energy of multi-point water jets, is responsible for generating a larger amount of suspended solids. In this work, water penetrating the jetted space under high pressure washes out the finest fractions from the soil located in the area of liquefied sediments above the power cable. The mass flow excavation method is intended only for clearing previously prepared excavations in the event of their re-filling naturally while waiting for the cable to be installed.

The geological works conducted in the Baltica-1 OWF area earlier allowed for adopting varied types of marine sediments occurring in the seabed at the construction site into the numerical model. In calculation simulations, the movement of devices embedding cables was taken into account. In modelling, the route of vessels carrying out underwater works causing the formation of suspended solids has to be defined in terms of geography and the speed of the vessel needs to be taken into account. When modelling suspended solids on the inter-array cable routes, a load of suspended solids is introduced into the marine environment during underwater work using a so-called "source in motion". The calculation results, as in the case of soil preparation for support structure foundations, concentrate on the assessment of suspended solids concentrations, their impact ranges, and the thickness of layers formed as a result of sedimentation. The results obtained from the geological identification allow adopting the assumption that the jetting method will be effective for burying power cables at the depth required.

Stone and boulder areas in the Baltica-1 OWF area were identified as well. The occurrence of such places along cable routes requires a preliminary boulder clearance. The device used for this purpose can operate in a corridor of approx. 12 m in width and with a blade reaching a depth of approx. 0.3 m.

Parameters characterising underwater works related to cable-laying in both variants (APV and RAV) have been presented in the table below [Table 3.3].

Table 3.3. The assumptions for the laying of power cables inside the field

Parameter	**Variants**	
	APV	**RAV**
Inter-array cables of the Baltica-1 OWF [km]	140*	150*
Depth of cable embedded in the seabed [m]	3 (6)	3 (6)
The width of the strip of seabed covered by the works [m]	7	7
Cable embedding method	Jetting Ploughing Chain cutting	Jetting Ploughing Chain cutting
The amount of material becoming suspended solids (fine fraction only) – sandy seabed [%]	3	3
The amount of material becoming suspended solids (fine fraction only) – seabed made of cohesive soil (easily washable) [%]	15	15
Solids agitation intensity – sandy seabed [$kg \cdot s^{-1}$]; *jetting* – cross-section of 3 m^2, v = 200 $m \cdot h^{-1}$; (A = 6 m^2, v = 120 $m \cdot h^{-1}$)	7.75 (9.30)	7.75 (9.30)
Solids agitation intensity – cohesive seabed [$kg \cdot s^{-1}$]; *jetting* – cross-section of 3 m^2, v = 200 $m \cdot h^{-1}$; (A = 6 m^2, v = 120 $m \cdot h^{-1}$)	31.0 (37.2)	31.0 (37.2)

**The maximum values as indicated by the Investor*

The model takes into account fine fractions of sediments below 64 μm in diameter, assuming that the sediment particles with larger diameters will fall onto the seabed instantly, not becoming suspended in the water depths. This model is described as "redundant", which means that only the sediment that became suspended is included in the modelling and that the modelling does not take into account the suspended solids constituting the natural background in the marine environment analysed. 0.5 $mm \cdot s^{-1}$ was assumed as the value of sediment free fall speed, which corresponds to the mean size of silt grains. The critical value of shear stresses for the initiation of erosive processes equals 0.3 $N \cdot m^{-2}$. Above this level, sediments deposited on the seabed become subject to the process of resuspension. The threshold shear stress of sediment settling was defined as 0.07 $N \cdot m^{-2}$. It is a shear stress value below which the sediment starts settling on the seabed.

4 CALCULATION SCENARIOS

The results of bathymetric measurements conducted in the analysed area of the Baltica-1 OWF indicate that the sea basin is diverse in terms of depth, inclining from the Central Bank towards an area of increasing depths, reaching a depth of 40 m in the area designated for the construction of wind turbine generators and reaching almost 50 m in the buffer zone [Figure 4.1]. An analysis of the sediments forming the seabed based on the results of geological scouting [Figure 3.10] leads to the conclusion that the vast majority of the top layers are non-cohesive soils. The performance of dredging works (pre-clearing works, cable embedment, preparing the seabed for foundation installation) in non-cohesive soils (with a predominant share of the sand fraction) as well as in cohesive soils with a predominant share of finer fractions (silt, clay) causes significant differences in the volume of the material becoming suspended in the water depths. Works conducted in sandy (non-cohesive) soils will generate lower amounts of suspended solids. In the modelling, however, where justified, calculations were also performed for underwater works conducted in cohesive soils, thus satisfying the criteria for the worst-case scenarios, because in such soils the number of fine fractions becoming suspended in the water column is greater than in the case of sandy soils.

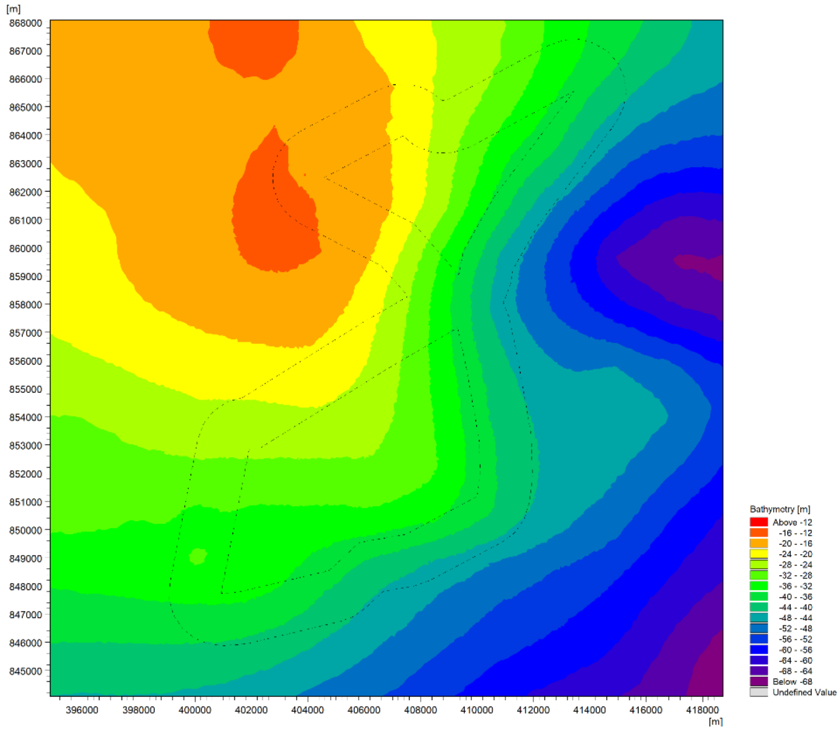


Figure 4.1. The bathymetric conditions of the sea basin of the Baltica-1 OWF area

The first set of calculation scenarios concerns the laying of foundations for offshore wind turbine generators. At the current stage of the project implementation, the Applicant allows for the use of a wide range of support structures. Both gravity-based structures placed directly on the prepared ground (levelled and possibly, possibly with the soil replaced) and structures with the foundation element driven into the seabed, i.e. monopiles and jacket foundations, are under consideration. In the latter two solutions, both the monopile and the jacket foundation piles are driven into the ground to considerable depths. Both of these solutions generate suspended solids in the marine environment to a very small extent, and driving a monopile with a maximum diameter of Ø 12 m will be responsible for the introduction of a greater amount of suspended solids than driving 3 or

4 foundation piles with maximum diameters of Ø 4.2 m. Using the developed numerical model, it was decided hat calculations should be made for the scenario with a monopile driven into cohesive soil, to obtain data that can be compared with the results of calculations for preparatory works for gravity-based foundation installation. In a situation where a monopile encounters a refusal point due to the presence of hard rocks in the subsoil or compact soils, it may be necessary to perform drilling as a supporting method. Drilling can be performed inside the pile. The material from drilling is usually extracted onto a barge. After the foundation installation is completed most of the material will go inside the monopile, and its excess will be spread over a place agreed with the Maritime Office. If possible, some of the excess material will be used to protect the foundation against scouring. It is also possible to spread the material from inside the pile in the immediate vicinity of the foundation without extracting it onto a barge. It should be emphasised that the use of technology requiring drilling for the monopile will not release a greater amount of suspended solids than in the case of work on a gravity-based foundation.

In a small part of the area under investigation, cohesive soils with discontinuous sandy covers have residual covers consisting of rocks and gravel with numerous boulders. Such seabed characteristics require calculations that take into account the works related to boulder clearance, especially along the cable routes. Clearing the seabed of stones and boulders using a device towed behind a vessel is an activity that agitates suspended solids and therefore, requires an assessment of the impact on the marine environment conducted with the use of a numerical model. The above-mentioned underwater work is included in the calculation scenarios.

The Investor assumes that in the ground conditions identified, only mechanical methods will be used to embed the inter-array cables of the wind farm, i.e. cutting the soil with a chain cutter, or ploughing. For the above-mentioned methods, the parameters of environmental disturbance caused by the agitated suspended solids are assessed (based on experience from other investment projects implemented in OWF areas) as lower than in water jetting methods. The calculation scenarios also included the cable embedding using various methods in conditions that were considered to potentially cause the most disturbance to the marine environment with suspended solids they agitate.

The last calculation scenarios are related to the study of the accumulation of suspended solids impacts caused by underwater works performed simultaneously close to each other. Without calculations, it is difficult to determine which works performed simultaneously may, under specific conditions, be responsible for the accumulation of suspended solids impacts and in which case the level of disturbance caused by such cumulative impact will be the highest. As a result, several possible scenarios were examined in which the works could be carried out simultaneously. The preparation of the ground for gravity-based foundations is possible in two locations simultaneously. In one scenario, the cumulation of the impact of suspended solids caused by preparatory works for the installation of gravity-based foundations is examined with the assumption that the works are carried out in cohesive soil and sandy soil. In the next scenario, the impact of an analogous set of works is examined, provided that both activities are conducted in cohesive soil. The next scenario reflects a set of two underwater works carried out simultaneously, the first of which is the levelling/replacement of the soil for a gravity-based support structure in the area of the Baltica-1 OWF, and the second is a cable embedding using the jetting method in the adjacent area of the export cables. The above scenarios were selected after a detailed analysis of the sets of works corresponding to the assumptions of the worst-case scenario method, i.e. the combinations that would be responsible for the potentially highest parameters of disturbance of the marine environment with suspended solids. Such works may be carried out at a certain distance from each other because, for each vessel working at sea, there is established a safety zone – the assumed minimum distance between vessels performing underwater works is 1000 m. Another scenario in which the effect of cumulative impacts is analysed is the work related to the soil reinforcement in the places where the spuds of an installation vessel are to rest. The technological assumptions for such an operation are presented in Chapter 3.3.5. The farthest-reaching scenario in terms of the strongest impact of suspended solids on the marine environment is the replacement of weak soil consisting of making an excavation and filling it with crushed stone, where the excavation would be carried out using a suction dredger. In such a case, the analysis was carried out in the case where the excavated soil is transported by a suction pipe and deposited a short distance away in the area of the wind farm. In work related to the preparation of the soil for spud cans using a cutter suction dredger, two underwater works carried out at the same time and at a small distance from each other (in the order of several hundred meters), cause the agitation of suspended solids. In the first location, at the place of soil collection, insignificant amounts of fine soil fractions become suspended, while in the second, at a distance of not less than 350 m from the edge of the excavation works, during the discharge of liquefied soil (pulp) from the suction pipe, significantly larger amounts of fine soil fractions become suspended solids. According to the information received from the Investor, the maximum volume of the excavation for the replacement of soil under one spud does not exceed 20,000 m^3, and its execution time is estimated at 8 hours.

In the area of the wind farm, preparatory works may also be carried out to remove obstacles on the cable routes, such as pre-lay grapnel runs and boulder picking, and to drive the foundation piles of jacket support structures and caisson embedment. However, no computational models were developed for such work due to the negligible environmental impact in terms of suspended solids release. For example, the results of calculations conducted for the driving of a monopile indicated that the clouds of suspended solids would be small in terms of space, with concentrations of approximately 7 $mg \cdot l^{-1}$ at a distance of 150 m from the central point of the worksite and 1 $mg \cdot l^{-1}$ at a distance of 500 m, and the concentrations of approximately 5 $mg \cdot l^{-1}$ would not be maintained for longer than 3 hours. Also, a pre-lay grapnel run aimed to remove, e.g. remnants of other linear objects or fishing gear on a cable route disturbs a significantly smaller volume of soil than the volume of soil moved during cable laying.

In the envelope method adopted, a set of calculations should be made covering the entire range of underwater works, including variants where the unfavourable environmental impact of suspended solids will have the highest parameters (concentrations, ranges, durations).

Assessment of the most unfavourable impact of environmental conditions on the dispersion of suspended solids cannot be conducted *a priori*. Higher wind velocities and dynamics of the water body will cause further movement of suspended solids, while lower values of wind and sea current parameters will be responsible for higher suspended matter concentrations. Therefore, computational simulations are carried out for longer periods (up to 2 months) so that various parameters of sea currents (velocities and directions) occur, allowing the envelope method to include the events most unfavourable for the marine environment in the analysis. These are precisely the sea currents, which are mostly determined by the winds blowing above the sea surface, which are the main factor responsible for movement and dispersion of suspended solids in a sea basin. The selection of points was dictated, of course, by the need to compare the operation in areas of cohesive and non-cohesive soils, which occur in the development area only in the northern part of the OWF. This dictated the selection of this particular area. At the same time, areas with the smallest depths occur in this part, which also indicated the selection of this area to determine the most unfavourable conditions for the dispersion of suspended solids and ensured the representativeness of this area also in hydrodynamic terms (circulations, faster and slower currents, stagnation periods – all of which were taken into account). The calculation results have been presented in the form of parameters characterising the marine environment disturbance with suspended solids for the following calculation scenarios:

- scenario 1 – the preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in cohesive soil within the Baltica-1 OWF area, with the maximum cubature of works of 22,000 m^3, execution time for a single foundation equal to 12 hours, and a stationary "source" of suspended solids generation;
- scenario 2 – the preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in non-cohesive soil within the Baltica-1 OWF area, with the maximum cubature of works of 22,000 m^3, execution time for a single foundation equal 12 hours, and a stationary "source" generating suspended solids;
- scenario 3 – the preparation of the substrate for a gravity-based structure with a diameter of Ø 45 m in cohesive soil within the Baltica-1 OWF area, with the maximum cubature of works of 16,500 m^3, execution time for a single foundation equal to 12 hours, and a stationary "source" of suspended solids generation;
- scenario 4 – the preparation of the substrate for a gravity-based structure with a diameter of Ø 45 m in non-cohesive soil within the Baltica-1 OWF area, with the maximum cubature of works of 16,500 m^3, execution time for a single foundation equal to 12 hours, and a stationary "source" generating suspended solids;
- scenario 5 – the driving of a monopile with a diameter of Ø 12 m area into cohesive soil; the assumed volume of disturbed soil is a cylinder with a diameter equal to that of the monopile installed with a height of 2 m, i.e. 226.2 m^3; the effective time of driving the monopile into the soil is approx. 4 h; the "source" of suspended solids is stationary;
- scenario 6 – boulder clearance along the cable route of the inter-array cable infrastructure in the Baltica-1 OWF area; the working corridor of the clearing plough is 6 m on each side of the designed cable axis; the device claws to the depth of 0.3 m into the soil; the cross-section of the disturbed soil is 3.6 m^2; the "source" of suspended solids is in motion; the movement speed of the clearing grapnel is 300 $m \cdot h^{-1}$ in the case of cohesive soil;
- scenario 7 – the cable embedment along a selected section of the inter-array cable infrastructure within the Baltica-1 OWF area using the method of water jetting at a speed of 200 $m \cdot h^{-1}$ to liquefy sediments dominated by cohesive soils; the cross-section of the excavation is 1 × 3.0 m; the "source" of suspended solids is in motion; this is the preferred method;
- scenario 8 – the cable embedment along a selected section of the inter-array cable infrastructure within the Baltica-1 OWF area using the method of water jetting at a speed of 200 $m \cdot h^{-1}$ in non-cohesive soils; the cross-section of the excavation is 1 × 3.0 m; the "source" of suspended solids is in motion; the preferred method;

- scenario 9 – the cable embedment along a selected section of the inter-array cable infrastructure within the Baltica-1 OWF area using the method of ploughing at a speed of 300 $m \cdot h^{-1}$ in sediments dominated by cohesive soils; the cross-section of the excavation is 7.5 m^2; the "source" of suspended solids is in motion;
- scenario 10 – the cable embedment along a selected section of the inter-array cable infrastructure within the Baltica-1 OWF area using the method of ploughing at a speed of 300 $m \cdot h^{-1}$ in non-cohesive soils; the cross-section of the excavation is 7.5 m^2; the "source" of suspended solids is in motion;
- scenario 11 – two underwater works carried out at the same time: location one – preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in cohesive soil in the area of the Baltica-1 OWF, the maximum cubature of works is 22,000 m^3, and the "source" generating suspended solids is stationary; location two – preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in cohesive soil in the area of the Baltica-1 OWF, the maximum cubature of works 22,000 m^3, the "source" of suspended solids is stationary;
- scenario 12 – two underwater works carried out at the same time: location one – preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in cohesive soil in the area of the Baltica-1 OWF, the maximum cubature of works is 22,000 m^3, and the "source" generating suspended solids is stationary; location two – preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in non-cohesive soil in the area of the Baltica-1 OWF, the maximum cubature of works 22,000 m^3, the "source" of suspended solids is stationary;
- scenario 13 – two underwater works carried out at the same time: location one – preparation of the substrate for a gravity-based structure with a diameter of Ø 55 m in cohesive soil in the area of the Baltica-1 OWF, the maximum cubature of works is 22,000 m^3, and the "source" generating suspended solids is stationary; location two – cable embedment along a selected section of the export cable infrastructure in the area of the Baltica-1 OWF using the method of jetting at the speed of 200 $m \cdot h^{-1}$ in cohesive soil; trench cross-section is 1 × 3.0 m; the "source" of suspended solids is stationary;
- scenario 14 – two underwater works carried out at the same time and at a small distance (of the order of several hundred meters) from each other: location one – soil collection site – dredging works related to the replacement of soil with low bearing capacity for four vessel spuds in the area of the Baltica-1 OWF using a CSD; location two – discharge site – the discharge of soil pulp at a distance of no less than 350 m from the edge of the excavation via a suction pipe, i.e. a pipeline used to transport the dredged material. The maximum volume of the excavation intended for soil replacement is approx. 19,000 m^3, the time of performing such an excavation is 8 hours, and the "sources" of suspended solids are stationary.

As underlined above, the main factor that forces the movement of suspended solids is the impact of sea currents. Since these currents constantly change their force and directions, for all assumed scenarios, the value distribution and directions of currents from two months – August and September – have been accepted as the boundary conditions. This manner of assuming hydrodynamic conditions in the calculations of suspended solids dispersion will ensure that:

- the requirement of dredging equipment operations being conducted in the spring-summer period (i.e. in the period with the largest number of days favourable for this type of work) is satisfied;
- the actual, chaotic (changeable) character of the forcings is taken into account.

For various current conditions occurring over these two months, models were prepared taking into consideration the installation of foundations for the offshore wind stations as well as cable embedment and seabed clearance works along selected sections of cable routes.

The speed ranges of cable laying equipment depend on the soil conditions, the seabed topography, and the parameters of the excavation. The highest speed levels are associated with the most workable soils (e.g. loose sands) and with the shallowest embedding of the cable, which translates into the smallest volumes of soil disturbed (and the smallest amount of suspended solids generated). Speed is not the key parameter here, because for the assumed possible cross-section of the soil disturbed, regardless of whether the device moves at a speed of, for example, 200 $m \cdot h^{-1}$ or 400 $m \cdot h^{-1}$, the same volume of soil will be moved per kilometre of the route. The speed ranges of specific equipment depend on the workability of the soil and the cross-section of the excavation/ground disturbance, hence lower speeds will be used for larger excavations and higher speeds for smaller excavations. The highest speeds can be used for very shallow trenches and smaller amounts of agitated suspended solids. The calculations were performed for the maximum given cross-sections of the soil being moved with the real speeds of the equipment; hence the results are representative of the analysed underwater works. In building the numerical models presenting the cable laying simulations, certain rational choices were made to present the results for the scenarios that are the least beneficial for the environment.

Under the technological assumptions presented in Chapter 3.3.5, the mechanical cutting method introducing the smallest amounts of suspended solids into the marine environment was not included in the calculation scenarios.

5 CALCULATION RESULTS

The calculations were carried out in the form of numerical simulations for all assumed variants described in Chapter 4. In the case of calculations that allow analysing the impact of underwater works on the marine environment, the acceptable forcing conditions (mainly the wind velocities and the associated sea current drift velocities) are prelimited, i.e. they do not exceed certain limits. The reason for this is that works of this type cannot be carried out in storm conditions, with excessive wind, or too high wave motion due to the restrictions on the vessels or devices used. However, the variability of sea current parameters (its velocities and directions) in the marine environment is wide, therefore, appropriately lengthy periods had been selected to capture the highly random character of its impact (there are no limitations concerning the wind and sea current directions). The calculation results presented in the study were obtained thanks to high-level processing and the development of basic simulation results.

This chapter includes figures (maps and graphs) presenting the maximum concentrations of suspended solids and maximum redeposition ranges of sediments agitated as a result of works carried out in the Baltica-1 OWF area associated with the setting of WTG foundations, clearing stones and boulders of the seabed, and cable embedment in the seabed. It also presents the results of the simulations of underwater works that could potentially be carried out at the same time. In these cases, the level of cumulative impact of suspended solids on the marine environment was examined.

The suspended solids concentrations presented on the following maps [Figure 5.5, Figure 5.10, Figure 5.15, Figure 5.20, Figure 5.26, Figure 5.31, Figure 5.36, Figure 5.41, Figure 5.46, Figure 5.51, Figure 5.56, Figure 5.61] show their maximum possible values at each computational point of the numerical grid, assuming a hypothetical forcing in the entire two-month simulation period. The simulation has been developed with an assumption of changeable hydrodynamic parameters for the multiple repeated sequences of a given underwater work type analysed. This means that these figures present the envelopes of the maximum concentration values for the entire two-month simulation period. These results do not refer to a specific moment in time, but rather they are maps indicating the distribution of these values (as in an envelope) at each point of the grid during the full (two-month) simulation period. During the entire simulation, calculations were made for 5696 time steps (with a resolution of 900 s) with various possible current fields and the corresponding suspended solids concentrations. Each point of the calculation grid was assigned the maximum value of the concentration recorded from the entire period of numerical simulation, thus, creating a map of the maximum concentrations of suspended solids. The results of the maximum concentrations of suspended solids are a theoretical presentation of possible situations, allowing an illustration of the possible maximum ranges and concentrations of suspended solids impact, because the calculation period lasts 2 months, and the work at a stationary point takes e.g. 12 hours, and in the case of a source in motion, it takes only a moment at one point, so the actual temporary range will be directed in one direction and will concern a much smaller area. The difference between an instantaneous situation and an envelope map generated in post-processing using advanced numerical tools is illustrated well by a comparison of the maximum concentration envelope map (unsaturated colour, lighter colour scale) for the full calculation period with an instantaneous concentration snapshot (saturated colour, darker colour scale) at a specific simulation time step (at a specific moment) [Figure 5.1] presented in the example figure (created for scientific purposes, in a model with high spatial and temporal resolution). In other words, an envelope map (unsaturated colour) is made of 5696 images, and the suspended solids concentration value at each grid point is determined as the maximum value of this concentration from 5696 simulation time steps.

The manner of presenting the maps in the form of the maximum concentration envelopes for the entire simulation period has been selected mainly due to the basic purpose of their use at the subsequent stage of work, namely for the impact assessment.

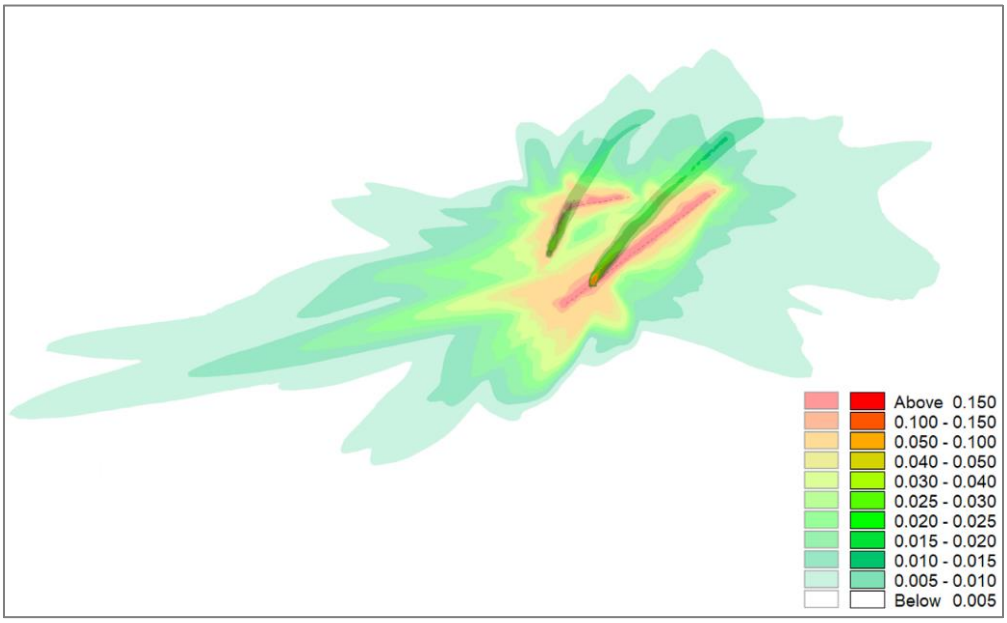


Figure 5.1. The comparison of an example maximum concentration envelope for the entire calculation period (unsaturated, lighter colours) and the instantaneous concentration distribution at a specific moment in time (saturated, darker colours). The concentrations are expressed in [g·l^{-1}]

As imposed in the MIKE 21 model, the results regarding the concentration of suspended solids are presented in all figures in the kg·m^{-3} unit, which is equivalent to the g·l^{-1} unit. In turn, in the written text, the unit used to express the concentration of suspended solids is mg·l^{-1} (i.e. 0.001 kg·m^{-3} and 0.001 g·l^{-1}).

The presented results also include the thickness values of sediments newly made of resedimenting small fractions of suspended solids. When assessing the thickness of the sediment layer representing the state after the completion of the simulation of the type of underwater work investigated, it should be remembered that this does not apply to a stabilised situation. Each exceedance of the critical, erosive shear stresses in sediments caused by currents and sea waves in the re-suspension process will reconfigure this system, leading to a reduction in the determined thickness and redistribution of sediments. Such a situation is a natural phenomenon and may occur during storm events, more intense gradient flows, or it may be of thermohaline origin.

From the calculation results obtained for selected calculation scenarios, the value of another environmental disturbance parameter is also estimated, namely the time the solids remain suspended in the water column – in particular, this concerns the time the solids remain suspended after the completion of works in a specific location. The study includes the limit suspended solids retention times for a concentration exceeding 5 mg·l^{-1}.

All obtained calculation results allow us to assess several aspects of the disturbance caused: the exceedance of the defined suspended solids concentrations, the areal (spatial) range, and the duration of the disturbance.

It is important to compare the values of suspended solids concentrations caused by the works related to the OWF construction with the values recorded in the natural environment. During the measurements performed as part of hydrometeorological monitoring for various investments in the southern Baltic Sea, water turbidity was measured with optical backscatter sensors (OBSs). A qualitative assessment of these measurements indicates that in natural conditions (during a storm peak, more specifically, in the phase of its decline), the measured water turbidity levels may exceed the mean turbidity values in these locations by approximately 20- to over 40-fold. In turn, physical tests conducted on the water samples collected (in calm conditions) showed suspended solids concentrations by the seabed in the range of 2–5.3 $mg{\cdot}l^{-1}$. It should be emphasised that sampling can only be performed in good weather conditions. Although the results of the conducted research do not give a clear answer regarding the extreme concentrations of suspended solids in the conditions of strong dynamic forcings (storms), they allow us to estimate these concentrations at over 40 times higher than the mean values. The literature (Jenner et al., 2013) presents the measurement results of suspended solids concentration in natural (stormy) conditions, however, they apply to tidal seas only. For sea basins the depths of which reach 16 m, concentrations of up to 250 $mg{\cdot}l^{-1}$ were measured, while in shallower areas of up to 10 m in depth, the concentrations were up to 500 $mg{\cdot}l^{-1}$.

At the stage of production of the research results, several levels of suspended solids concentrations were adopted, which were next used in the interpretation of the results of calculations conducted on the numerical model:

- 5 $mg{\cdot}l^{-1}$ – the background of suspended solids recorded under normal conditions in the environment;
- 10 $mg{\cdot}l^{-1}$ – a concentration considered not significant for the environment in short-term exposure, however, according to research conducted by ichthyologists, it causes a noticeable increase in the mortality of cod larvae in the case of a permanent exposure;
- 30 $mg{\cdot}l^{-1}$ – the most frequently encountered level of suspended solids according to the best practices developed in Denmark and Germany, considered acceptable for both breeding and recreational areas on the condition that it is not exceeded 90% of the time;
- 100 $mg{\cdot}l^{-1}$ – the level of visible water turbidity (however, higher concentrations may occur in storm and post-storm periods).

5.1 Result presentation outline

The main aim of the calculations performed was to show the results for the works and methods causing the greatest disturbances associated with suspended solids, following the principle of the worst-case scenarios for the environment. For selected underwater works and cable embedment methods, the results of calculations of the averaged suspended solids concentration values over the entire model area, at defined time steps, are presented graphically in the form of the following collations:

- Waveform charts of wind speed and direction changes over time, above the sea area (the black, vertical line represents the simulation moment presented simultaneously on the current field maps and the suspended solids concentration map);

- a map of sea current circulation in the cable embedment modelling area (with directions and averaged velocities);
- a map of suspended solids dispersion with an enlarged image of the area under investigation (or its most important fragment).

The defined time step illustrates the instantaneous extreme situation, and it may concern:

- t1 – the moment of far-field (maximum) spread of dispersion cloud during the performance of works;
- t2 – the moment of the appearance of a high concentration of dispersion cloud, i.e. one of several situations with the highest instantaneous concentrations from the entire calculation period, in which a significant gradient of concentration fall occurs with the distance from the work being carried out.

Another calculation result presented in the form of a map is the thickness of the sediment layer consisting of the finest fractions of soil re-sedimenting during the implementation of specific seabed intervention works. The figures show the distribution and thickness of the seabed sediment layer formed after the entire operation analysed (excavation, seabed clearing, cable insertion, etc.). It should be emphasised that sediments consisting of sands and coarser fractions, which will always be deposited in the immediate vicinity of the underwater worksite, are not taken into account here as they are not transported suspended in the water.

The next graphic representation included in the results is the maximum concentration of suspended solids at each point of the assumed calculation area. As mentioned earlier, the maps do not show a specific moment, but rather an envelope of the concentration values as estimated for the full simulation period. This result does not concern the time of performing a specific task but rather illustrates a theoretical situation in which the analysed underwater work could be performed under various environmental forcing conditions (wind, currents, waves) over a simulation period of approximately two months.

However, to illustrate the differences in the impact of suspended solids agitated by external environmental conditions, the graphs of suspended solids concentrations as a function of the distance from the place of underwater works were compared. The situations presented in the graphs illustrating the results of single momentary steps of computational simulation indicate that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low. To be more precise, these are the distributions of suspended solids concentration during the analysed operation, most often in its final phase. In the initial phase of the operation, i.e. in the first hours from the start of the suspended solids emission in the conditions of a weak current moving the cloud, the concentration is not yet as high in the water column as in the case of, for example, continuous emission for several/a dozen hours or so or at the end of the work under unchanging hydrodynamic conditions.

The concept of "rapid disappearance" does not refer to time in this case, but presents a large gradient (time t2), i.e. a significant decrease in concentration with distance from the place of work. A large decrease in the concentration will occur when hydrodynamic conditions do not force the dispersion cloud to move but cause its clearly stationary location (this occurs in the case of low current speeds or a circulating nature of the current field). In turn, a large (wide) range of suspended solids occurs because the currents move it faster, so high concentrations do not occur. At the "far-field spread" (time t1), the initial concentration is much lower, because the cloud is already stretched, and it spreads over a long distance. However, the amount of the emitted suspended solids is the same, and its concentration in the vicinity is determined by the current conditions existing at the time of simulation, forcing its movement in the water column.

5.2 CALCULATIONS

5.2.1 Scenario 1. Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil

The technology for the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field.

At time t1, i.e. at the moment of far-field spread [Figure 5.2], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 8.2 km. The highest concentration value at a distance of 150 m from the worksite is 32 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.3], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.5 km and a cloud with concentrations of over 30 $mg \cdot l^{-1}$ spread over 0.4 km. The highest concentration value at a distance of 150 m from the worksite is 130 $mg \cdot l^{-1}$.

The figure below [Figure 5.4] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.5] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 250 $mg \cdot l^{-1}$, and at a distance of 500 m, they are up to 95 $mg \cdot l^{-1}$. In a major part of the area where sediment agitation appears, the concentration is in the range of 6–20 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.6] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 5.6 mm.

In this scenario, the process of preparing the ground for the gravity-based structure was modelled. The suspended solids with a mean concentration of 5 $mg \cdot l^{-1}$ will remain in the marine environment for approximately 24 hours after the underwater work is completed. The impact of suspended solids on the marine environment is short-term.

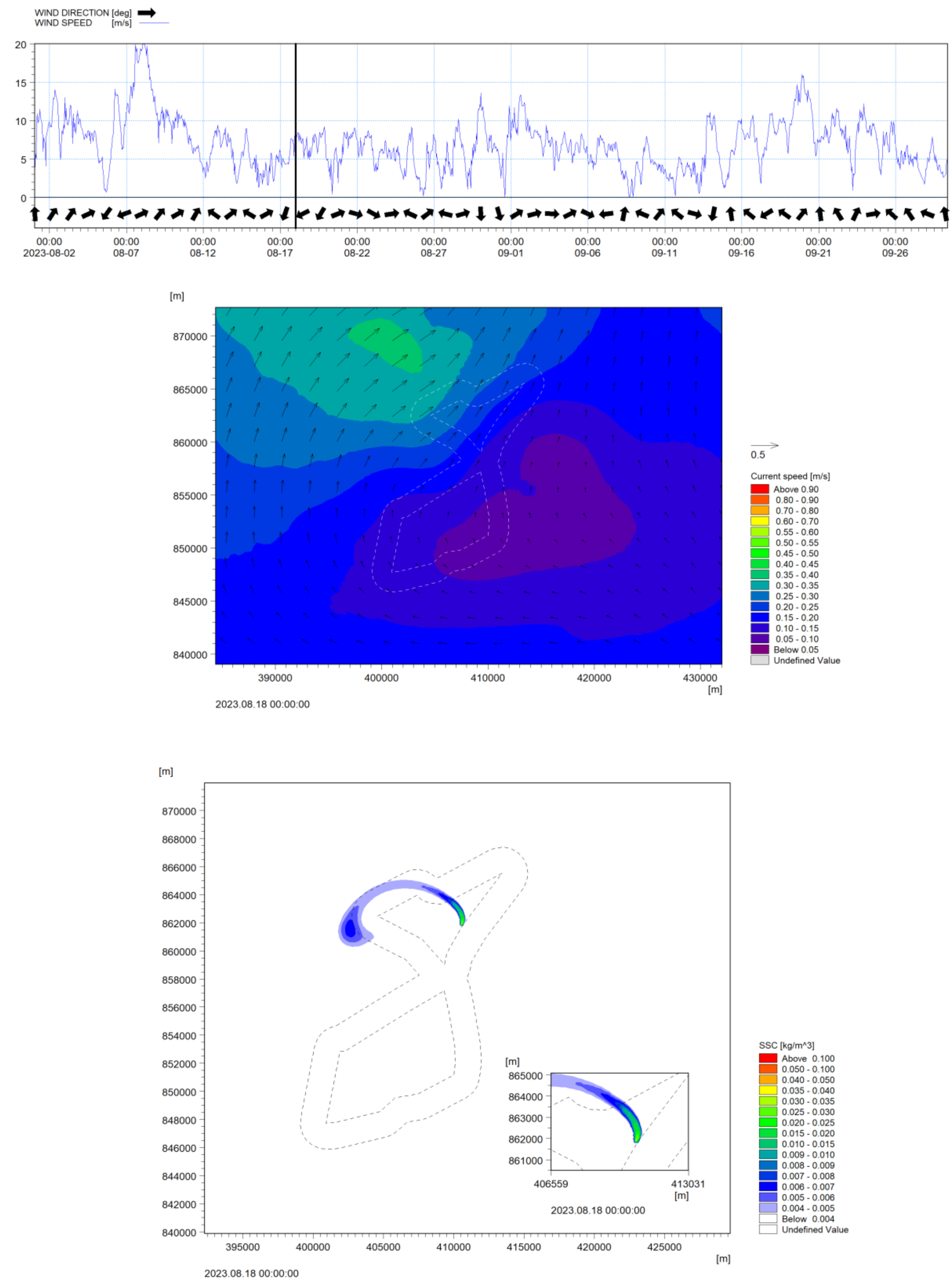
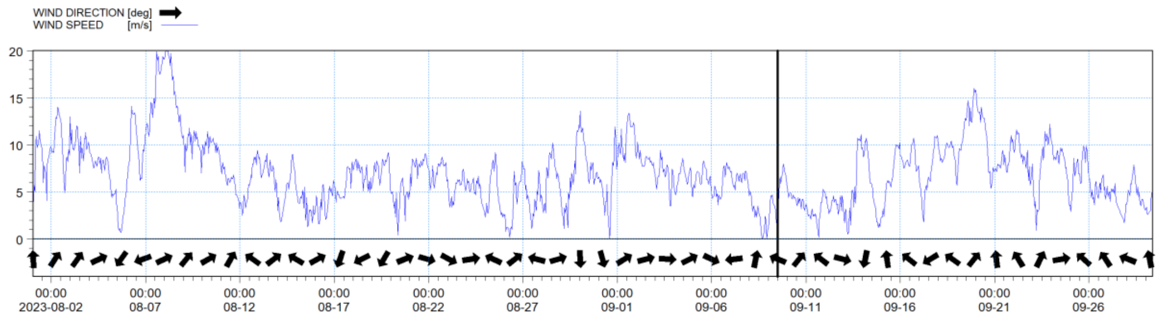
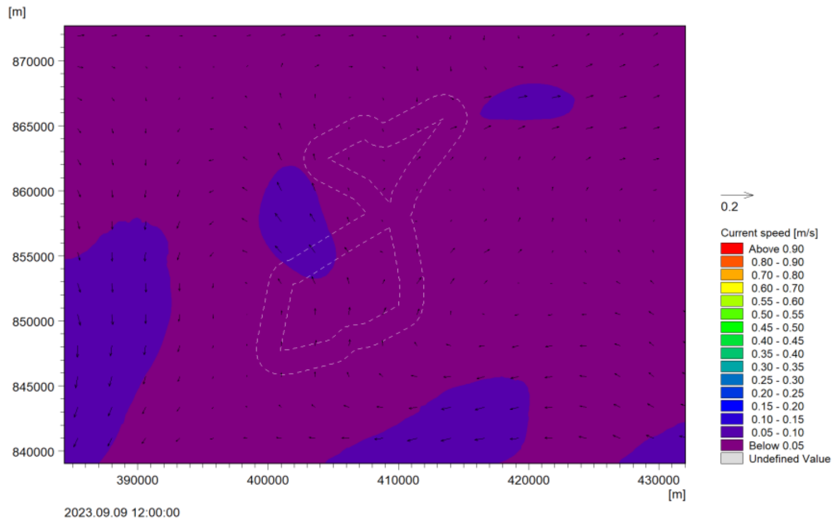


Figure 5.2. The simulation results of operations related to seabed preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil, under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field





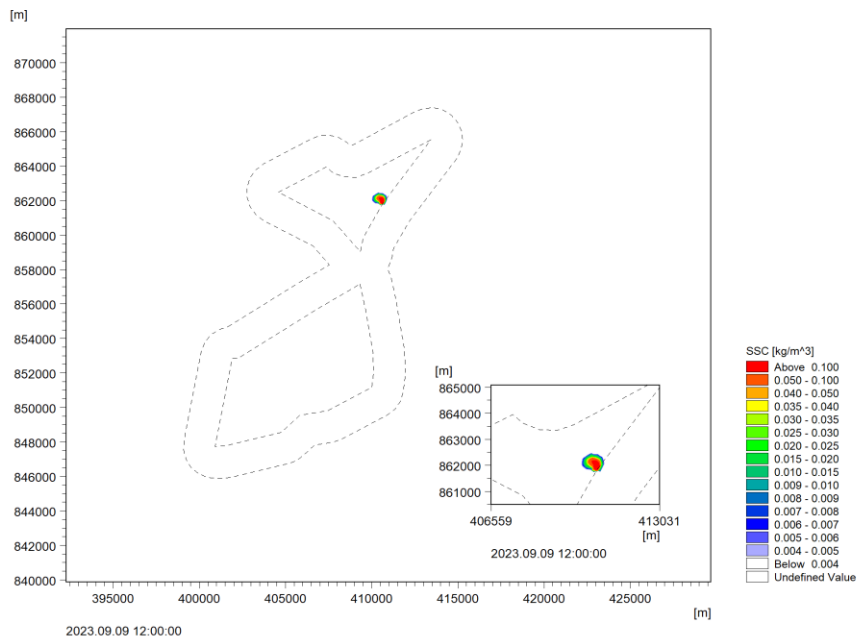


Figure 5.3. The simulation results of operations related to seabed preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil, under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

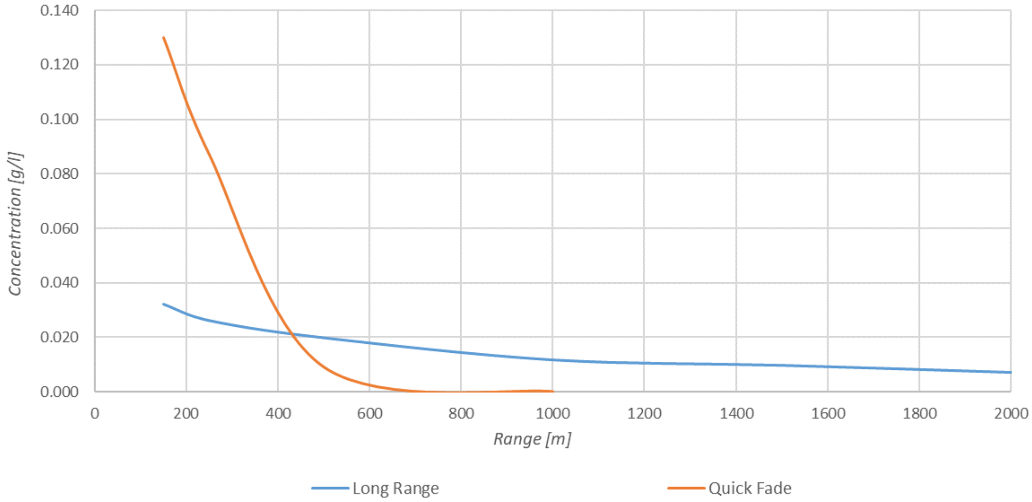


Figure 5.4. *The distributions of suspended solids concentration during the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field*

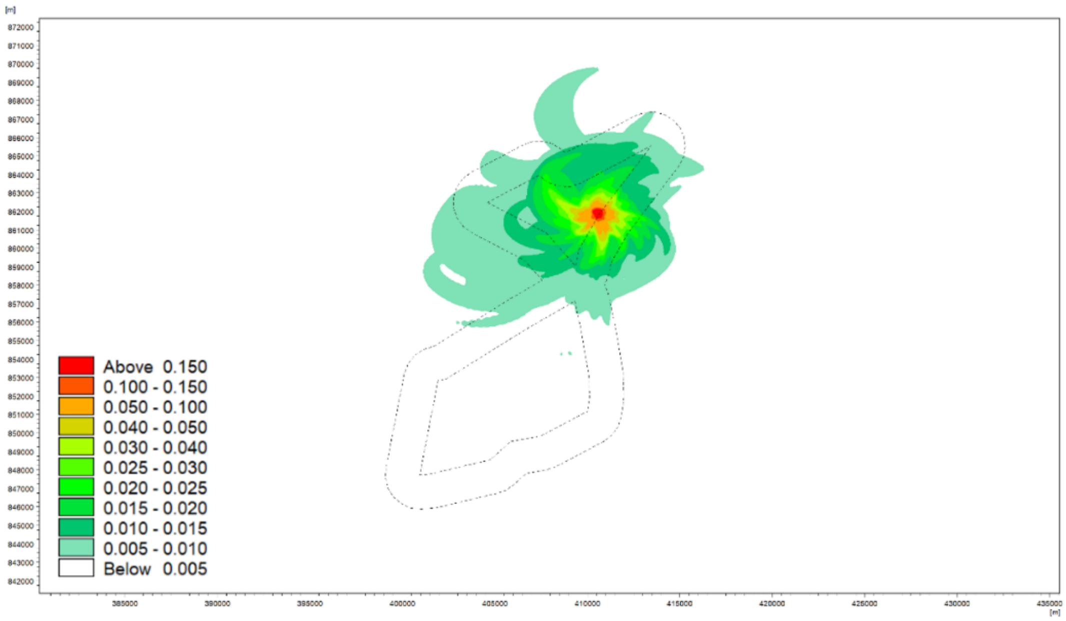


Figure 5.5. *The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field*

Figure 5.6. The distributions of sediment layer thickness [m] after the completion of the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field

5.2.2 Scenario 2. Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil

The technology for preparing the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field.

At time t1, i.e. at the moment of far-field spread [Figure 5.7], the dispersion cloud with concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 5 km. The highest concentration value at a distance of 150 m from the worksite is 15 mg·l^{-1}.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.8], a dispersion cloud with solids concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 0.5 km, while a cloud with a concentration of over 30 mg·l^{-1} spreads to 0.3 km. The highest concentration value at a distance of 150 m from the worksite is 110 mg·l^{-1}.

The figure below [Figure 5.9] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.10] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 195 mg·l^{-1}, and at a distance of 500 m, they are up to 58 mg·l^{-1}. In a major part of the area where the disturbance appears, the concentration is in the range of 6–15 mg·l^{-1}.

The subsequent figure [Figure 5.11] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m off the worksite) is up to 3.4 NM.

In this scenario, the process of preparing the ground for the installation of a gravity-based structure was modelled. The suspended solids with a mean concentration of 5 mg·l^{-1} will remain in the marine environment for approximately 16 hours after the completion of underwater works. The impact of suspended solids on the marine environment is short-term.

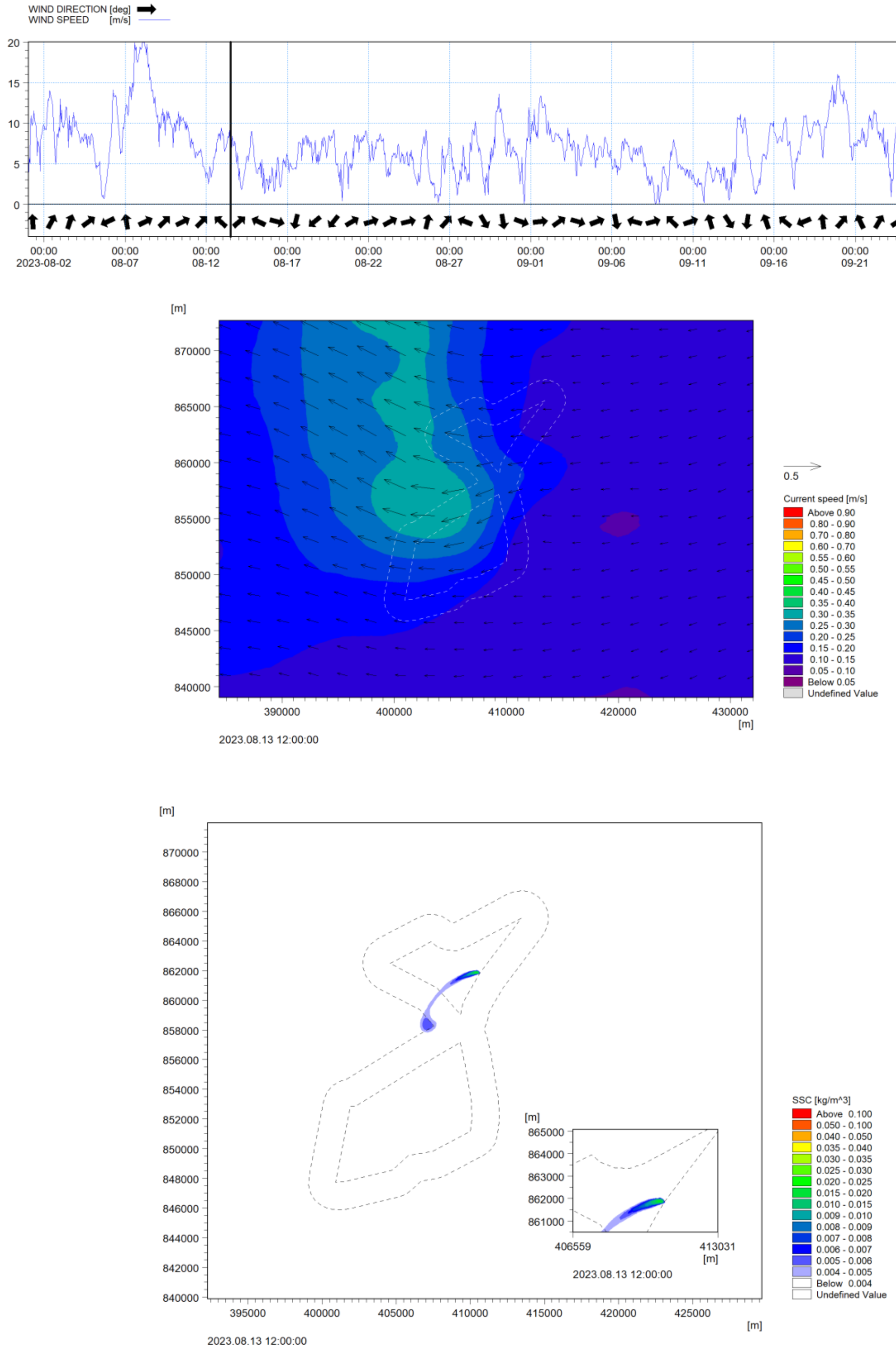


Figure 5.7. The simulation results of the preparation of the seabed substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

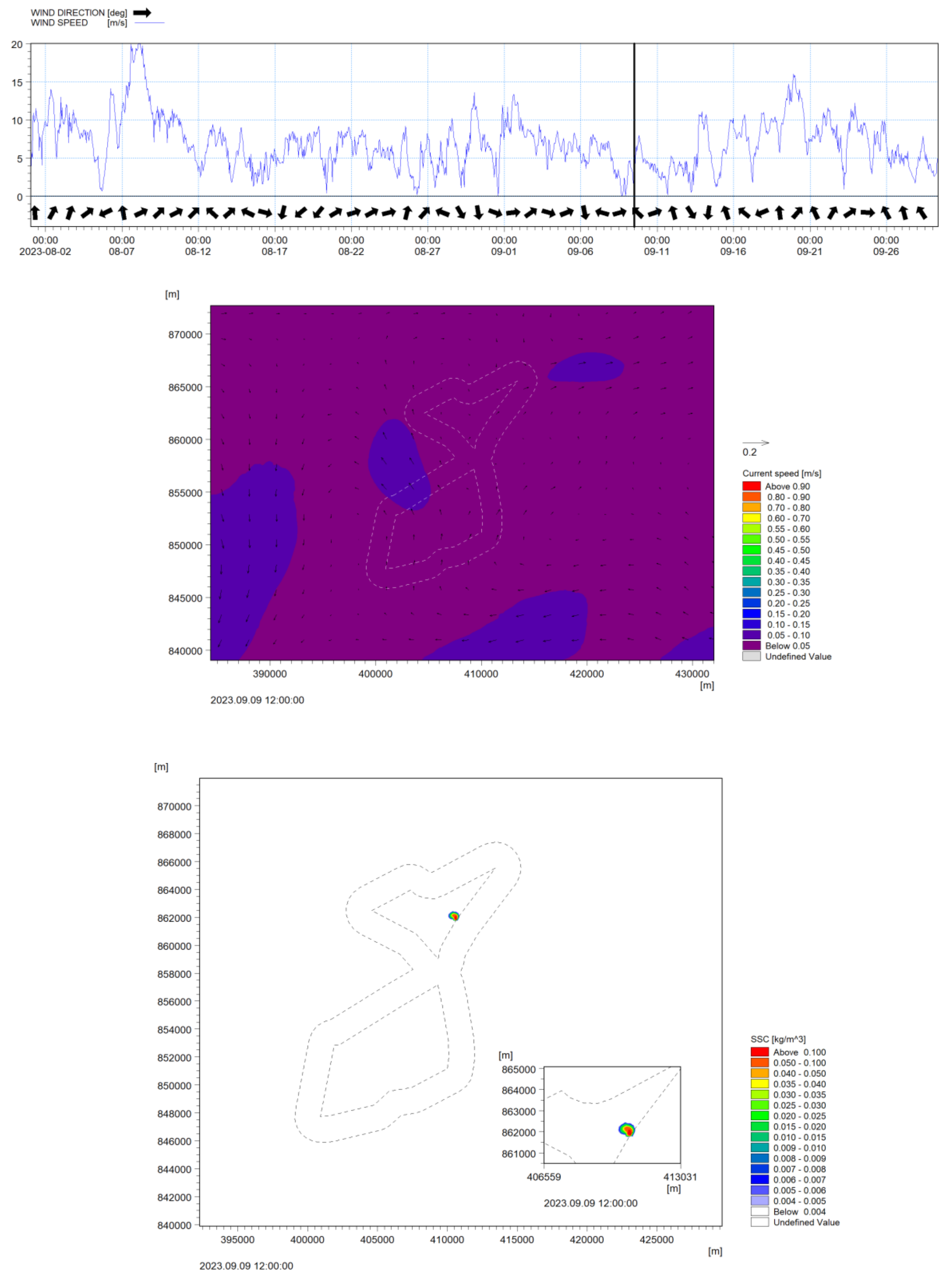


Figure 5.8. The simulation results of the preparation of the seabed substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

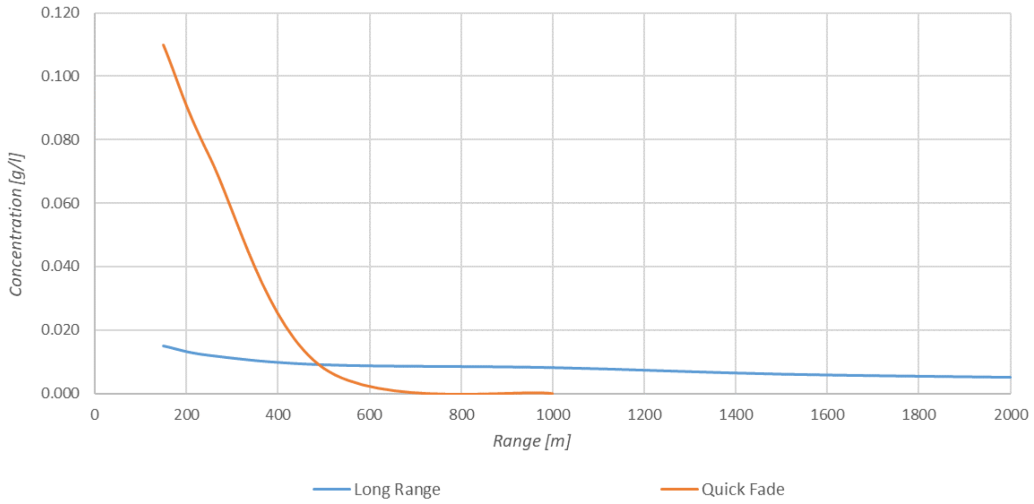


Figure 5.9. *The distributions of suspended solids concentration during the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field*

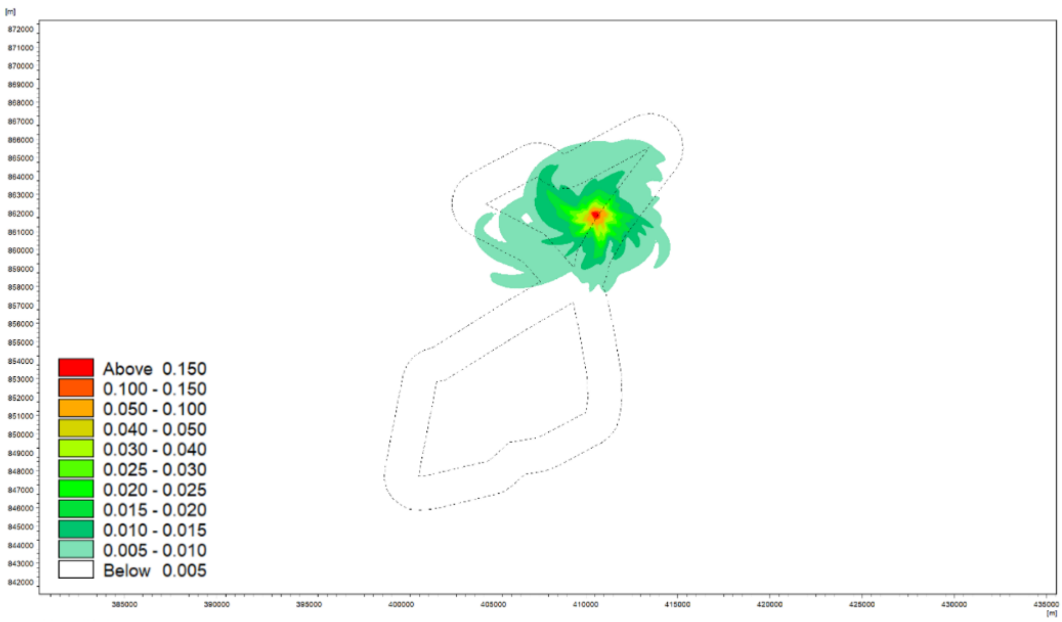


Figure 5.10. *The concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle during the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field*

Figure 5.11. The distributions of sediment layer thickness [m] after the completion of the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field

5.2.3 Scenario 3. Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil

The technology for preparing the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field.

At time t1, i.e. at the moment of far-field spread [Figure 5.12], a dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 6.4 km. The highest concentration value at a distance of 150 m from the worksite is 11 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.13], a dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.5 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.3 km. The highest concentration value at a distance of 150 m from the worksite is 120 $mg \cdot l^{-1}$.

The figure below [Figure 5.14] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.15] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 220 $mg \cdot l^{-1}$, and at a distance of 500 m, they are up to 75 $mg \cdot l^{-1}$. In a major part of the area where the disturbance appears, the concentration is in the range of 6–20 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.16] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of a new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 12 mm.

In this scenario, the process of preparing the ground for the installation of a gravity-based structure was modelled. The suspended solids with a mean concentration of 5 $mg \cdot l^{-1}$ will remain in the marine environment for approximately 16 hours after the completion of underwater works. The impact of suspended solids on the marine environment is short-term.

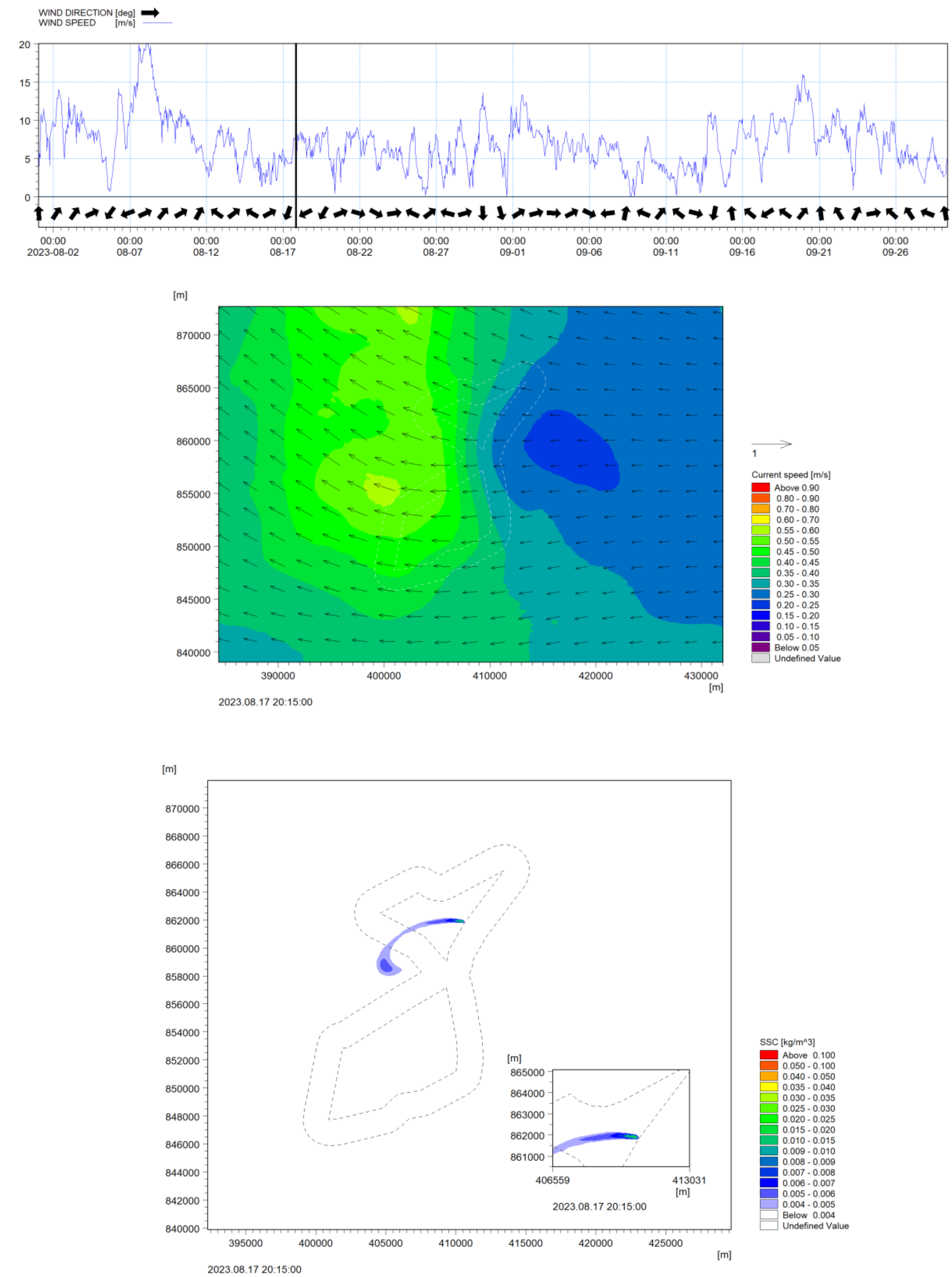


Figure 5.12. The simulation results of operations related to seabed preparation for the installation of a Ø 45 m gravity-based structure in cohesive soil, under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

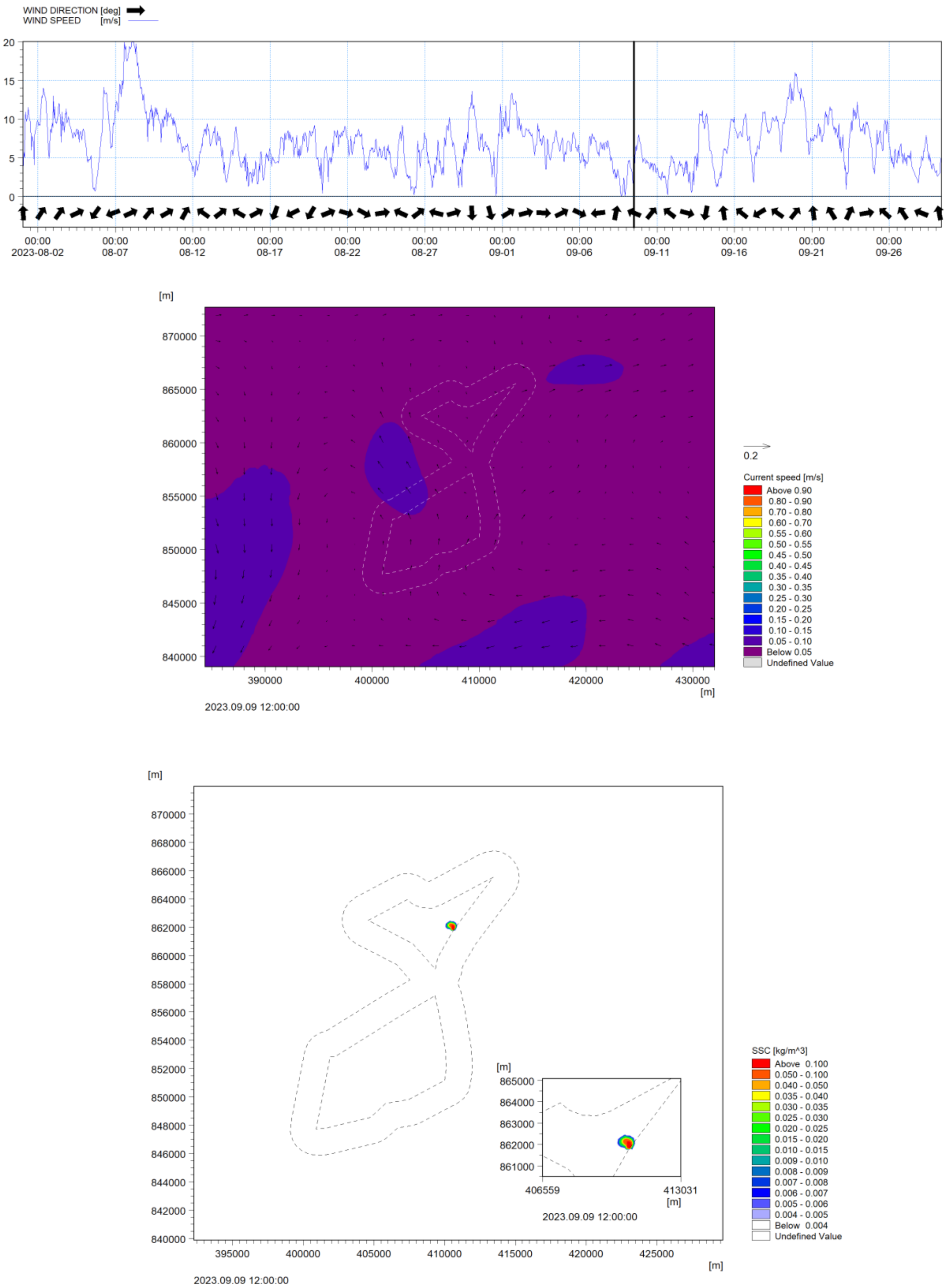


Figure 5.13. The simulation results of operations related to seabed preparation for the installation of a Ø 45 m gravity-based structure in cohesive soil, under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

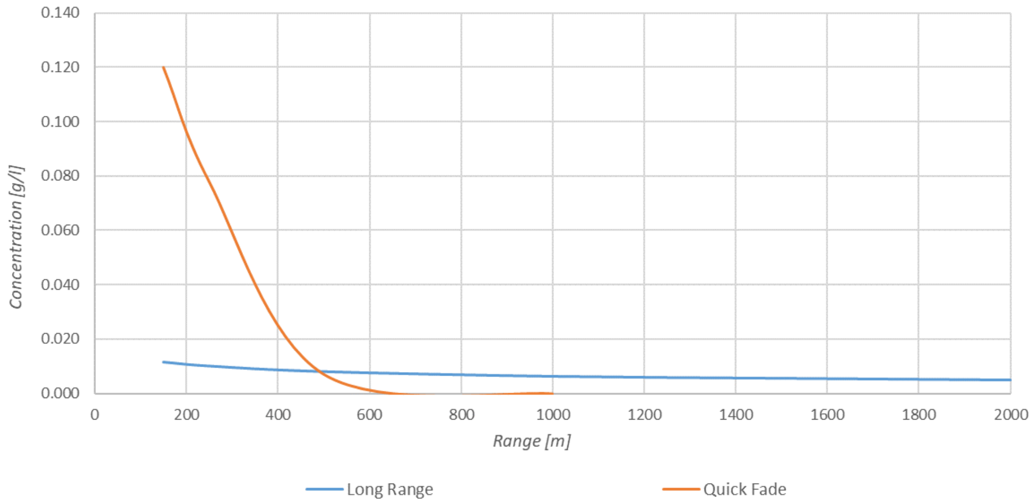


Figure 5.14. The distribution of suspended solids concentration during the seabed preparation for the installation of a Ø 45 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field

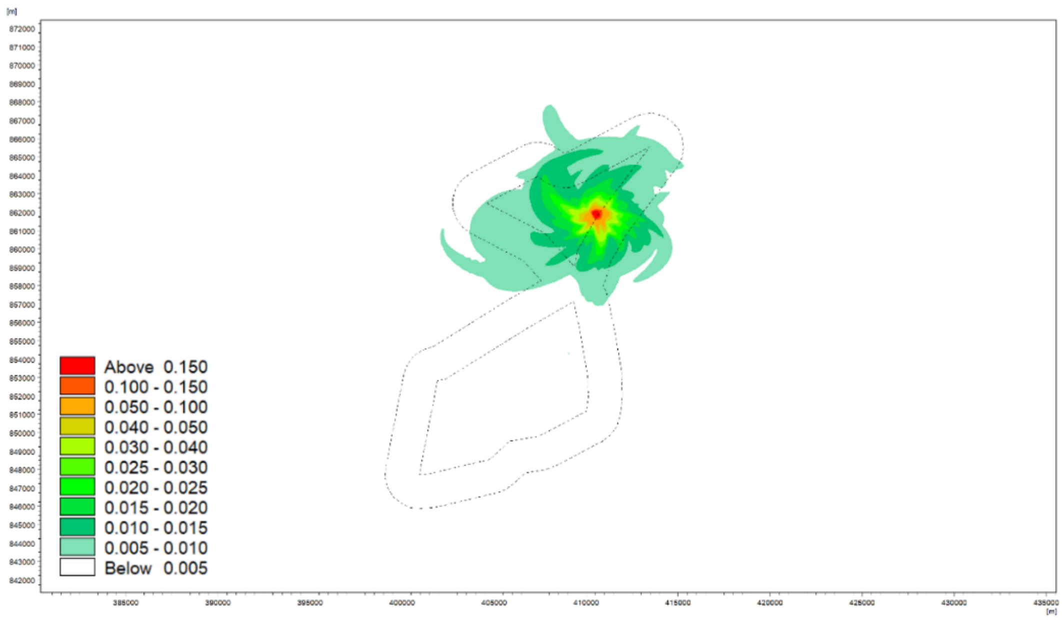


Figure 5.15. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field

Figure 5.16. The distributions of sediment layer thickness [m] after the completion of the preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil, in the Baltica-1 OWF field

5.2.4 Scenario 4. Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil

The technology for preparing the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field.

At time t1, i.e. at the moment of far-field spread [Figure 5.17], a dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 3.2 km. The highest concentration value at a distance of 150 m from the worksite is 8 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.18], a dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.4 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.3 km. The highest concentration value at a distance of 150 m from the worksite is 69 $mg \cdot l^{-1}$.

The figure below [Figure 5.19] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.20] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 160 $mg \cdot l^{-1}$, and at a distance of 500 m, they are up to 45 $mg \cdot l^{-1}$. In a major part of the area where the disturbance appears, the concentration is in the range of 6–15 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.21] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 2.6 mm.

In this scenario, the process of preparing the ground for a gravity-based structure was modelled. The suspended solids with a mean concentration of 5 $mg \cdot l^{-1}$ will remain in the marine environment for approximately 13 hours after the completion of underwater works. The impact of suspended solids on the marine environment is short-term.

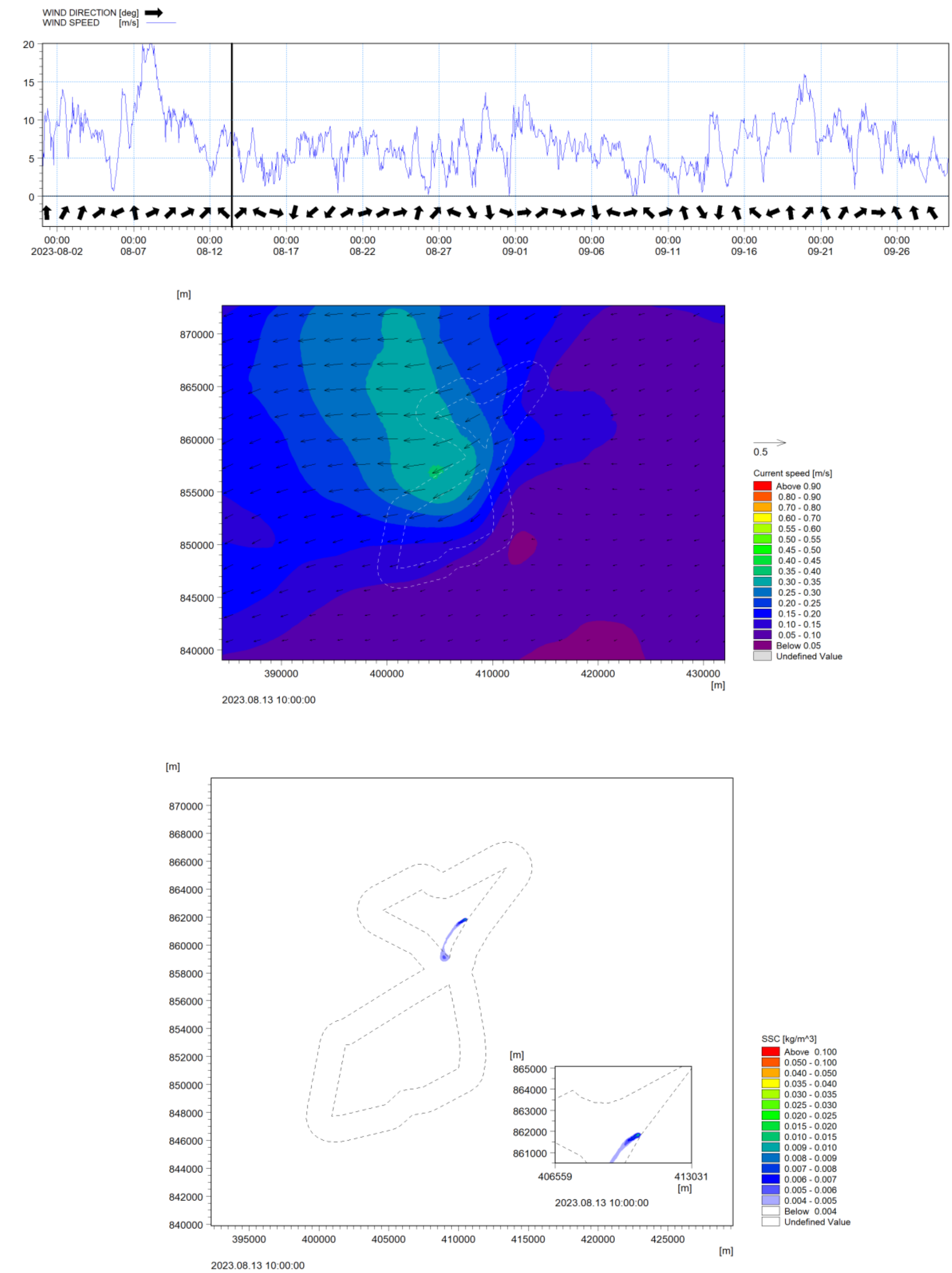


Figure 5.17. The simulation results of the preparation of the seabed substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

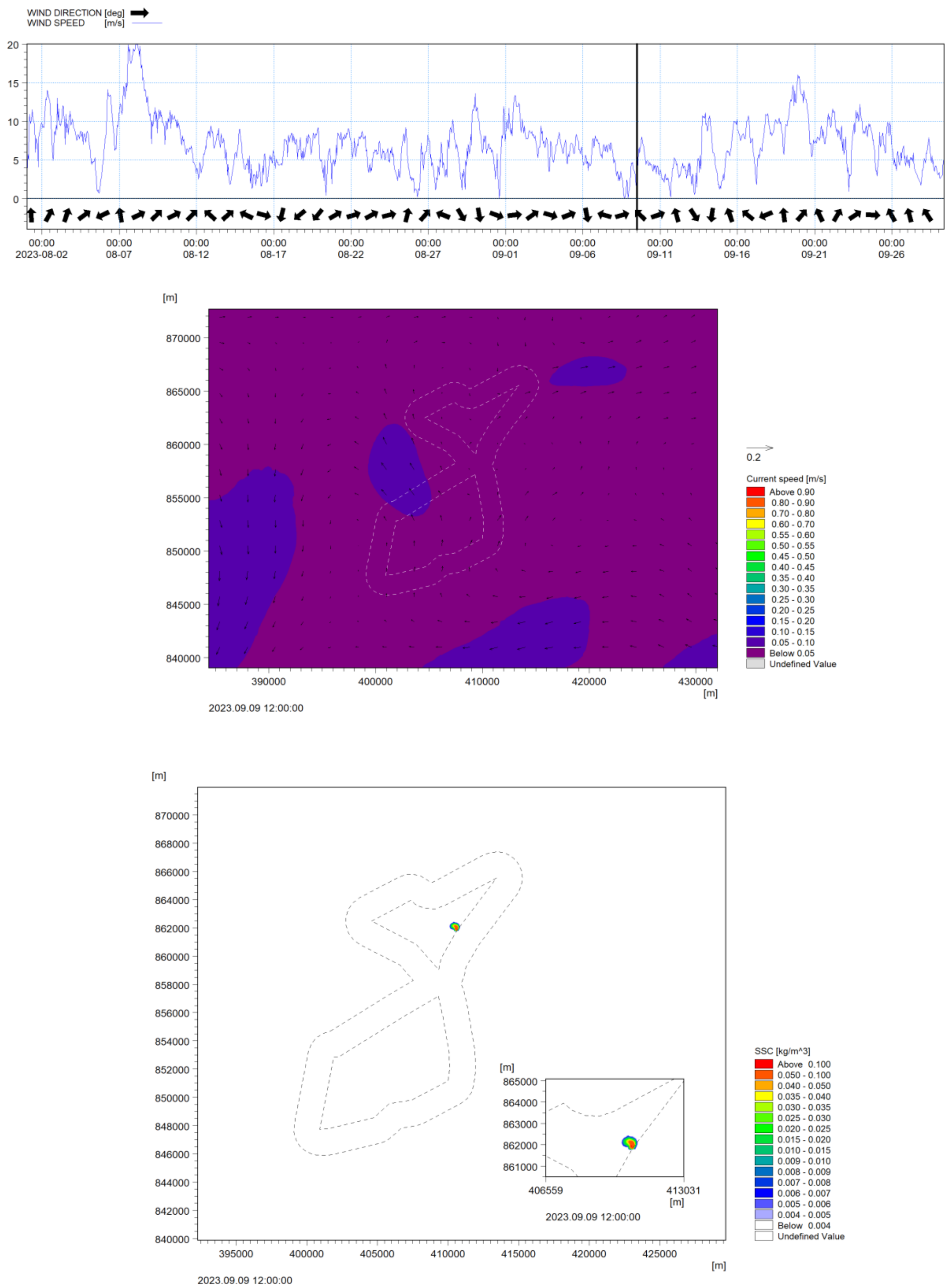


Figure 5.18. The simulation results of the preparation of the seabed substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

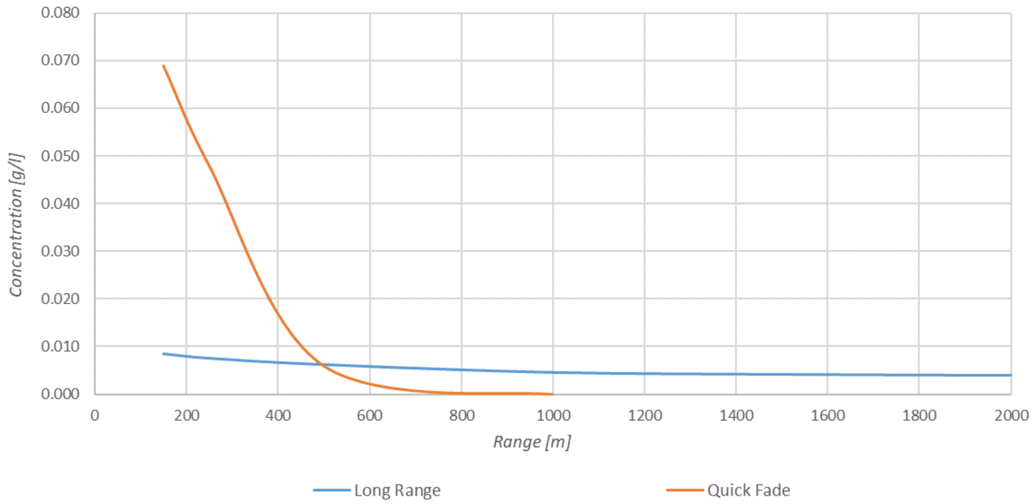


Figure 5.19. The distribution of suspended solids concentration during the seabed substrate preparation for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field

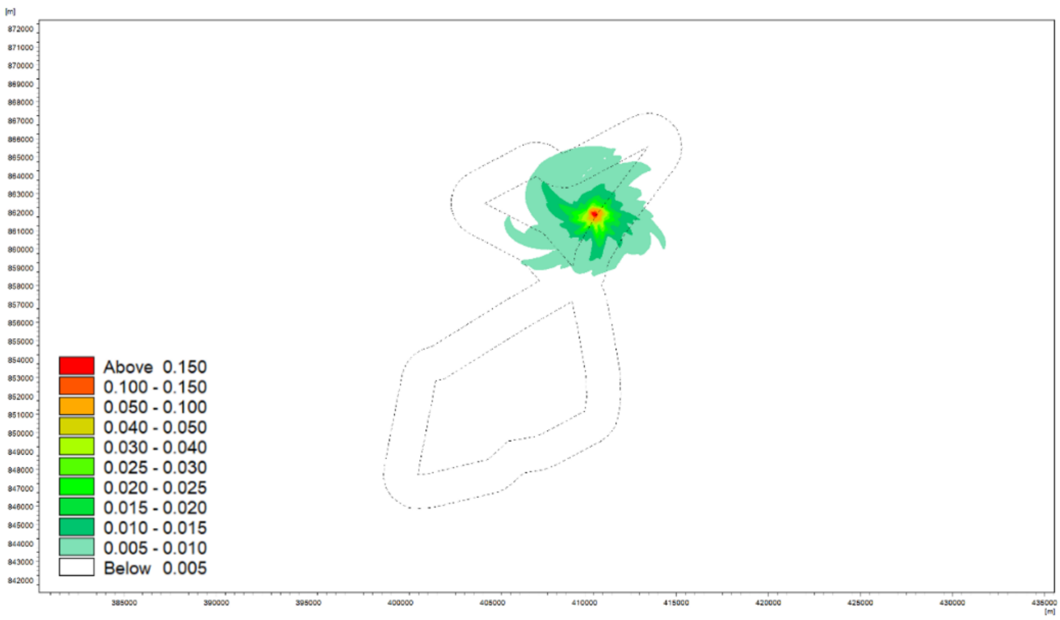


Figure 5.20. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field

Figure 5.21. *The distributions of sediment layer thickness [m] after the completion of the preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil, in the Baltica-1 OWF field*

5.2.5 Scenario 5. Driving of a Ø 12 m pile into the seabed consisting of cohesive soil

The technology of driving a monopile into the seabed consisting of cohesive soil.

The figure below [Figure 5.22] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 6 mg·l^{-1}, and at a distance of 500 m, they are up to 3 mg·l^{-1}. In a major part of the area where the disturbance appears, the concentration is in the range of 4–6 mg·l^{-1}.

In the scenario involving driving a monopile into the soil, suspended solids with a concentration of 5 mg·l^{-1} will not remain in the water column for longer than 2 hours after the completion of underwater works. In every aspect – the period of deteriorated conditions, suspended solids concentration values, the spatial extent of the impact, and thickness of newly formed sediments – the impact of suspended solids is basically negligible.

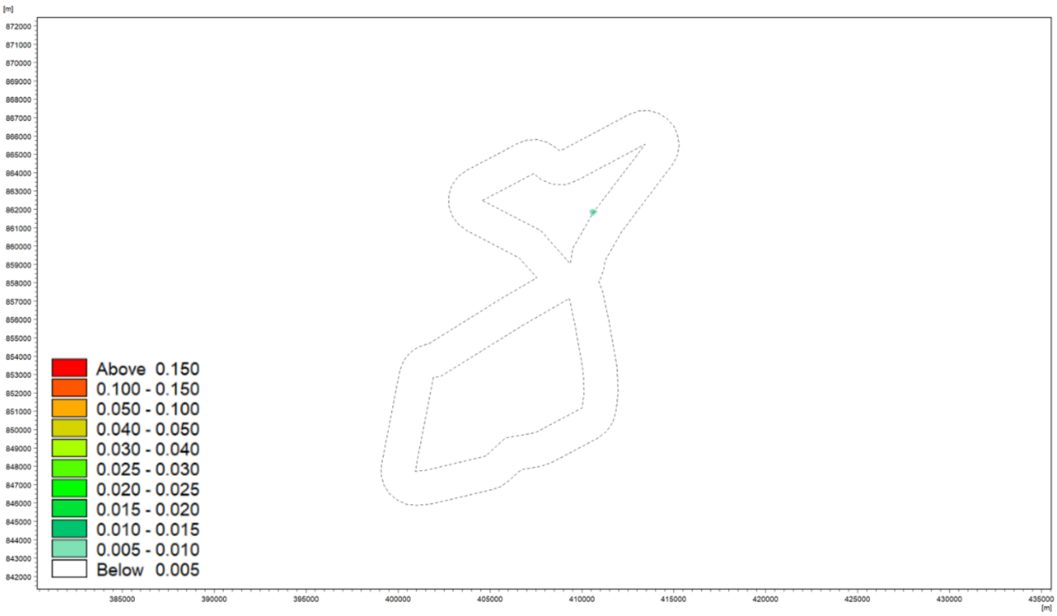


Figure 5.22. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle during the driving of a Ø 12 m monopile into cohesive soil in the Baltica-1 OWF field

5.2.6 Scenario 6. Boulder clearance (300 m·h^{-1})

The boulder clearance technology with the device moving at an operational speed of 300 m·h^{-1} within the area of the inter-array cable construction in the Baltica-1 OWF field.

At time t1, i.e. at the moment of far-field spread [Figure 5.23], the dispersion cloud with concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 6 km. The highest concentration value at a distance of 150 m from the vessel worksite is 12 mg·l^{-1}.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.24], a dispersion cloud with solids concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 0.7 km, while a cloud with a concentration of over 30 mg·l^{-1} spreads to 0.1 km. The highest concentration value at a distance of 150 m from the vessel's operation site is 46 mg·l^{-1}.

The figure below [Figure 5.25] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.26] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. The instantaneous concentrations, locally (approx. 150 m from the route of the vessel), reach the value of 88 mg·l^{-1}, and at a distance of 500 m, they are 46 mg·l^{-1}. In a major part of the area where the disturbance appears, the concentration is in the range of 7–20 mg·l^{-1}.

The subsequent figure [Figure 5.27] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the operating vessel's route) is up to 0.9 mm.

In the case of works associated with stone and boulder clearance from the seabed, the retention time of the dispersion cloud with a concentration of over 5 mg·l^{-1} has been estimated at 15 hours from the moment the work is completed. The impact is short-term, while its extent and the thickness of sediments newly formed on the seabed should be classified as very small.

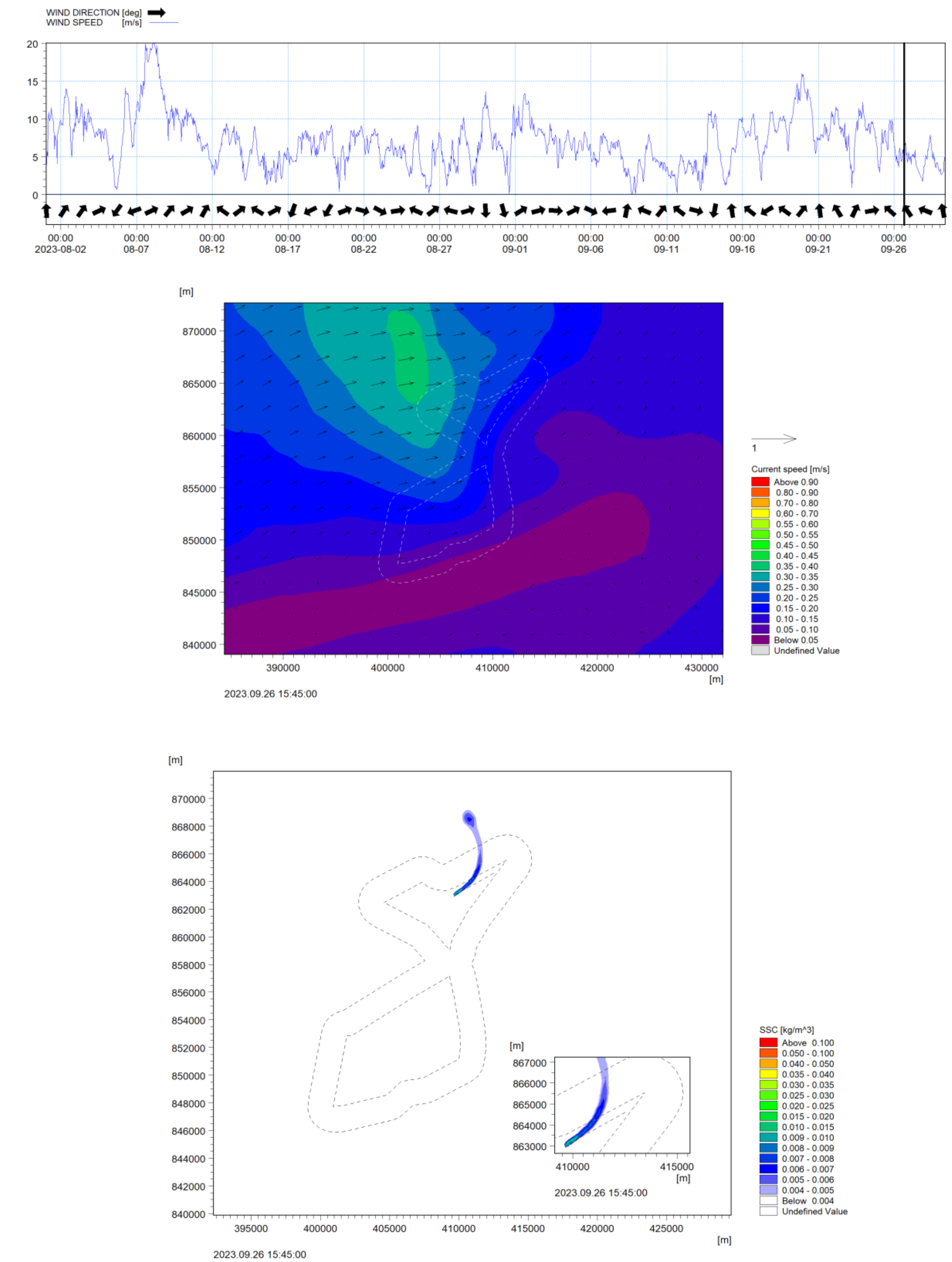
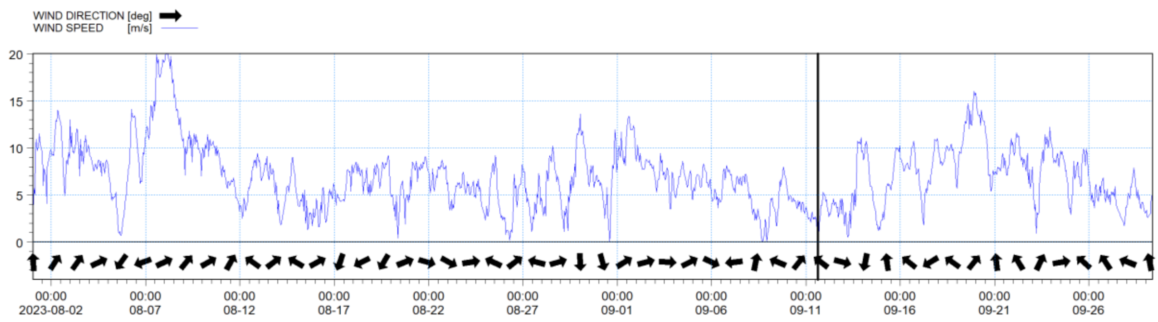
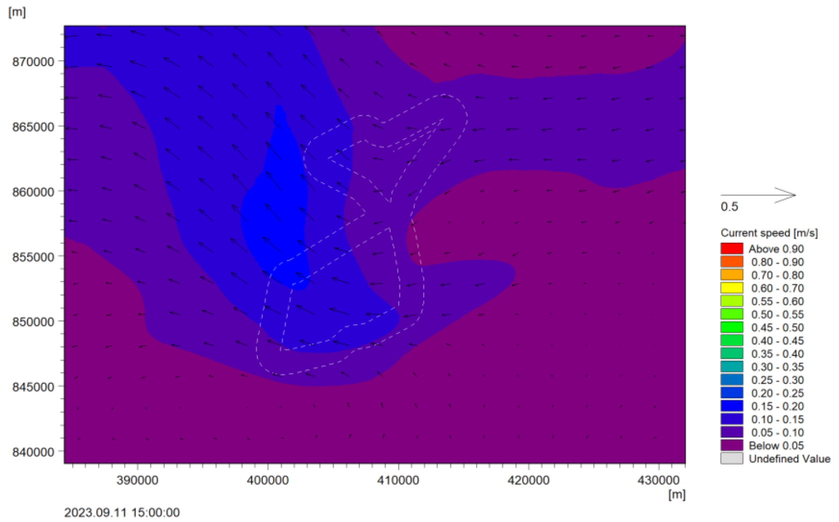


Figure 5.23. The simulation results of stone and boulder clearance conducted under real hydrodynamic conditions at time step t1 for the technology of performing work with a device moving at an operational speed of 300 m·h^{-1} in the area of inter-array cable lines in the Baltica-1 OWF field, in cohesive soil





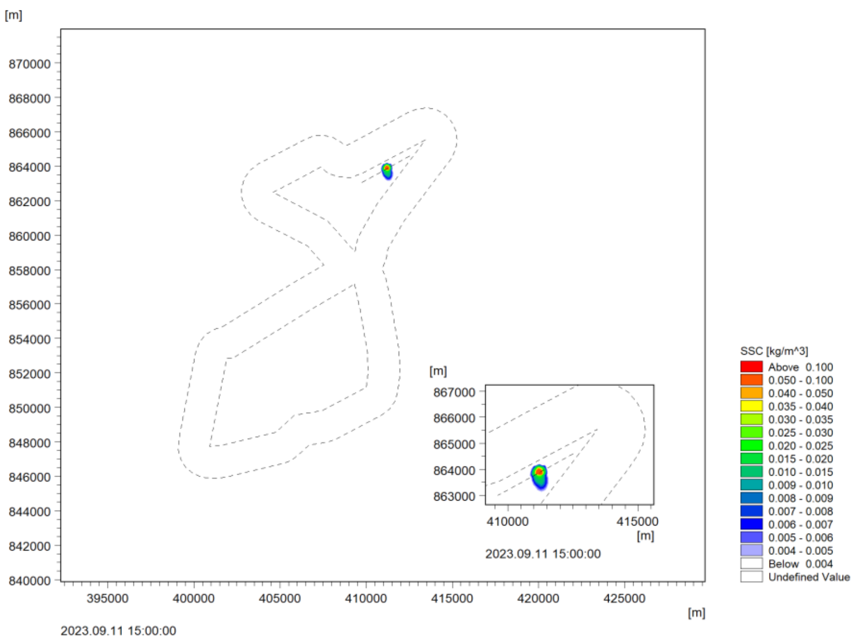


Figure 5.24. The simulation results of stone and boulder clearance conducted under real hydrodynamic conditions at time step t2 for the technology of performing work with a device moving at an operational speed of 300 m·h^{-1} in the area of inter-array cable lines in the Baltica-1 OWF field, in cohesive soil

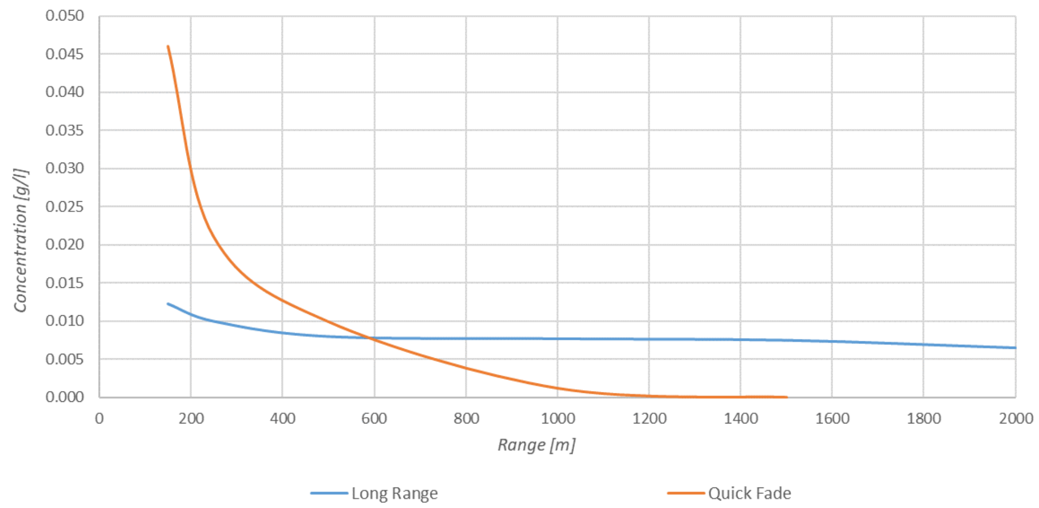


Figure 5.25. The suspended solids concentration distributions during the boulder clearance in cohesive soil, in the Baltica-1 OWF field with a device moving at a speed of 300 m·h^{-1}

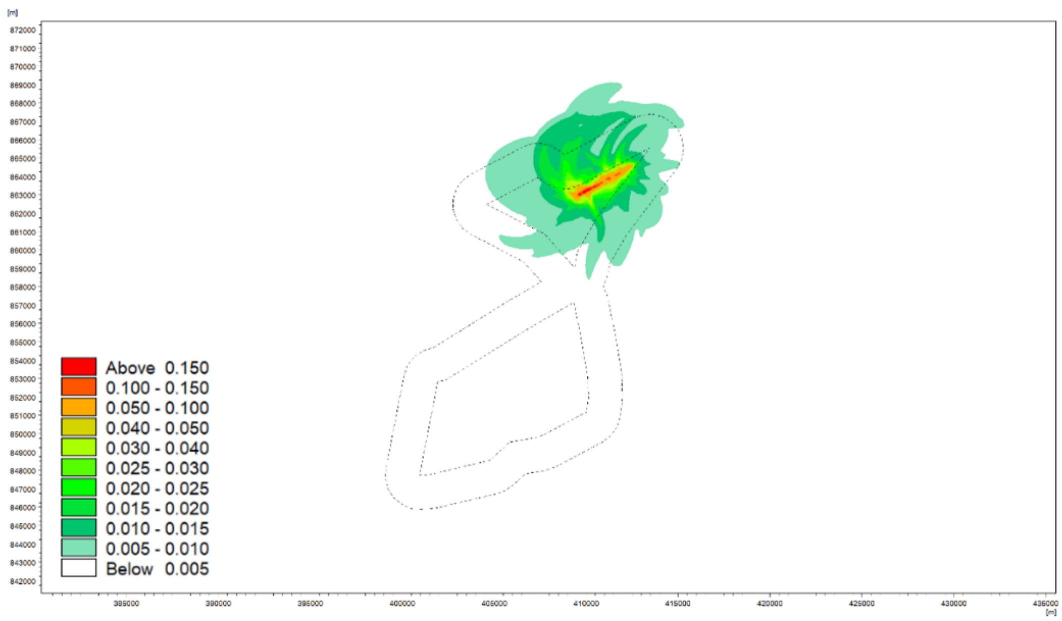


Figure 5.26. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle for the technology of boulder clearance with the device moving at an operational speed of 300 m·h^{-1} in the area of laying the inter-array cable lines in cohesive soil in the Baltica-1 OWF field

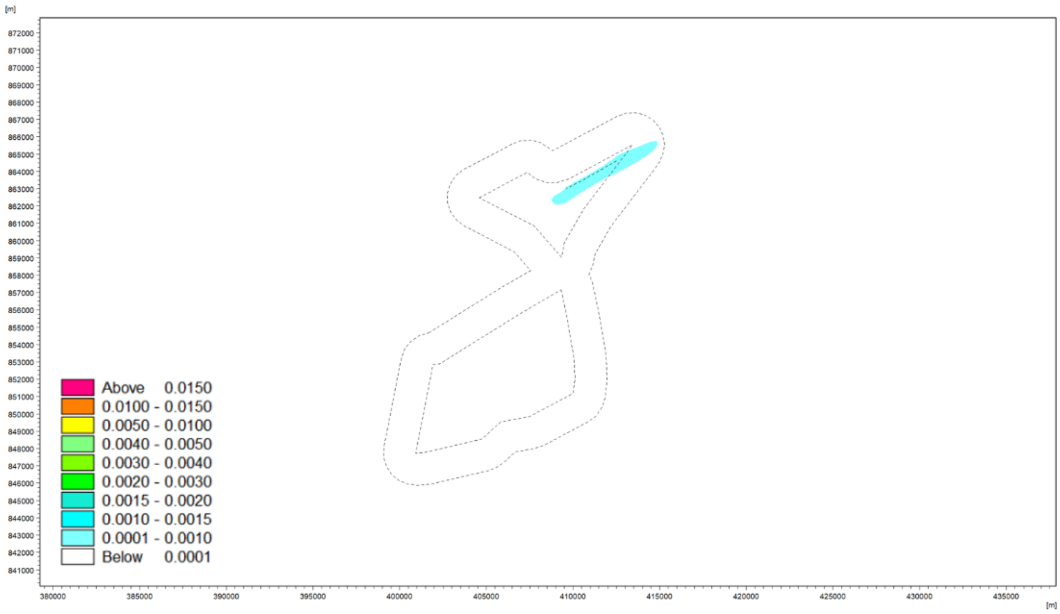


Figure 5.27. The sediment layer thickness distribution [m] after the completion of works conducted in the technology of boulder clearance with the device moving at a speed of 300 m·h^{-1} in the area of laying the inter-array cable lines in cohesive soil, in the Baltica-1 OWF field

5.2.7 Scenario 7. Cable embedment with the jetting method (200 $m \cdot h^{-1}$), cohesive soil

The technology of work performance with the water jetting method using a device moving at a speed of 200 $m \cdot h^{-1}$ in the area of the inter-array cable laying in the Baltica-1 OWF field in cohesive soil.

At time t1, i.e. at the moment of far-field spread [Figure 5.28], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 6.8 km. The highest concentration value at a distance of 150 m from the vessel worksite is 19 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.29], a dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.8 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.6 km. The highest concentration value at a distance of 150 m from the vessel's operation site is 90 $mg \cdot l^{-1}$.

The figure below [Figure 5.30] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.31] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. The instantaneous concentrations, locally (approx. 150 m from the route of the vessel), reach the value of 160 $mg \cdot l^{-1}$, and at a distance of 500 m, they are 65 $mg \cdot l^{-1}$. In a major part of the area where the disturbance appears, the concentration is in the range of 7–25 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.32] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the operating vessel's route) is up to 1.0 mm.

In this scenario, the span of the dispersion cloud with the concentration of 5 $mg \cdot l^{-1}$ is 21 hours from the moment the work is completed. The impact of suspended solids is short-term.

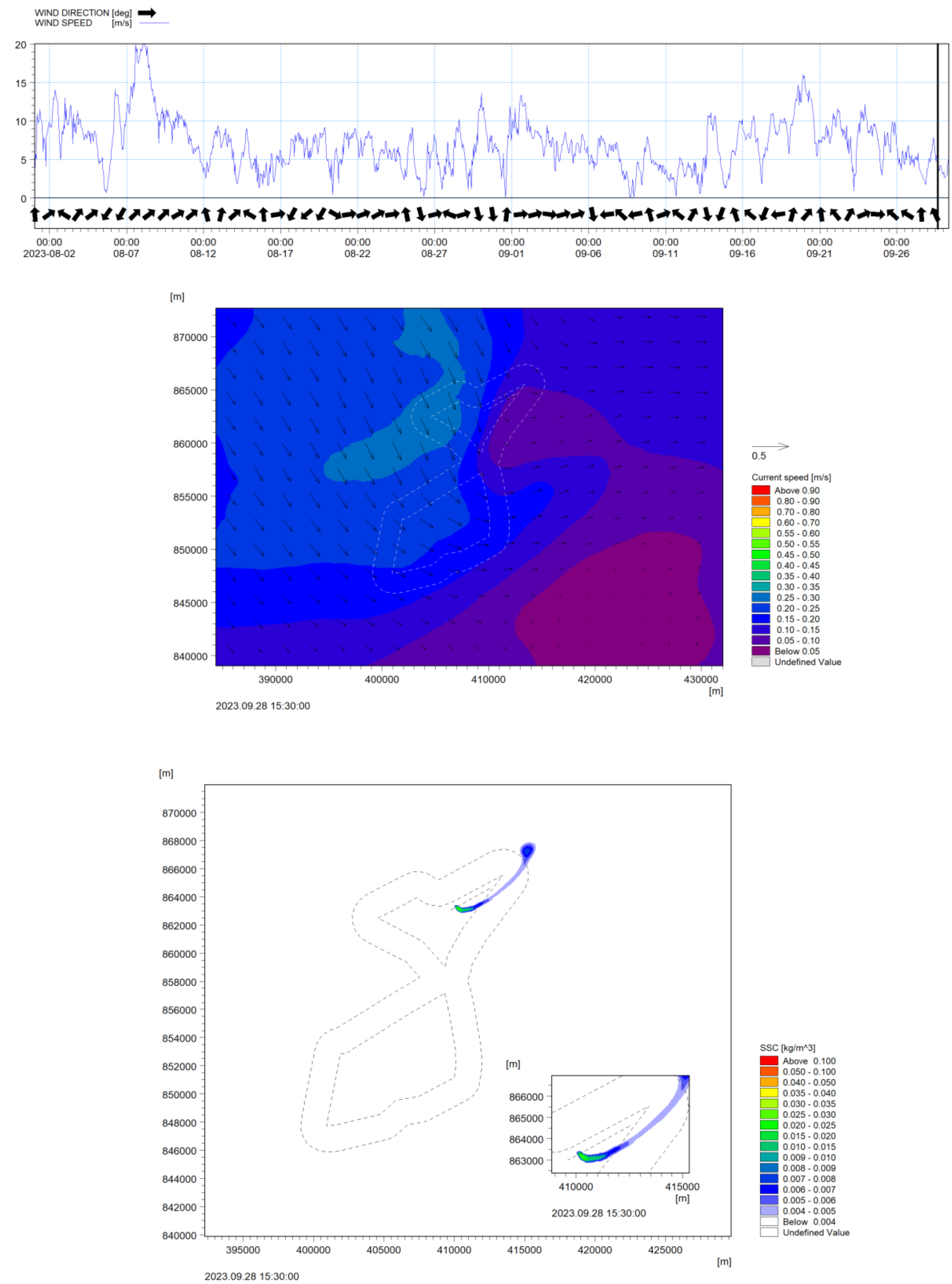


Figure 5.28. The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t1 for the technology of work performance with a jetting device moving at a speed of 200 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in cohesive soil

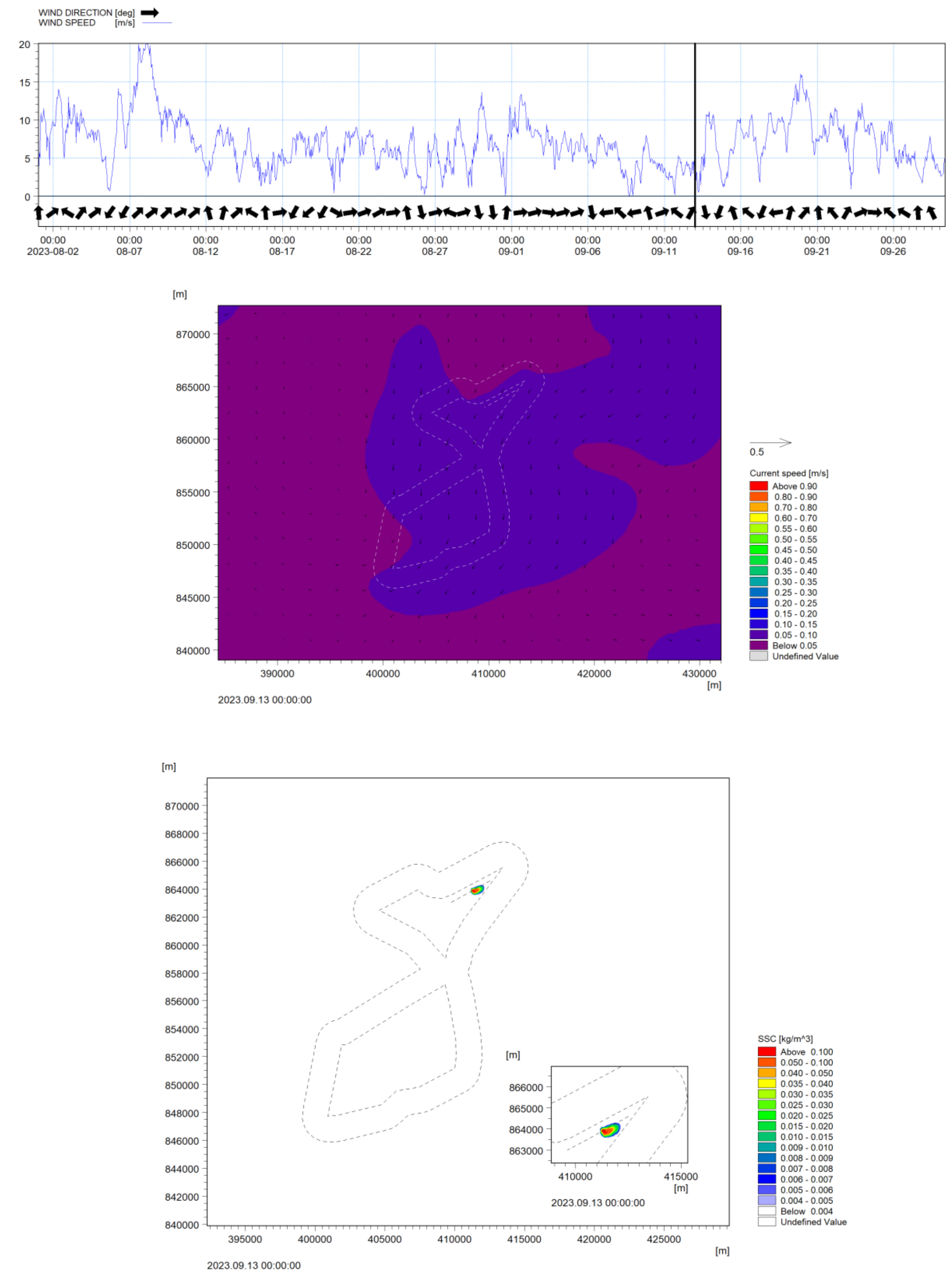


Figure 5.29. The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t2 for the technology of work performance with a jetting device moving at a speed of 200 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in cohesive soil

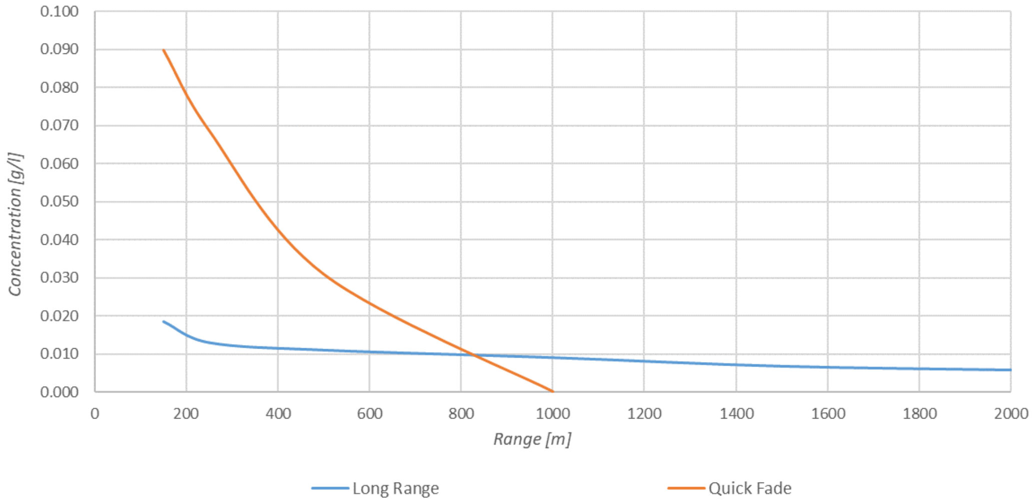


Figure 5.30. The suspended solids concentration distributions during the power cable installation using the jetting methods with the device moving at a speed of 200 m·h^{-1} in cohesive soil

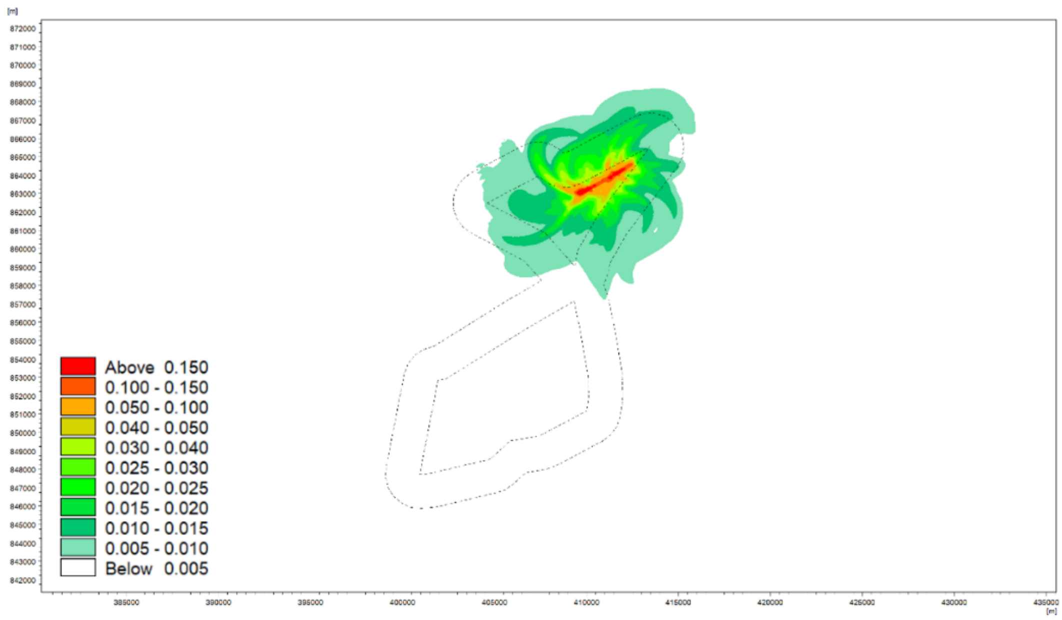


Figure 5.31. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle for the technology of work performance using a jetting device moving at an operational speed of 200 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in cohesive soil

Figure 5.32. The sediment layer thickness distribution [m] after completion of works conducted in the technology of water jetting with the device moving at a speed of 200 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in cohesive soil

5.2.8 Scenario 8. Cable embedment using the jetting method (200 $m \cdot h^{-1}$), non-cohesive soil

The technology of work performance with the water jetting method using a device moving at a speed of 200 $m \cdot h^{-1}$ in the area of the inter-array cable laying in the Baltica-1 OWF field in non-cohesive soil.

At time t1, i.e. at the moment of far-field spread [Figure 5.33], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 2.7 km. The highest concentration value at a distance of 150 m from the vessel worksite is 12 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.34], a dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.7 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.1 km. The highest concentration value at a distance of 150 m from the vessel's operation site is 26 $mg \cdot l^{-1}$.

The figure below [Figure 5.35] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.36] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. The instantaneous concentrations, locally (approx. 150 m from the route of the vessel), reach the value of 52 $mg \cdot l^{-1}$, and at a distance of 500 m, they are 21 $mg \cdot l^{-1}$. In a major part of the area where the disturbance appears, the concentration is in the range of 5–15 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.37] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the operating vessel's route) is up to 0.6 mm.

In this scenario, the span of the dispersion cloud with the concentration of 5 $mg \cdot l^{-1}$ is 7 hours from the moment the work is completed. The impact of suspended solids is short-term.

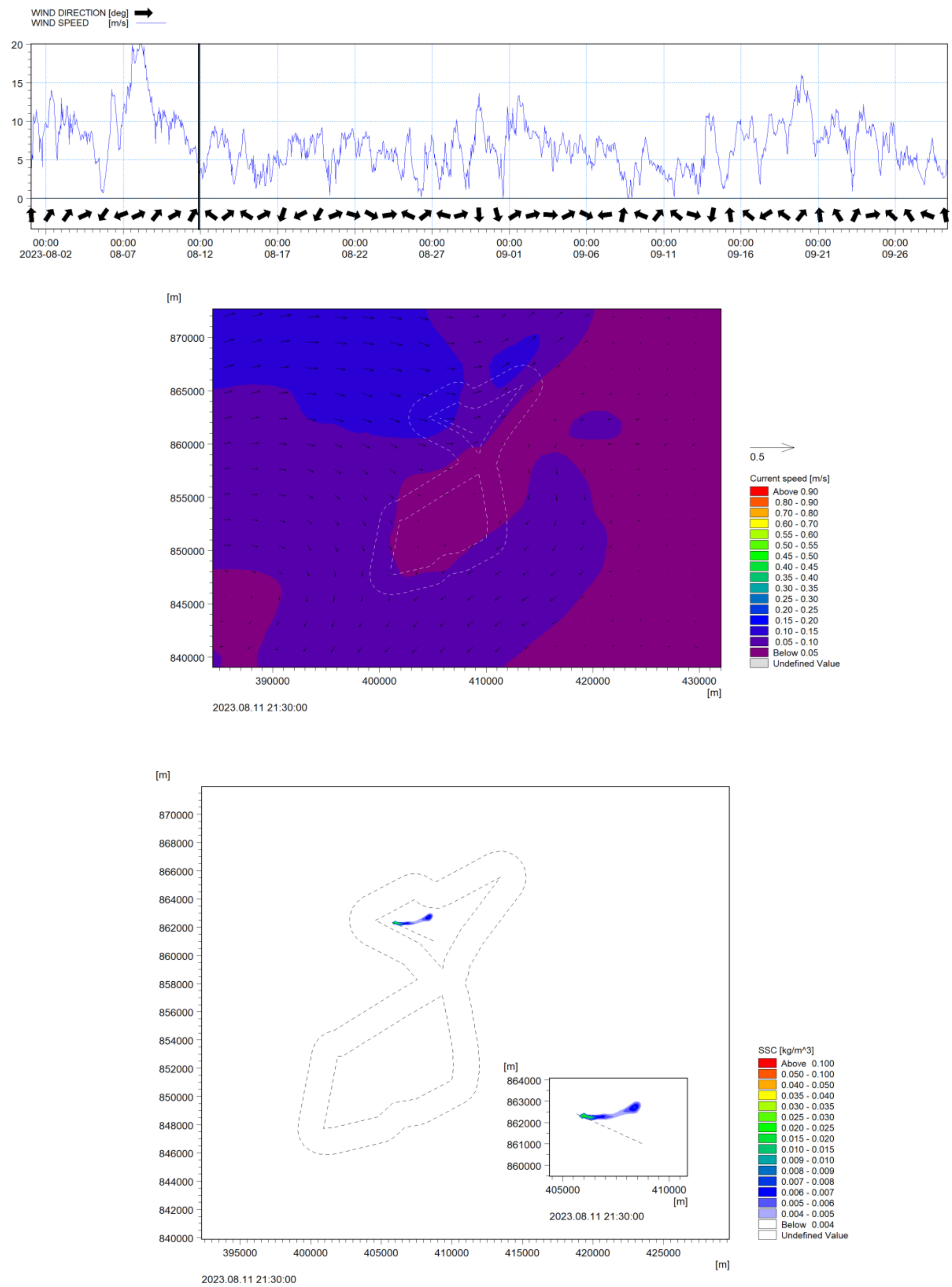


Figure 5.33. The simulation results for power cable installation works conducted under real hydrodynamic conditions cohesive in the time step t1 for the technology of work performance with a jetting device moving at a speed of 200 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in non-cohesive soil

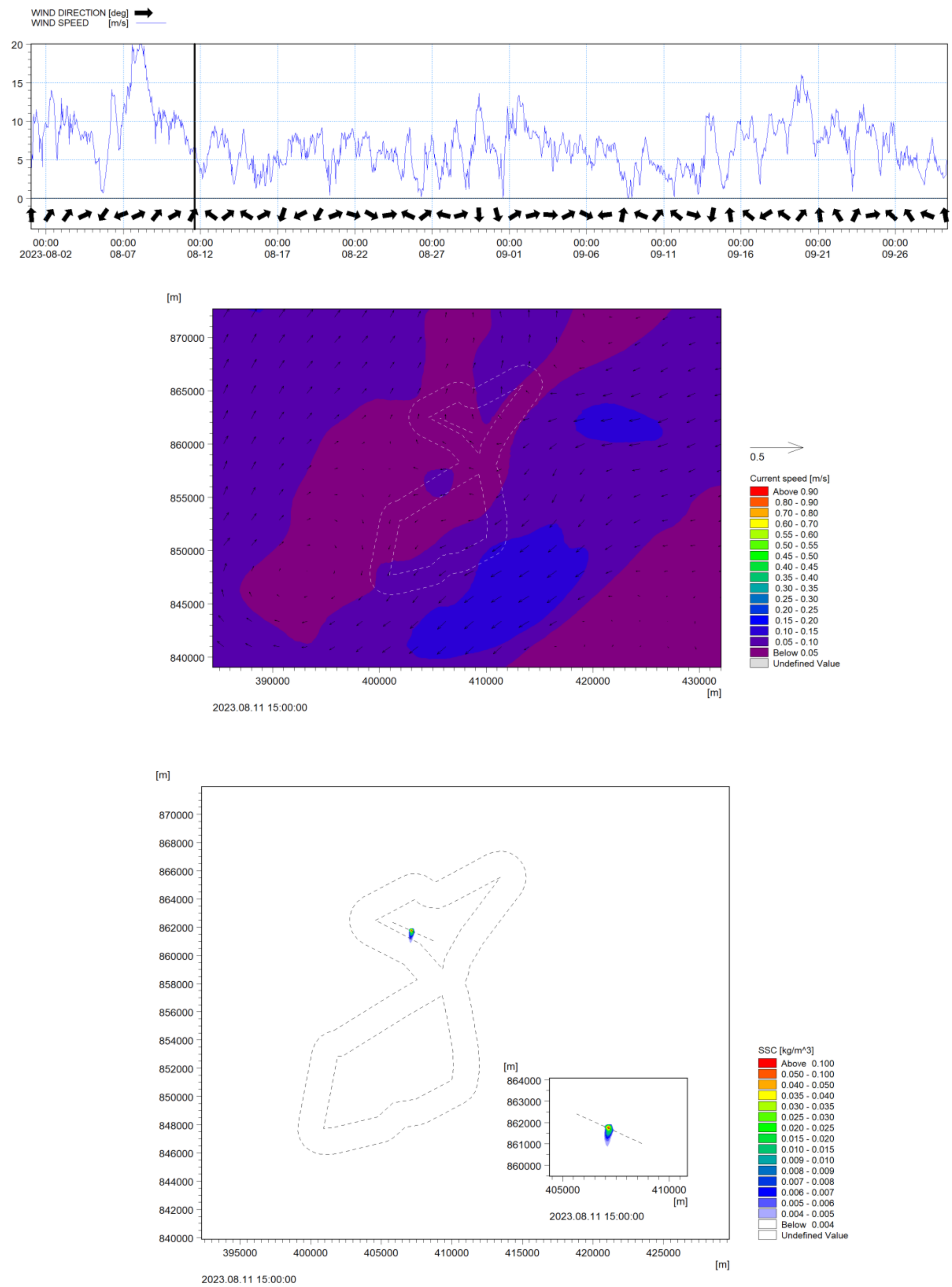


Figure 5.34. The simulation results for power cable installation works conducted under real hydrodynamic conditions cohesive in the time step t2 for the technology of work performance with a jetting device moving at a speed of 200 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in non-cohesive soil

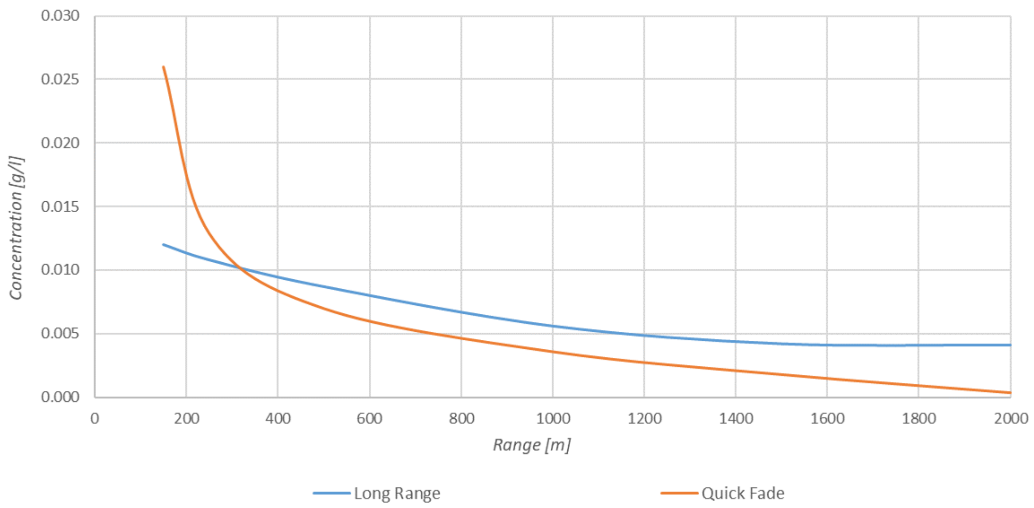


Figure 5.35. The suspended solids concentration distributions during the power cable installation in the Baltica-1 OWF field, using the jetting method with the device moving at a speed of 200 m·h^{-1}, in non-cohesive soil

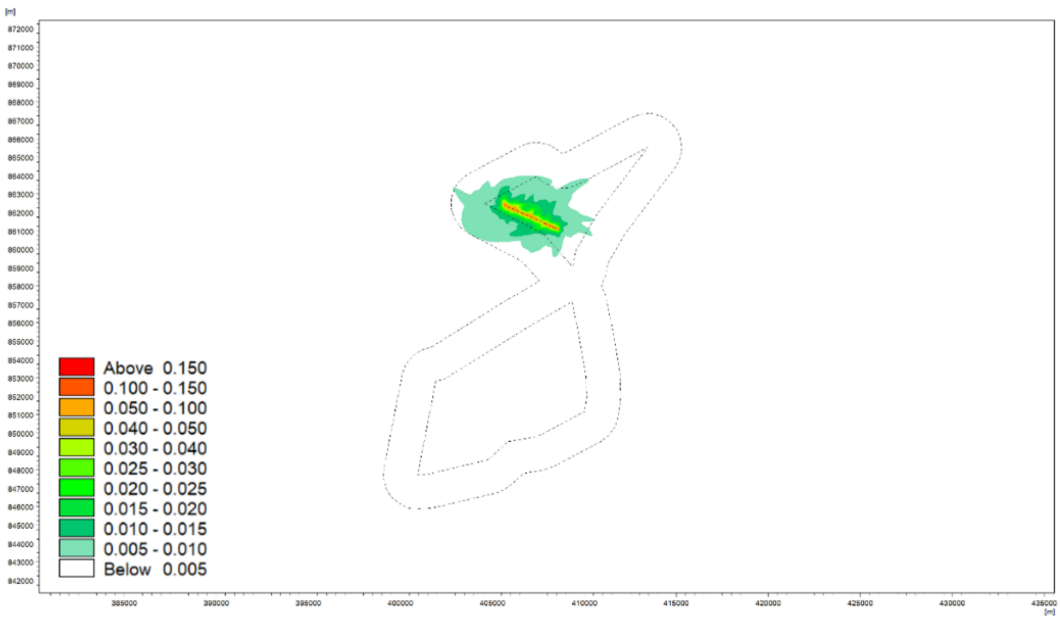


Figure 5.36. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle for the technology of work performance using a jetting device moving at an operational speed of 200 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in non-cohesive soil

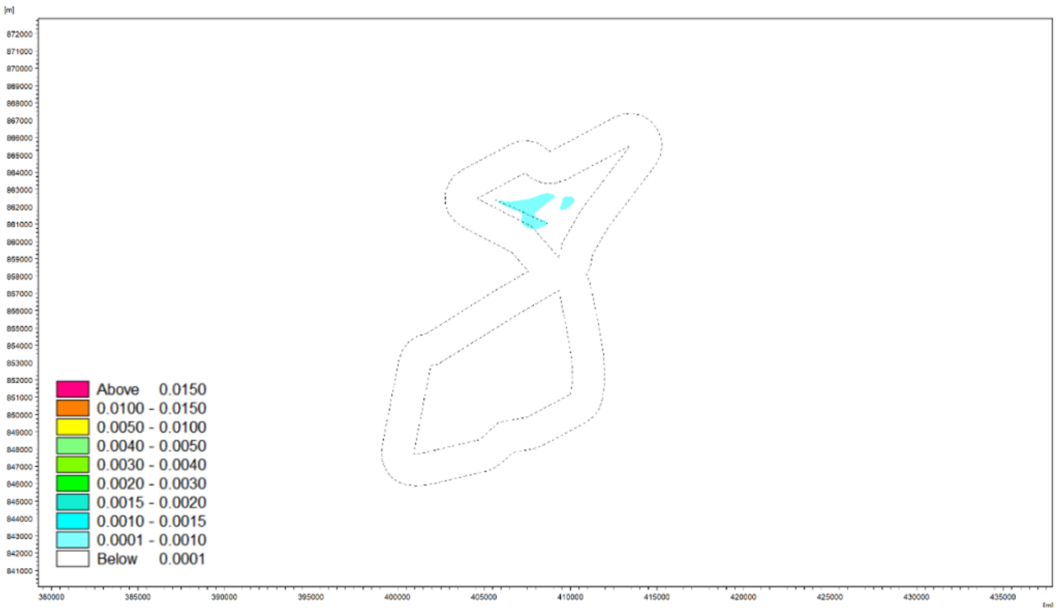


Figure 5.37. The sediment layer thickness distribution [m] after completion of works conducted in the technology of water jetting with the device moving at a speed of 200 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in non-cohesive soil

5.2.9 Scenario 9. Cable embedment with the ploughing method (300 m·h^{-1}), cohesive soil

The work performance technology using the method of ploughing with a device moving at a speed of 300 m·h^{-1} in the area of inter-array cable laying in the Baltica-1 OWF field in cohesive soil

At time t1, i.e. at the moment of far-field spread [Figure 5.38], the dispersion cloud with concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 6.4 km. The highest concentration value at a distance of 150 m from the vessel worksite is 13 mg·l^{-1}.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.39], a dispersion cloud with solids concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 0.8 km, while a cloud with a concentration of over 30 mg·l^{-1} spreads to 0.6 km. The highest concentration value at a distance of 150 m from the vessel's operation site is 63 mg·l^{-1}.

The figure below [Figure 5.40] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.41] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. The instantaneous concentrations, locally (approx. 150 m from the route of the vessel), reach the value of 115 mg·l^{-1}, and at a distance of 500 m, they are 51 mg·l^{-1}. In a major part of the area where the disturbance appears, the concentration is in the range of 5–25 mg·l^{-1}.

The subsequent figure [Figure 5.42] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the operating vessel's route) is up to 1.0 mm.

In this scenario, the span of the dispersion cloud with the concentration of 5 mg·l^{-1} is 19 hours from the moment the work is completed. The impact of suspended solids is short-term.

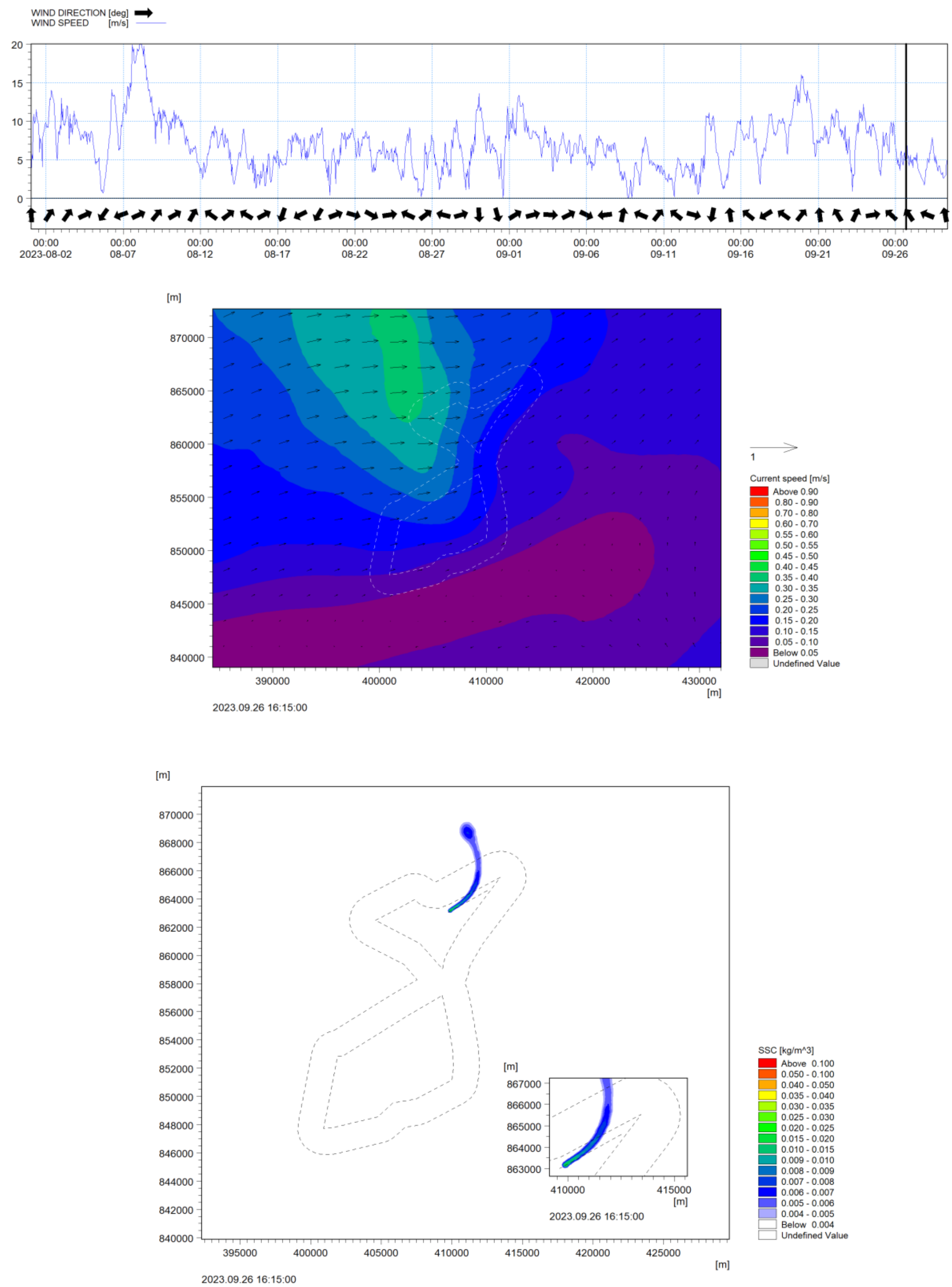


Figure 5.38. The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t1 for the technology of work performance with a ploughing device moving at a speed of 300 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in cohesive soil

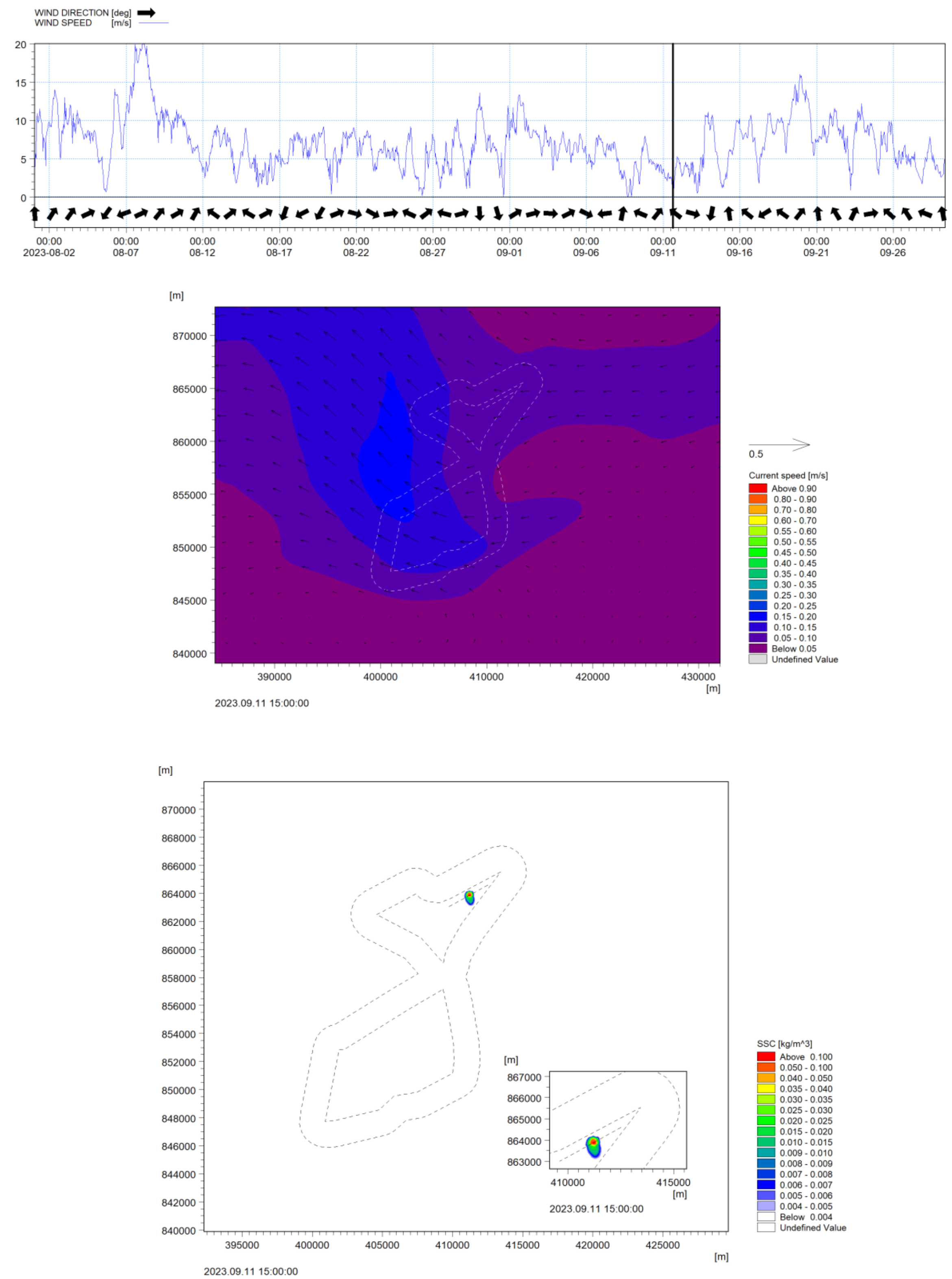


Figure 5.39. The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t2 for the technology of work performance with a ploughing device moving at a speed of 300 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in cohesive soil

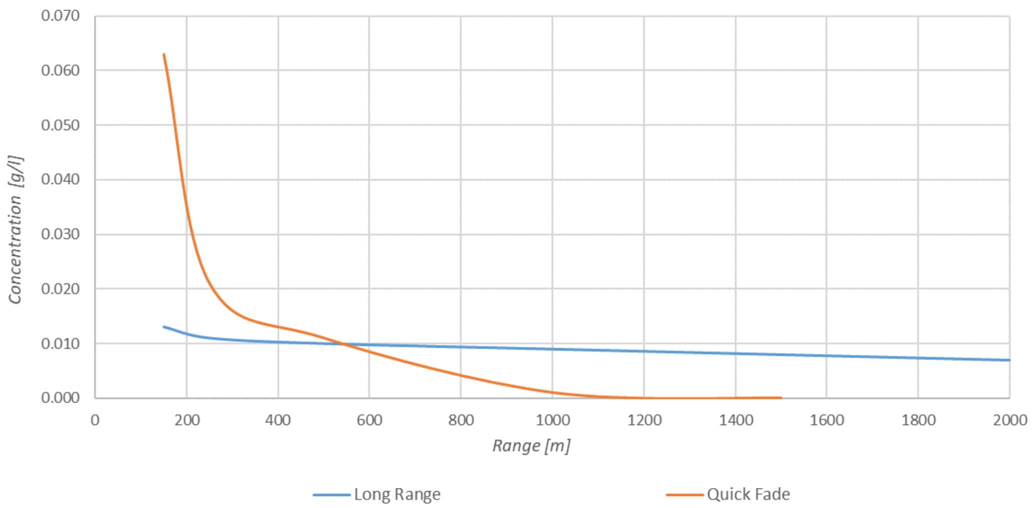


Figure 5.40. *The suspended solids concentration distributions during the power cable installation in the field using the ploughing method with the device moving at a speed of 300 m·h^{-1} in cohesive soil*

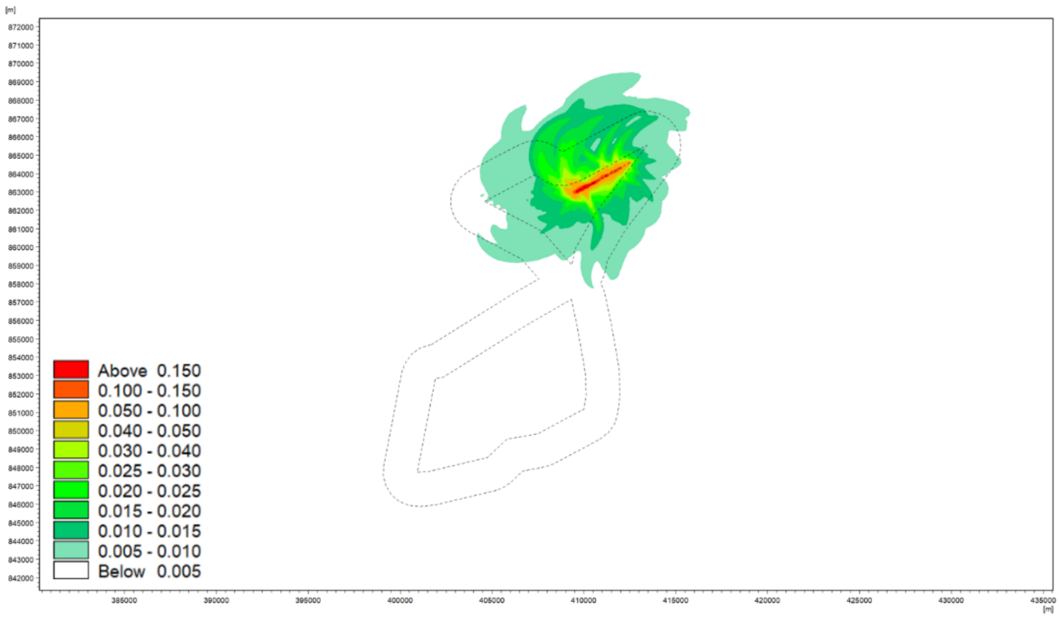


Figure 5.41. *The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle for the technology of work performance using a ploughing device moving at an operational speed of 300 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in cohesive soil*

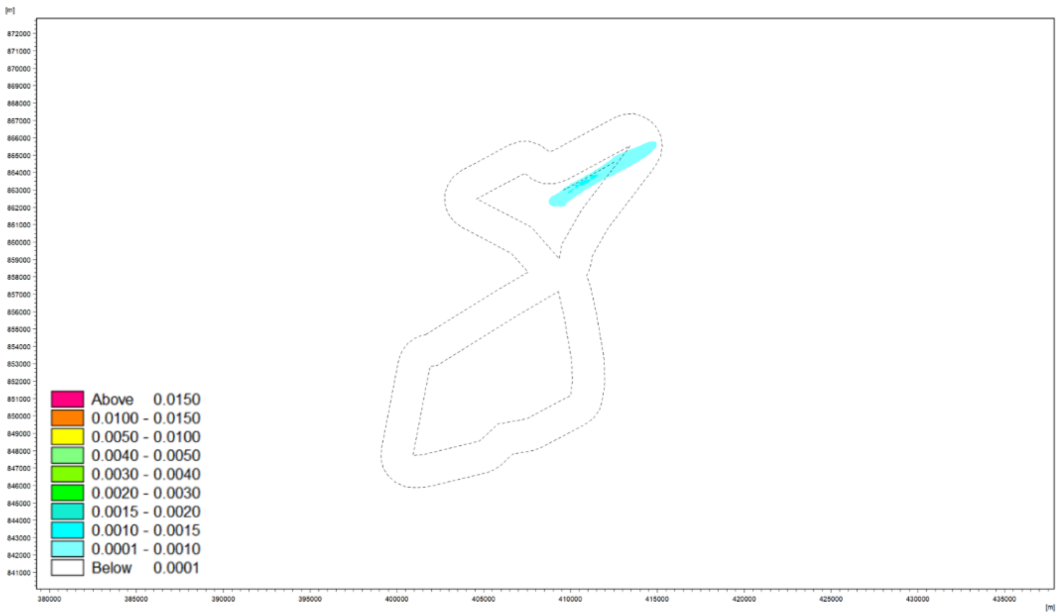


Figure 5.42. The sediment layer thickness distribution [m] after completion of works conducted in the technology of ploughing with a device moving at a speed of 300 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in cohesive soil

5.2.10 Scenario 10. Cable embedment with the ploughing method (300 $m \cdot h^{-1}$), non-cohesive soil

The work performance technology using the method of ploughing with a device moving at a speed of 300 $m \cdot h^{-1}$ in the area of inter-array cable laying in the Baltica-1 OWF field in non-cohesive soil

At time t1, i.e. at the moment of far-field spread [Figure 5.43], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 4.6 km. The highest concentration value at a distance of 150 m from the vessel worksite is 12 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.44], a dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.78 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.58 km. The highest concentration value at a distance of 150 m from the vessel's operation site is 25 $mg \cdot l^{-1}$.

The figure below [Figure 5.45] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.46] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. The instantaneous concentrations, locally (approx. 150 m from the route of the vessel), reach the value of 85 $mg \cdot l^{-1}$, and at a distance of 500 m, they are 42 $mg \cdot l^{-1}$. In a major part of the area where the disturbance appears, the concentration is in the range of 5–20 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.47] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the operating vessel's route) is up to 0.4 mm.

In this scenario, the span of the dispersion cloud with the concentration of 5 $mg \cdot l^{-1}$ is 10 hours from the moment the work is completed. The impact of suspended solids is short-term.

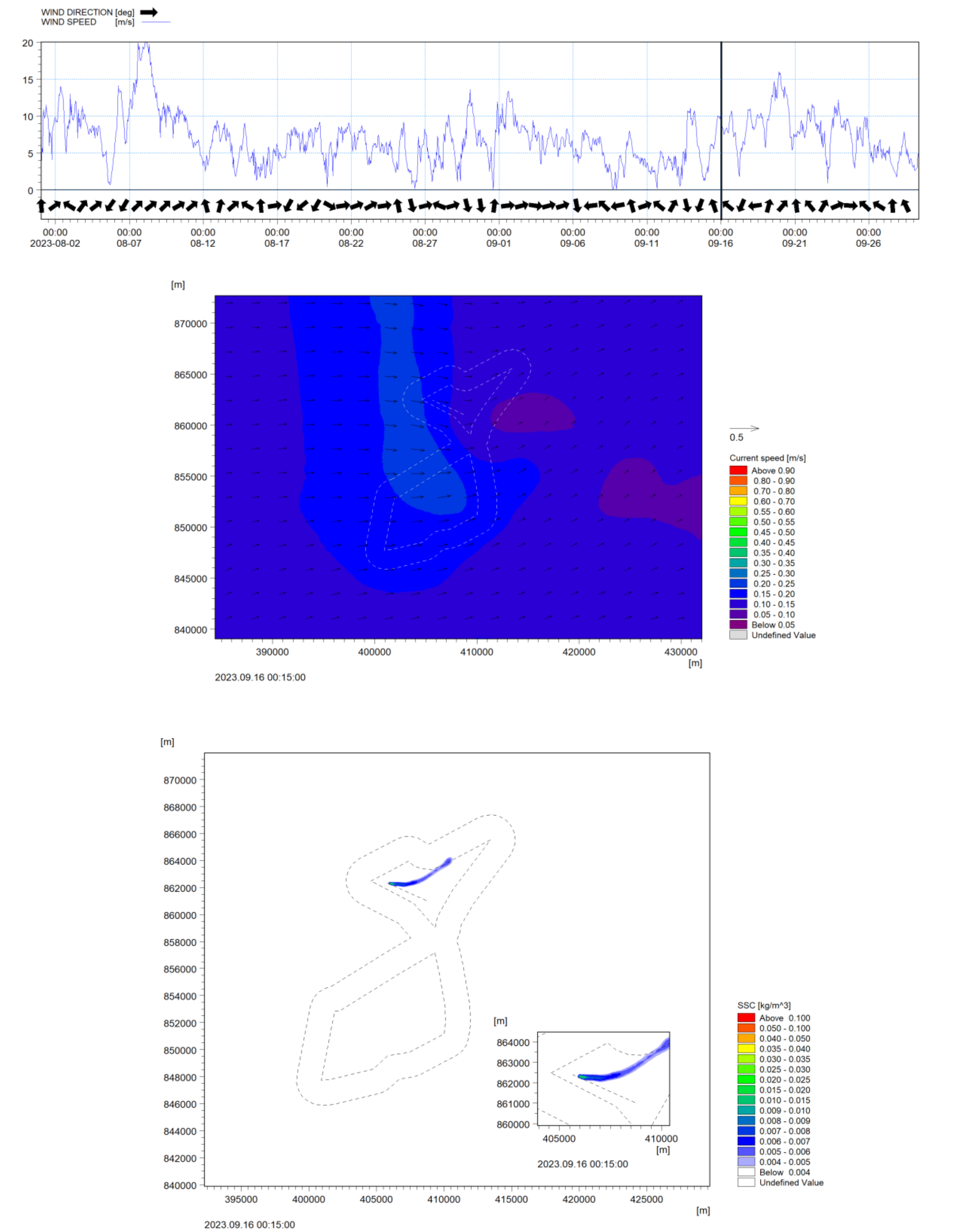


Figure 5.43. The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t1 for the technology of work performance with a ploughing device moving at a speed of 300 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in non-cohesive soil

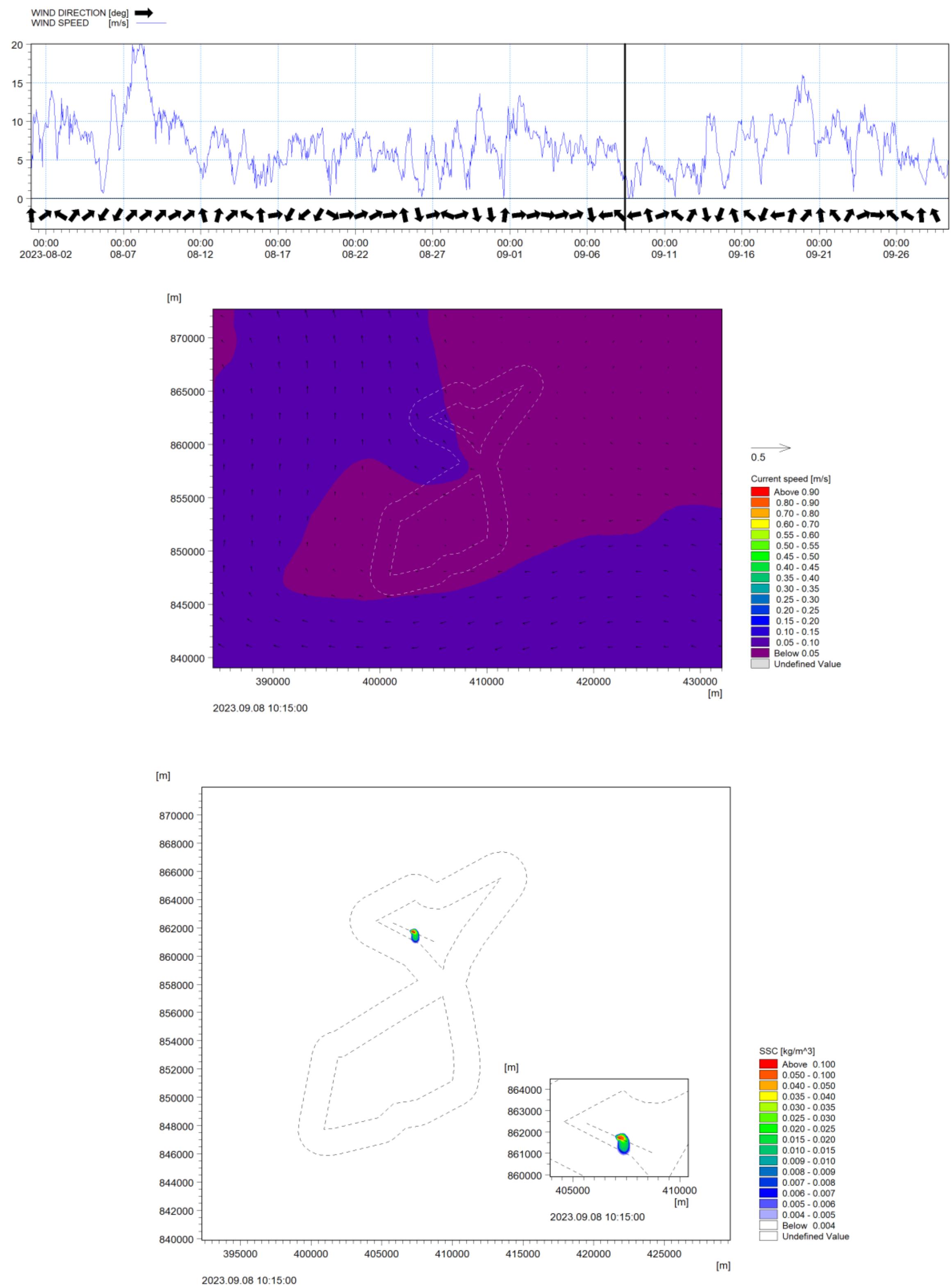


Figure 5.44. *The simulation results for power cable installation works conducted under real hydrodynamic conditions in the time step t2 for the technology of work performance with a ploughing device moving at a speed of 300 m·h^{-1} over the area of the inter-array cable laying in the Baltica-1 OWF field, in non-cohesive soil*

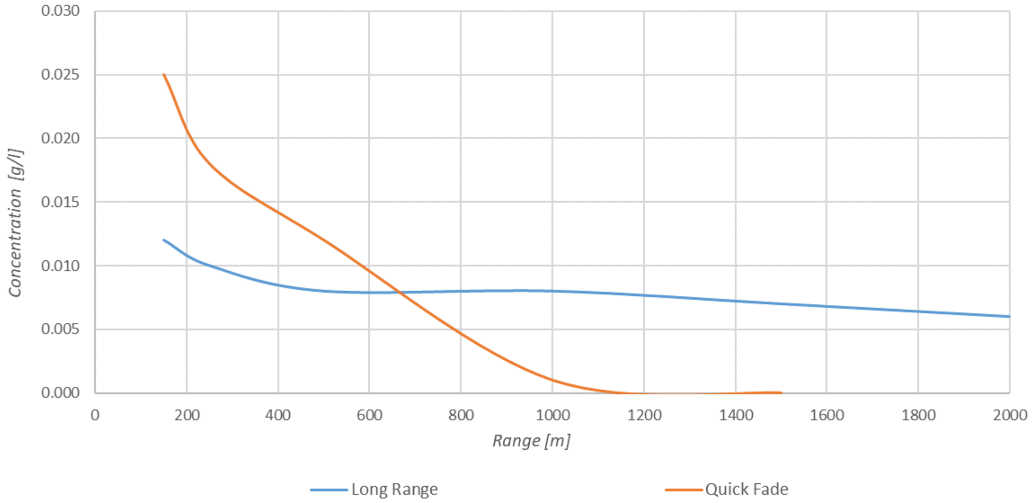


Figure 5.45. *The suspended solids concentration distributions during the power cable installation in the field using the ploughing method with the device moving at a speed of 300 m·h^{-1} in non-cohesive soil*

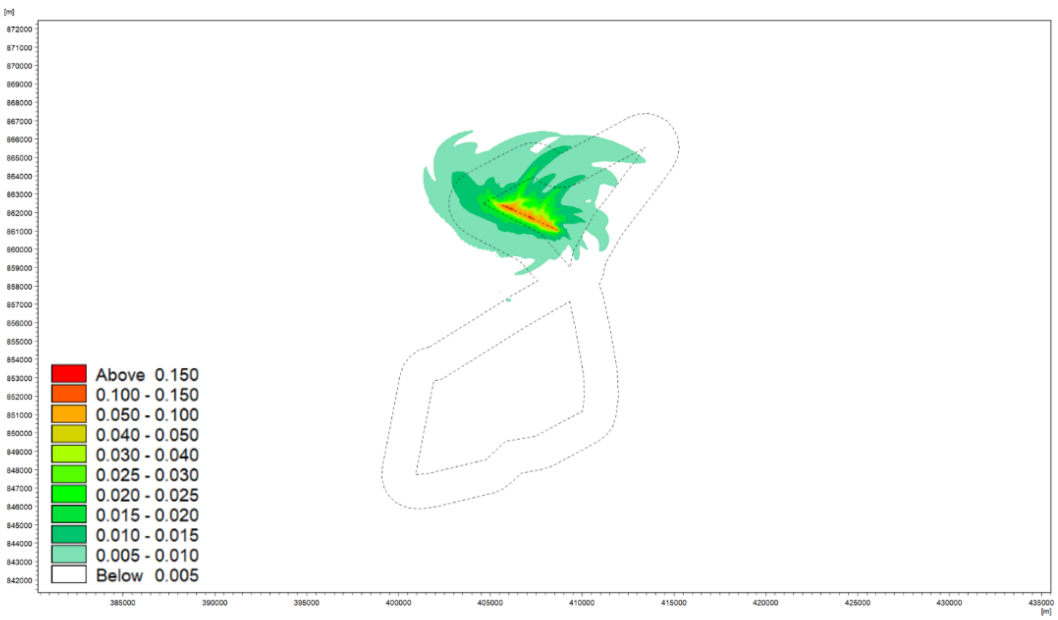


Figure 5.46. *The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle for the technology of work performance using a ploughing device moving at an operational speed of 300 m·h^{-1} in the area of laying the inter-array cable lines in the Baltica-1 OWF field in non-cohesive soil*

Figure 5.47. The sediment layer thickness distribution [m] after the completion of works conducted in the technology of ploughing with a device moving at a speed of 200 m·h^{-1} over the area of the inter-array cable line laying in the Baltica-1 OWF field in non-cohesive soil

5.2.11 Scenario 11. Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in both locations

Two underwater works carried out at the same time in two locations approximately 1 km apart: location one – the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in the area of the Baltica-1 OWF; location two – the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in the area of the Baltica-1 OWF.

At time t1, i.e. at the moment of far-field spread [Figure 5.48], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 13.5 km. The highest concentration value at a distance of 150 m from the worksite is 25 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.49], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.8 km and a cloud with concentrations of over 30 $mg \cdot l^{-1}$ spreads over 0.4 km. The highest concentration value at a distance of 150 m from the worksite is 124 $mg \cdot l^{-1}$.

The figure below [Figure 5.50] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.51] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. In places approx. 150 m from the worksite, instantaneous concentrations reach the level of 270 $mg \cdot l^{-1}$, and at a distance of 500 m, they are up to 139 $mg \cdot l^{-1}$. In a majority of the area where the disturbance appears, the concentration ranges from 6 to 20 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.52] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 5.9 mm.

In this scenario, the retention time of the dispersion cloud with the concentration of 5 $mg \cdot l^{-1}$ is 41 hours from the moment the work is completed. Such an impact of suspended solids is classified as short-term.

In comparison with similar work performed at a given time in only one location, it can be concluded that both the increase in suspended solids concentration and the thickness of the newly formed sediment layer resulting from the work carried out at the neighbouring location is insignificant. This results from the fact that dispersion clouds behave similarly under specific forcing conditions for both locations, i.e. they spread in the same directions and do not move towards each other. Therefore, the increase in suspended solids concentration in the vicinity of the current underwater worksite caused by work at the neighbouring location in the most unfavourable conditions does not exceed 25 $mg \cdot l^{-1}$, and the increase in sediment layer thickness caused by such operations does not exceed 0.5 mm. The next disturbance parameter, i.e. the time the solids remain suspended in the marine environment, if of different character. The dispersion cloud formed as a result of the combination of two neighbouring impacts is strengthened and the time the solids remain suspended in the water at a low concentration of 5 $mg \cdot l^{-1}$ reaches 41 hours for the cumulative impact, which is approximately 70% longer than the time determined for a single installation of a gravity-based structure.

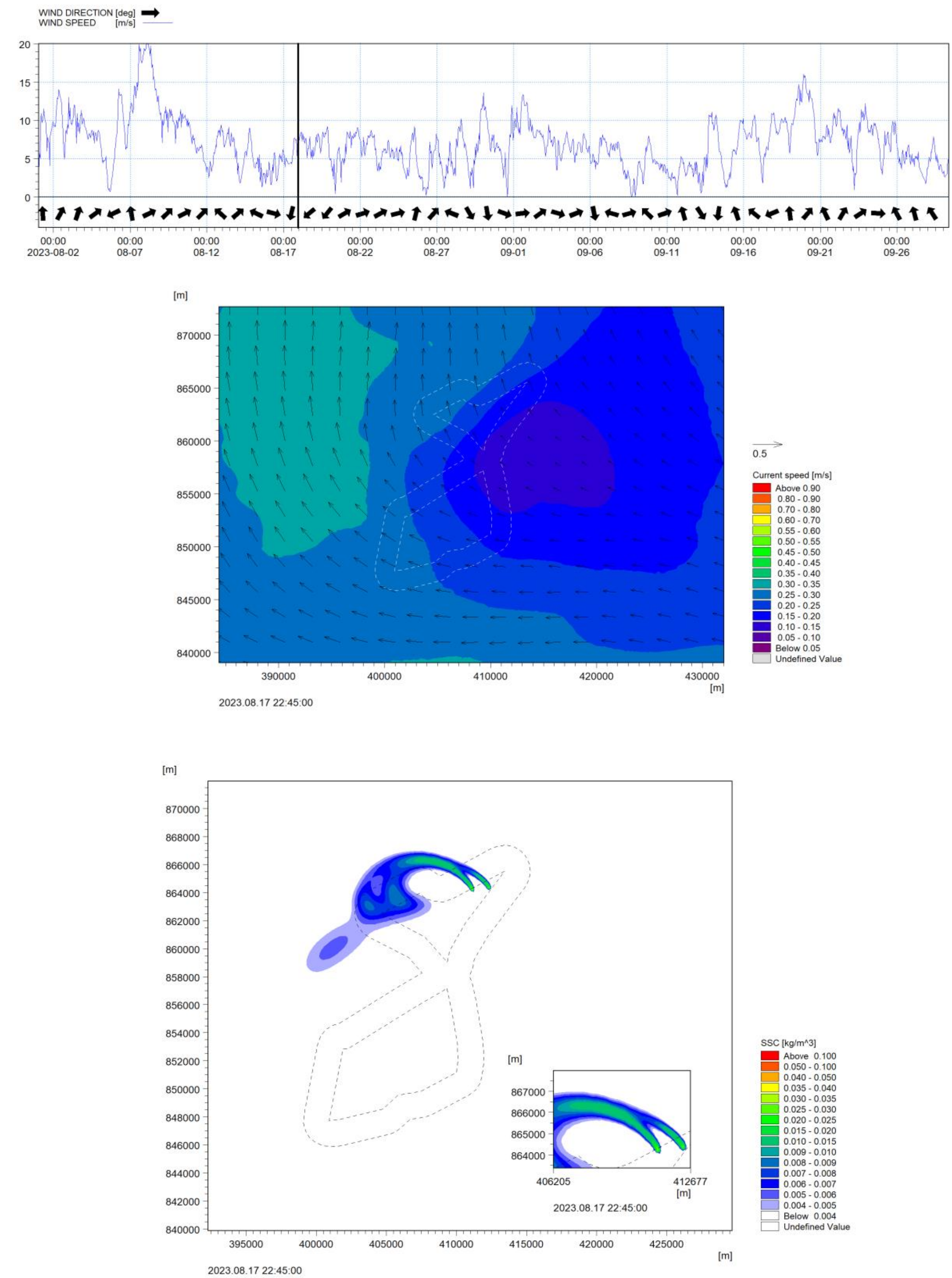


Figure 5.48. The simulation results for the operations related to seabed preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (in cohesive soil), under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

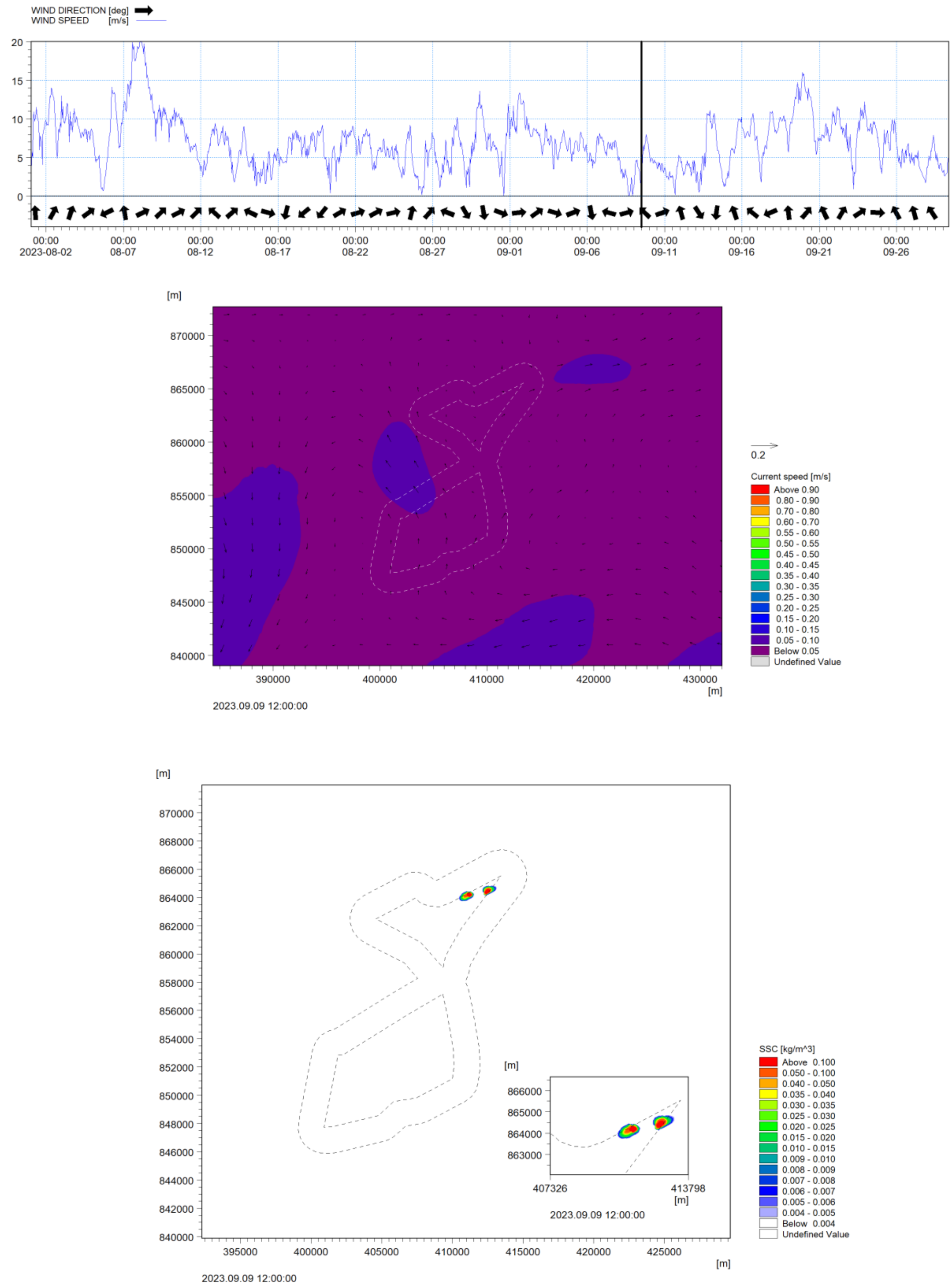


Figure 5.49. *The simulation results for the operations related to seabed preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (in cohesive soil), under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field*

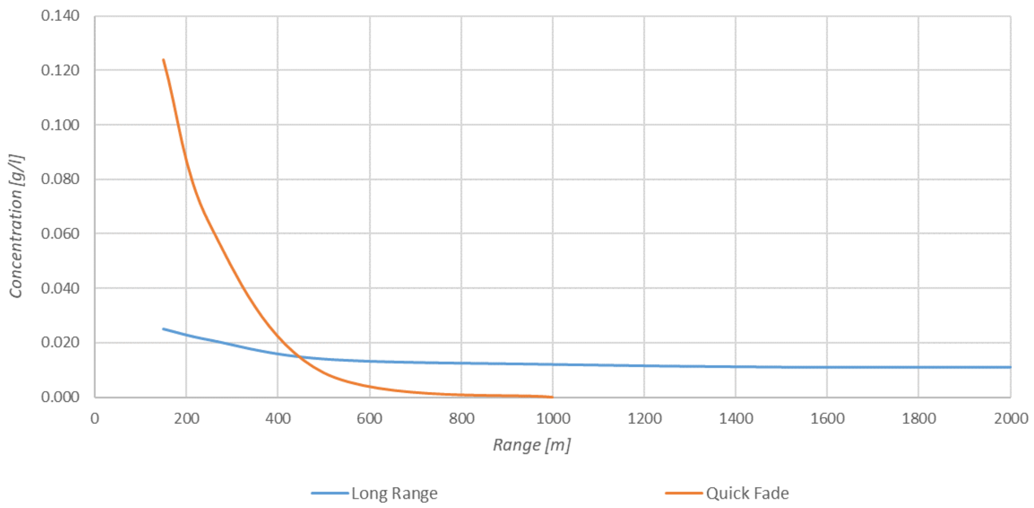


Figure 5.50. The distributions of suspended solids concentration during the preparation of the seabed substrate for the installation of Ø 55 m gravity-based structures in two locations simultaneously (in cohesive soils;), in the Baltica-1 OWF field

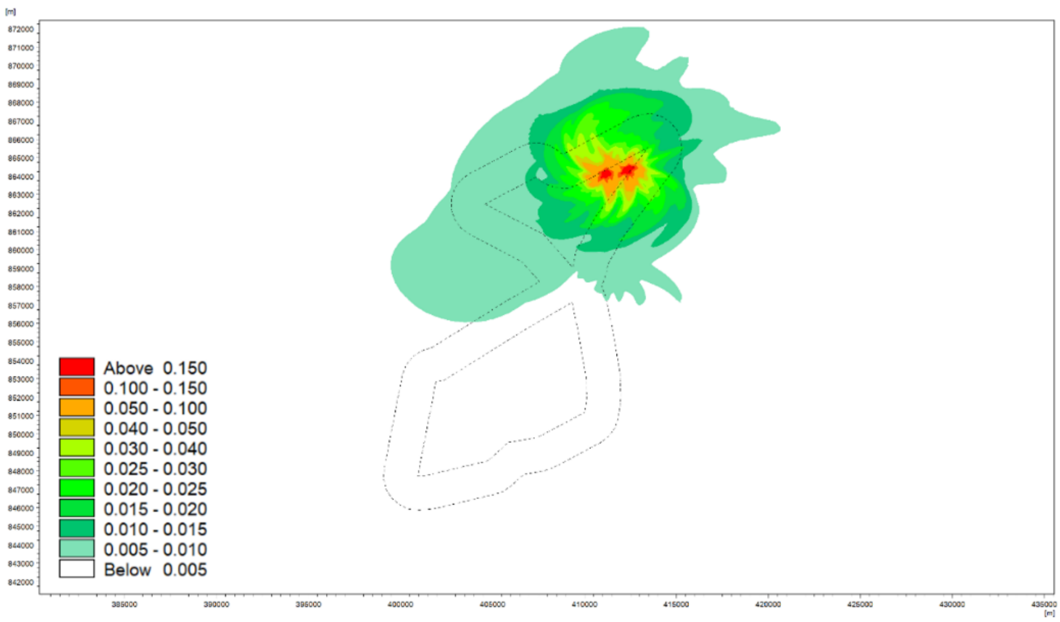


Figure 5.51. The maximum concentration values [$g \cdot l^{-1}$] in the form of an envelope encompassing events from the entire calculation cycle, during the preparation of the substrate for the installation of Ø 55 m gravity-based structures in two locations simultaneously (in cohesive soils), in the Baltica-1 OWF field

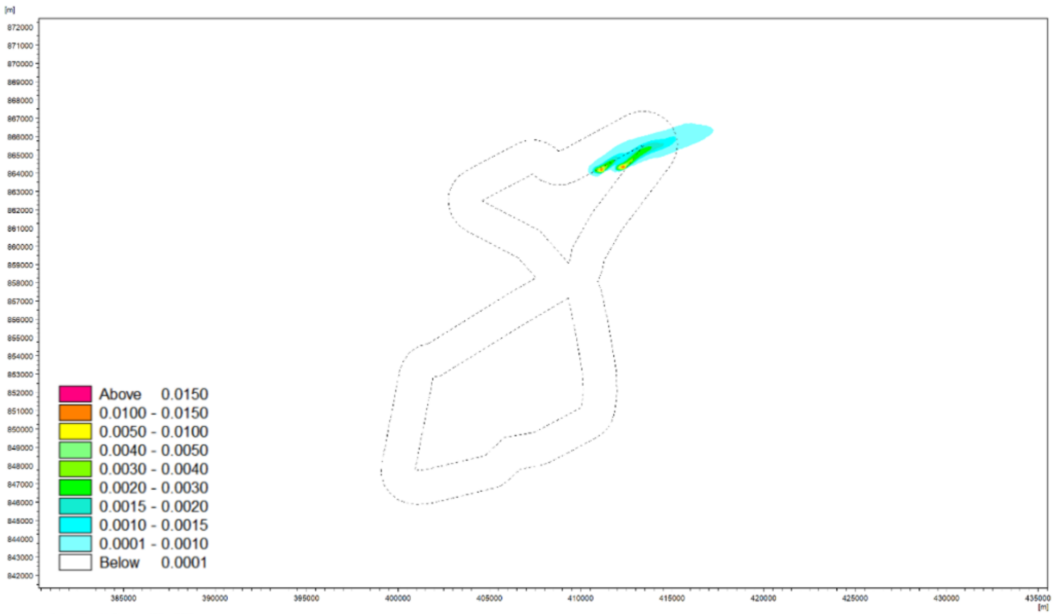


Figure 5.52. The distributions of sediment layer thickness [m] after the completion of the seabed substrate preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (in cohesive soil), in the Baltica-1 OWF field

5.2.12 Scenario 12. Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures with cohesive soil in one location and non-cohesive soil in the second location

Two underwater works carried out at the same time in two locations approximately 1 km apart: location one – the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in the area of the Baltica-1 OWF; location two – the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in the area of the Baltica-1 OWF.

At time t1, i.e. at the moment of far-field spread [Figure 5.53], the dispersion cloud with concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 14.9 km. The highest concentration value at a distance of 150 m from the worksite is 25 $mg \cdot l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.54], the dispersion cloud with solids concentrations exceeding 5 $mg \cdot l^{-1}$ spreads over a distance of approximately 0.5 km, while a cloud with a concentration of over 30 $mg \cdot l^{-1}$ spreads to 0.4 km. The highest concentration value at a distance of 150 m from the worksite is 130 $mg \cdot l^{-1}$. These results were obtained from a cloud with higher maximum concentrations (in this case, from the first location, i.e. the site being prepared for a gravity-based structure to be installed in cohesive soil).

The figure below [Figure 5.55] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The figure below [Figure 5.56] shows a map of the maximum suspended solids concentrations at each point of the assumed computational region in the entire simulation period. Locally, in places approx. 150 m from the worksite, instantaneous concentrations reach the level of 250 $mg \cdot l^{-1}$, and at a distance of 500 m, they are up to 98 $mg \cdot l^{-1}$. In a majority of the area where the disturbance appears, the concentration ranges from 6 to 20 $mg \cdot l^{-1}$.

The subsequent figure [Figure 5.57] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 5.7 mm.

In this scenario, the retention time of the dispersion cloud with the concentration of 5 $mg \cdot l^{-1}$ is 40 hours from the moment the work is completed. The impact of suspended solids is short-term.

The obtained results are similar to the values from the previous scenario. The increase in the concentration of suspended solids and the thickness of the newly formed sediment layer resulting from the work carried out simultaneously in the neighbouring location is insignificant. The concentration in the dispersion cloud at a distance of approx. 1 km from the location of works carried out in the least favourable conditions can reach 20 $mg \cdot l^{-1}$ and such an increase in suspended solids concentration can be expected in the neighbouring location as a result of the cumulative impacts. The increase in the thickness of sediments resulting from the cumulative impact is negligible. On the other hand, the time the solids remain suspended in the marine environment has been extended, just as in scenario 11. The dispersion cloud formed as a result of the combination of two neighbouring impacts is strengthened and for the cumulative impact, the time the solids remain suspended in the water with a low concentration of 5 mg·l^{-1} reaches 40 hours, so in comparison with the time determined for a single installation of a gravity-based structure in cohesive soil, it is extended by approx. 70%.

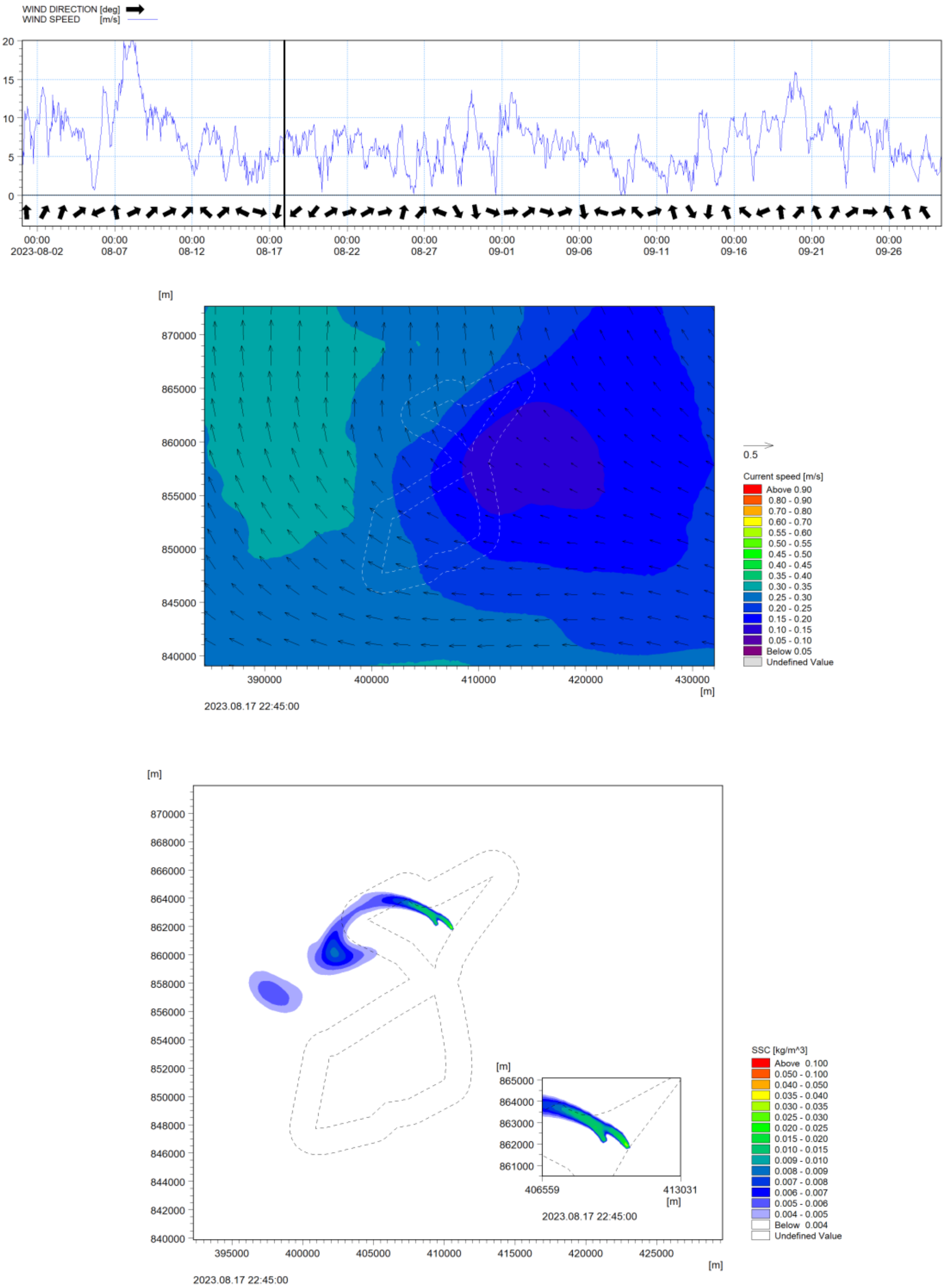


Figure 5.53. The simulation results for the operations related to seabed preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (with cohesive soil in one location and non-cohesive soil in the second), under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

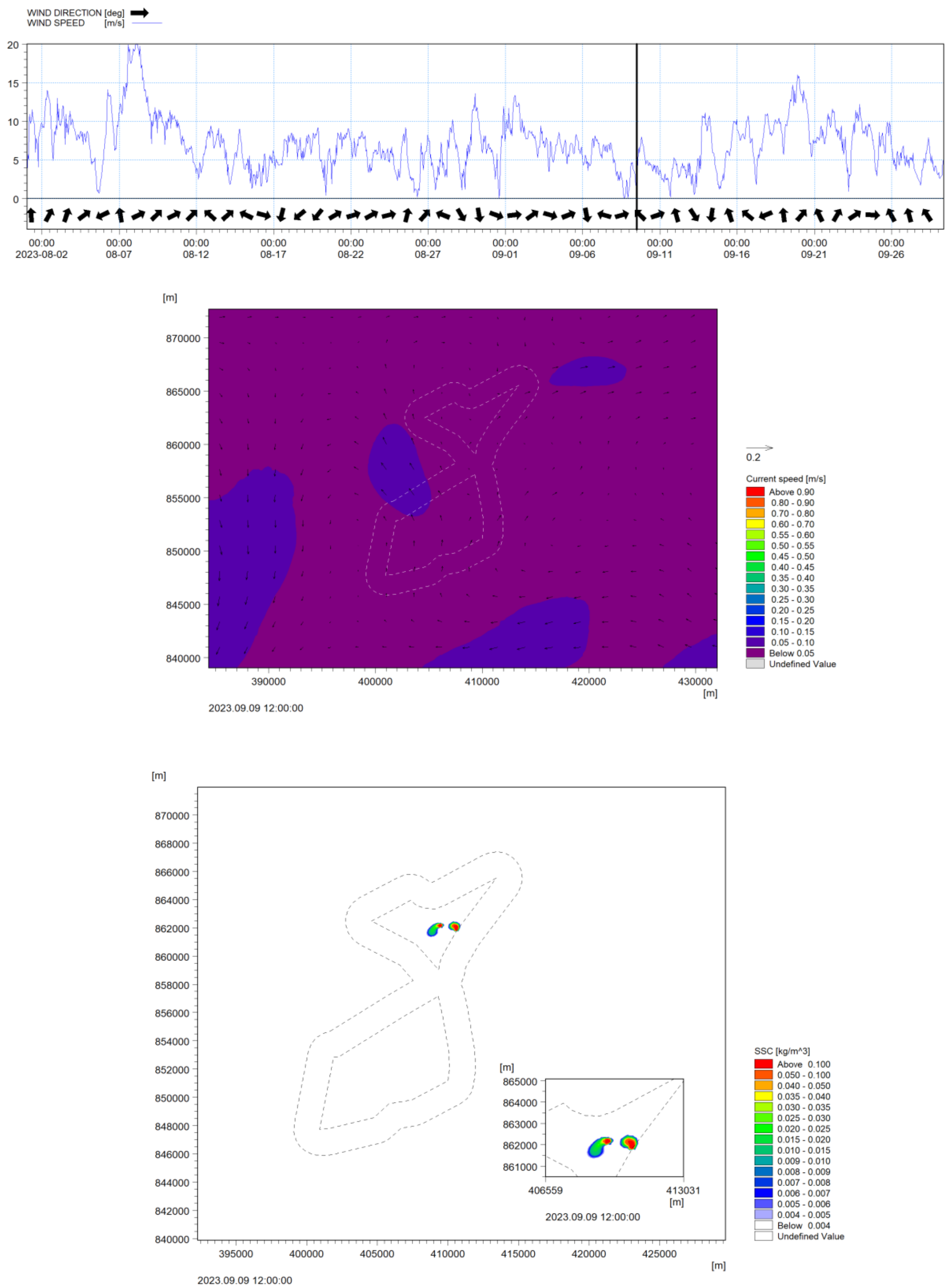


Figure 5.54. The simulation results for the operations related to seabed preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (with cohesive soil in one location and non-cohesive soil in the second), under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

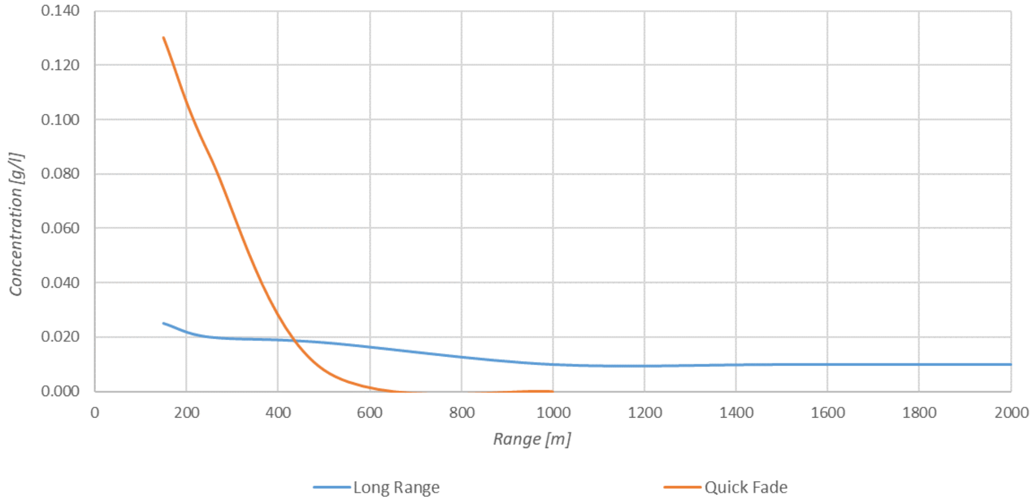


Figure 5.55. The distributions of suspended solids concentration during the preparation of the seabed substrate for the installation of Ø 55 m gravity-based structures in two locations simultaneously (with cohesive soil in one location and non-cohesive soil in the second), in the Baltica-1 OWF field

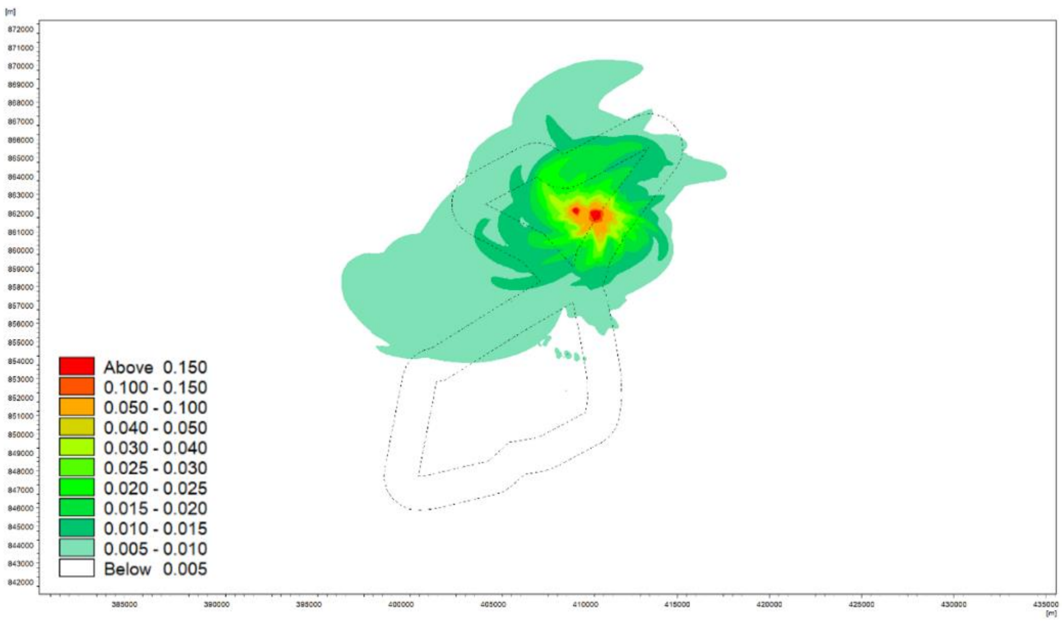


Figure 5.56. The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the preparation of the substrate for the installation of Ø 55 m gravity-based structures in two locations simultaneously (with cohesive soil in one location and non-cohesive soil in the second), in the Baltica-1 OWF field

Figure 5.57. The distributions of sediment layer thickness [m] after the completion of the seabed substrate preparation for the installation of Ø 55 m gravity-based structures in two locations simultaneously (with cohesive soil in one location and non-cohesive soil in the second), in the Baltica-1 OWF field

5.2.13 Scenario 13. Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil and cable embedment using the jetting method at a speed of 200 m·h^{-1} in cohesive soil

Two underwater works carried out at the same time: location one – the seabed substrate preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil in the area of the Baltica-1 OWF; location two – cable embedment along a selected section of the export cable in the area of the Baltica-1 OWF using the method of jetting at a speed of 200 m·h^{-1} in cohesive soil.

At time t1, i.e. at the moment of far-field spread [Figure 5.58], the dispersion cloud with concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 9 km. The highest concentration value at a distance of 150 m from the worksite is 34 mg·l^{-1}.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.59], a dispersion cloud with solids concentrations exceeding 5 mg·l^{-1} spreads over a distance of approximately 0.5 km, while a cloud with a concentration of over 30 mg·l^{-1} spreads to 0.4 km. The highest concentration value at a distance of 150 m from the worksite is 130 mg·l^{-1}. The results presented above were obtained for a cloud with higher maximum concentrations (in this case, from the first location– the site being prepared for a gravity-based structure to be installed in cohesive soil).

The figure below [Figure 5.60] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in the largest area of the dispersion cloud, the concentrations are low.

The next figure [Figure 5.61] presents a map of the maximum suspended solids concentrations at each point of the assumed calculation area in the entire simulation period. Locally, in places approx. 150 m from the worksite, instantaneous concentrations reach the level of 250 mg·l^{-1}, and at a distance of 500 m, they are up to 99 mg·l^{-1}. In a majority of the area where the disturbance appears, the concentration ranges from 6 to 20 mg·l^{-1}.

The subsequent figure [Figure 5.62] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed after the works are completed (in a range of the assumed 150 m from the worksite) is up to 5.7 mm.

According to the remarks presented in Chapter 4, this scenario involved the highest probability of cumulative impacts. Indeed, the dispersion clouds caused by works of both types may combine, which slightly strengthens the impact. The calculated time of solids remaining suspended in the water with a concentration exceeding 5 mg·l^{-1} is up to 31 hours.

The increase in the concentration of suspended solids and the thickness of the newly formed sediment layer resulting from the operations carried out in the neighbouring location is negligibly small. The works carried out in this scenario differ in that the first one is quasi-stationary (the preparation of the seabed for the foundation installation), and the second one is represented by a "moving source of suspended solids", hence both worksites are located in the immediate vicinity for only a short time. Dispersion clouds resulting from two different underwater works may, under certain forcing conditions, combine, causing amplification of the cumulated cloud, which will extend the maximum span of the suspended solids with a residual concentration of 5 mg·l^{-1} to 31 hours, i.e. by approx. 30% in relation to the disturbance caused only by the foundation works.

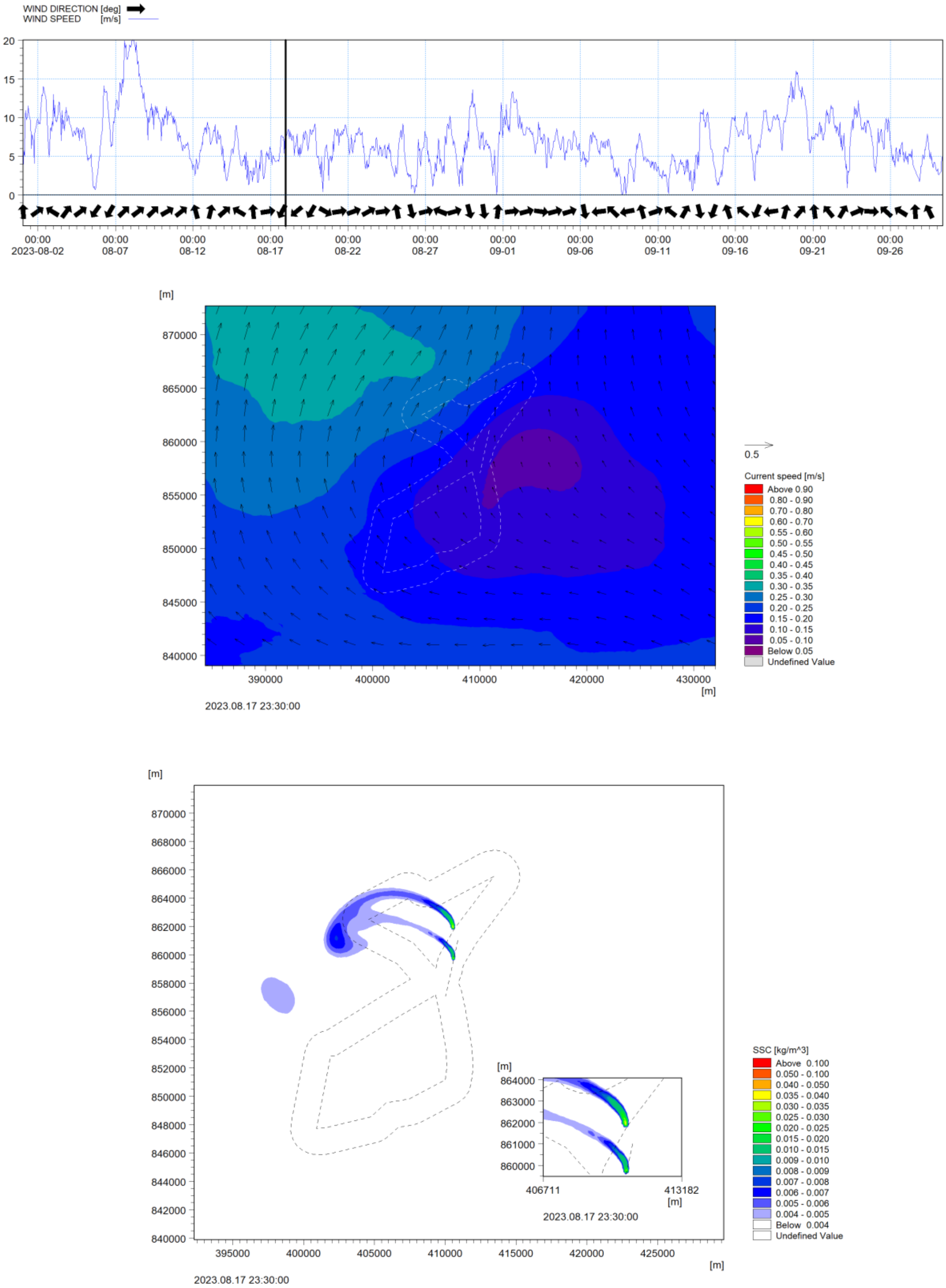


Figure 5.58. The simulation results for operations conducted at the same time: the seabed substrate preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil in one location and export cable embedding with the use of the jetting method at a speed of 200 m·h^{-1} in cohesive soil, under real hydrodynamic conditions, at time step t1, in the Baltica-1 OWF field

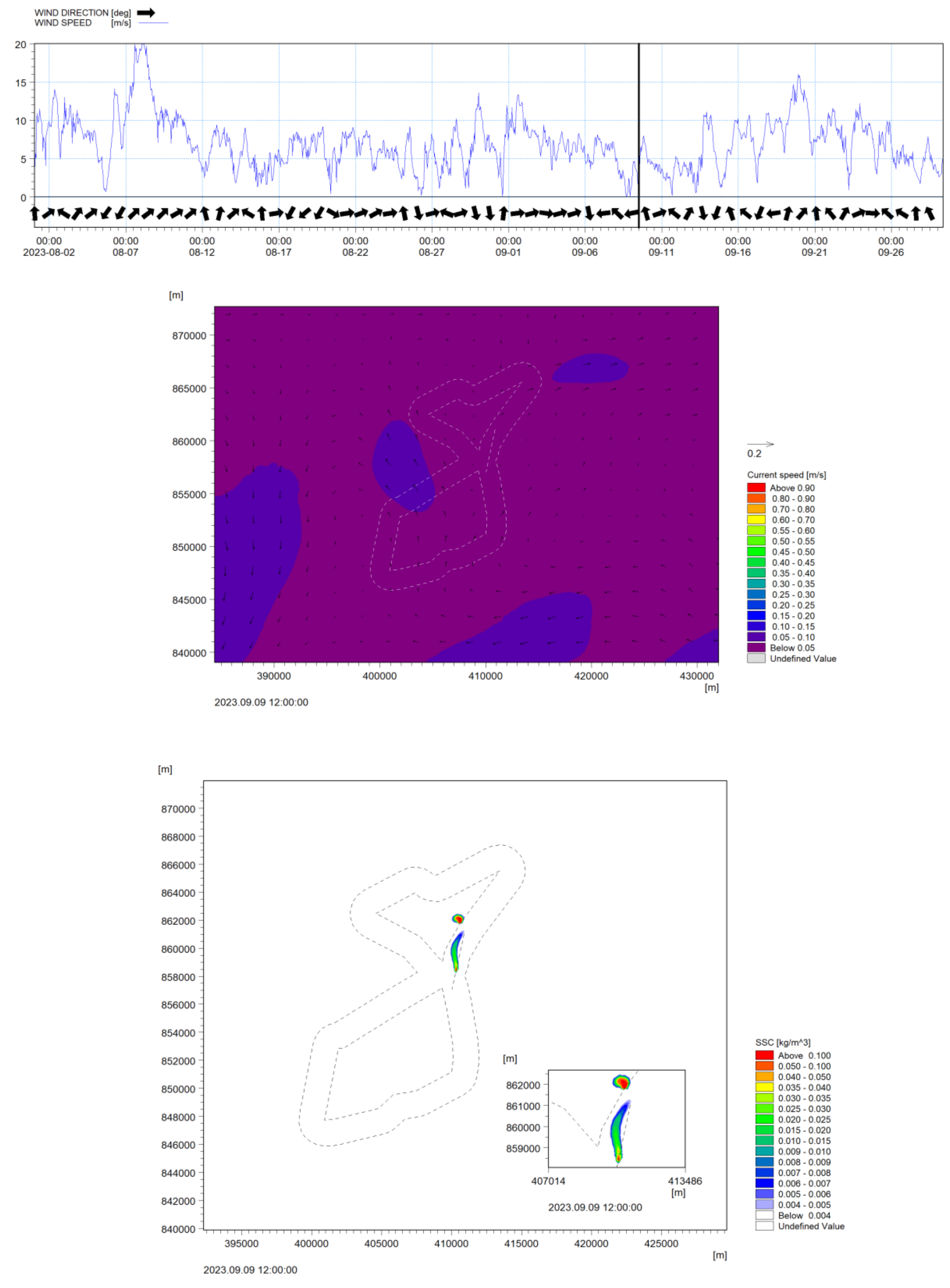


Figure 5.59. The simulation results for operations conducted at the same time: the seabed substrate preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil in one location and export cable embedding with the use of the jetting method at a speed of 200 m·h^{-1} in cohesive soil, under real hydrodynamic conditions, at time step t2, in the Baltica-1 OWF field

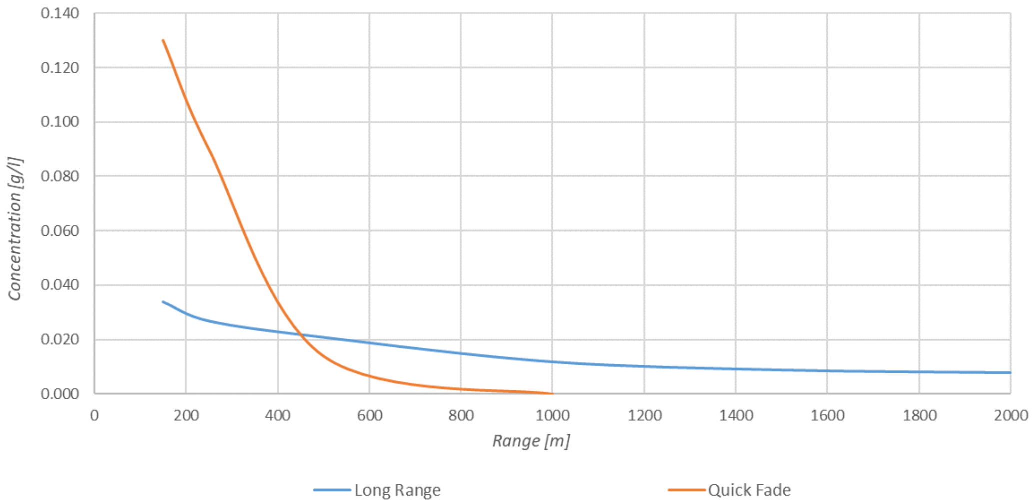


Figure 5.60. *The distributions of suspended solids concentration during the performance of two simultaneous underwater works: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in one location and export cable embedment using the jetting method at a speed of 200 m·h^{-1} in cohesive soil in the second location*

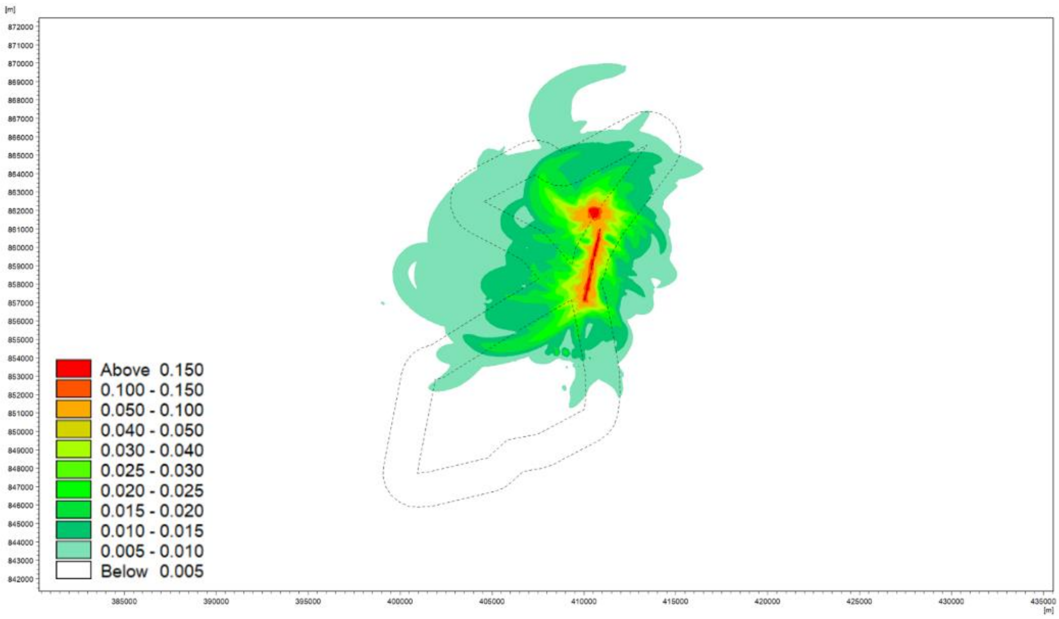


Figure 5.61. *The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the performance of two simultaneous underwater works: the preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil in one location and export cable embedment using the jetting method at a speed of 200 m·h^{-1} in cohesive soil in the second location, in the Baltica-1 OWF field*

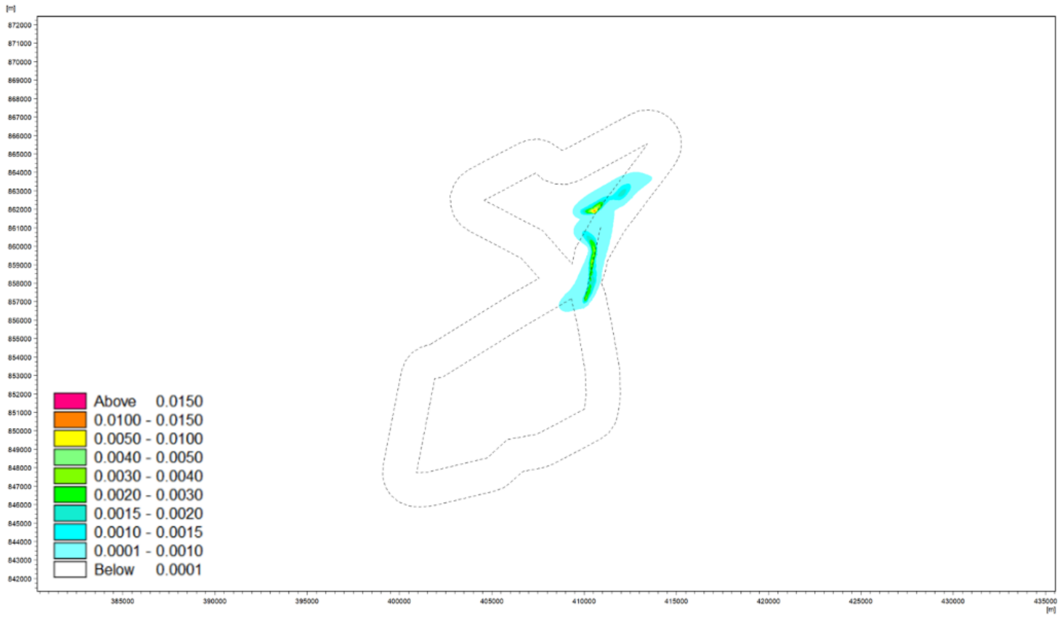


Figure 5.62. The distribution of sediment layer thickness [m] after the completion of two simultaneous operations: the seabed substrate preparation for the installation of a Ø 55 m gravity-based structure in cohesive soil in one location and export cable embedding with the use of the jetting method at a speed of 200 m·h^{-1} in cohesive soil in the second location, in the Baltica-1 OWF field

5.2.14 Scenario 14. Two underwater works carried out at the same time: the replacement of weak soil under the vessel spud cans together with the discharge of the dredged soil in the area of the wind farm

Two underwater works carried out at the same time and at a small distance (of the order of several hundred meters) from each other: location one – soil collection site – dredging works related to the replacement of soil with low bearing capacity for four vessel spuds in the area of the Baltica-1 OWF using a CSD; location two – discharge site – the discharge of soil pulp at a distance of no less than 350 m from the edge of the excavation via a suction pipe, i.e. a pipeline used to transport the dredged material. The scenario for works related to soil reinforcement at the locations of the vessel spuds refers to the most unfavourable case for the environment, i.e. when the maximum assumed volume of soil for each support of the installation vessel is replaced and the works are carried out in weak cohesive soils (in the case of non-cohesive soils, replacement is not planned – soil reinforcement will consist of making a bed of crushed stone on the native soil). It is assumed that excavations could be carried out using trailing suction hopper dredgers (TSHDs), where the dredged material goes into the dredger's own hold and is then transported to a designated dumping site, where it is unloaded (with no local unloading in the wind farm area involved). However, excavations carried out for the spud cans of a jack-up installation vessel have smaller cubic capacities than excavations made for gravity-based structures of wind turbine generators. Therefore, assuming the dredged material is deposited outside the farm area, the interference with the environment during the performance of this work will be smaller than during the work related to the preparation of the substrate for gravity-based structures. Due to the fact that this impact is smaller (because the excavation itself is smaller), calculations were not repeated for this type of work. The use of a cutter suction dredger (CSD) with local deposition of the dredged material is the farthest-reaching scenario in terms of the impact of suspended solids on the marine environment.

At time t1, i.e. at the moment of far-field spread [Figure 5.63], the dispersion cloud with concentrations exceeding 5 $mg{\cdot}l^{-1}$ spreads over a distance of approximately 12 km. The highest concentration value at a distance of 150 m from the worksite is 92 $mg{\cdot}l^{-1}$.

At time t2, i.e. at the moment of high concentration occurrence [Figure 5.64], a dispersion cloud with solids concentrations exceeding 5 $mg{\cdot}l^{-1}$ spreads over a distance of approximately 3.5 km, while a cloud with a concentration of over 30 $mg{\cdot}l^{-1}$ spreads to 3 km. The highest concentration value at a distance of 150 m from the worksite is 260 $mg{\cdot}l^{-1}$.

The figure below [Figure 5.65] shows situations illustrating the results of single instantaneous steps of computational simulation (t1, t2), indicating that where the gradient of suspended solids concentration fall is high, the disturbance is only local, while in the case of the longest ranges of trace suspended solids concentrations in a major part of dispersion cloud, the concentrations are lower and they do not exceed the level of 30 $mg{\cdot}l^{-1}$.

The next figure [Figure 5.66] presents a map of the maximum suspended solids concentrations at each point of the assumed calculation area in the entire simulation period. The instantaneous point concentrations are high and locally, approx. 150 m from the worksite, they reach the level of 1500 $mg{\cdot}l^{-1}$, and at a distance of 500 m, they are up to 850 $mg{\cdot}l^{-1}$. In the majority of the area where disturbance appears, the concentration ranges from 10 to 60 $mg{\cdot}l^{-1}$. These high concentrations require additional explanations. The analysed scenario involving two activities causing the agitation of suspended solids was assessed *a priori* as the least environmentally friendly, especially the second operation – the disposal of dredger material using a dredger with a suction pipe. The dredged cohesive soil transported by the suction pipeline becomes highly liquefied and a significantly larger percentage of its volume passes into the state of suspension during its discharge/deposition. In comparison with other activities analysed in this study, the percentage of solids becoming suspended is from several to a dozen times higher. In addition, the use of a numerical tool determining the maximum concentration at each calculation point means that point concentrations may differ to a greater extent from the instantaneous concentrations (for time t2 of reaching the highest concentrations in the simulation) determined for the areas. This difference will increase both in the case of a less dense numerical grid and in the case of higher concentrations.

The subsequent figure [Figure 5.67] shows a map of the thickness distribution of the sediment layer formed in the course of sedimentation after the simulation of seabed intervention works is completed. The maximum thickness of the new sediment layer formed by re-sedimenting suspended solids after the works are completed (in a range of the assumed 150 m from the worksite) is up to 12 mm.

According to the remarks presented in Chapter 4, this scenario involved the highest probability of cumulative impacts. Indeed, the dispersion clouds caused by works of both types may combine, which slightly strengthens the impact (with the discharge/deposition of dredged material as the dominant factor). The calculated time of solids remaining suspended with a concentration exceeding 5 $mg \cdot l^{-1}$ is up to 72 hours.

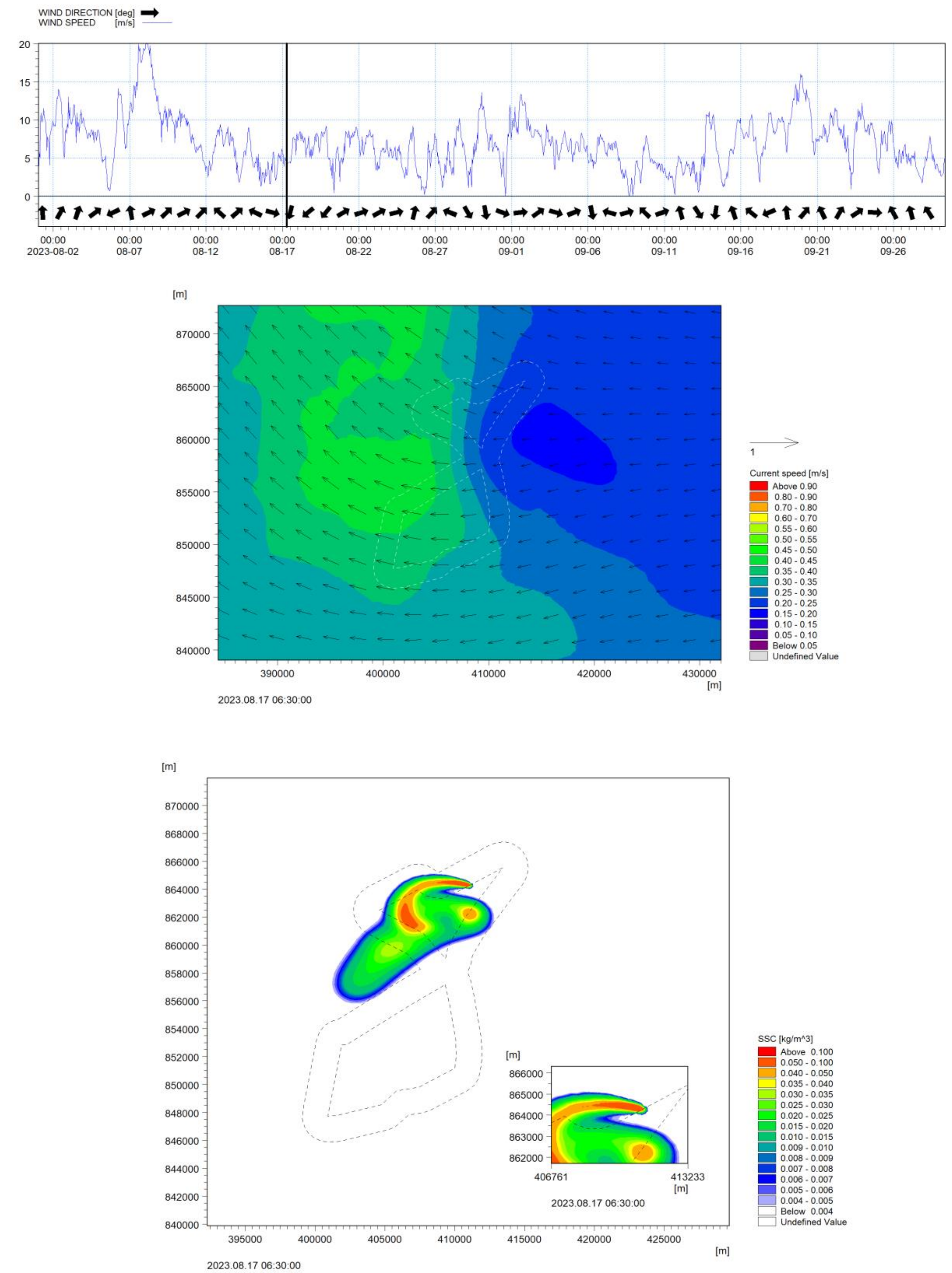


Figure 5.63. The simulation results for two simultaneous works (the dredging of the seabed substrate for the vessel spud cans), under real hydrodynamic conditions, at time step t1 (far-spread), in the Baltica-1 OWF field

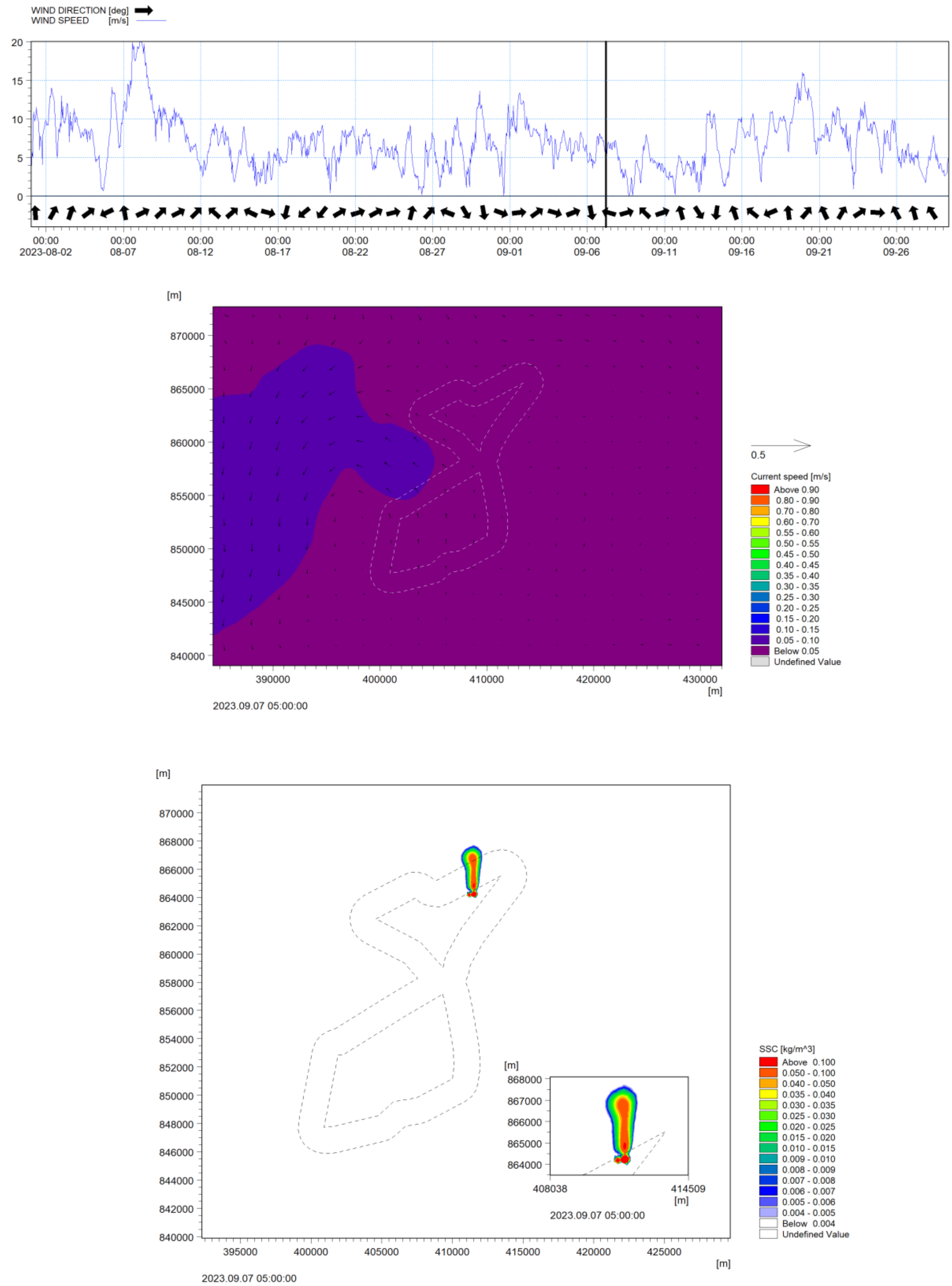


Figure 5.64. The simulation results for two simultaneous works (the dredging of the seabed substrate for the vessel spud cans) under real hydrodynamic conditions, at time step t2 (high concentration), in the Baltica-1 OWF field

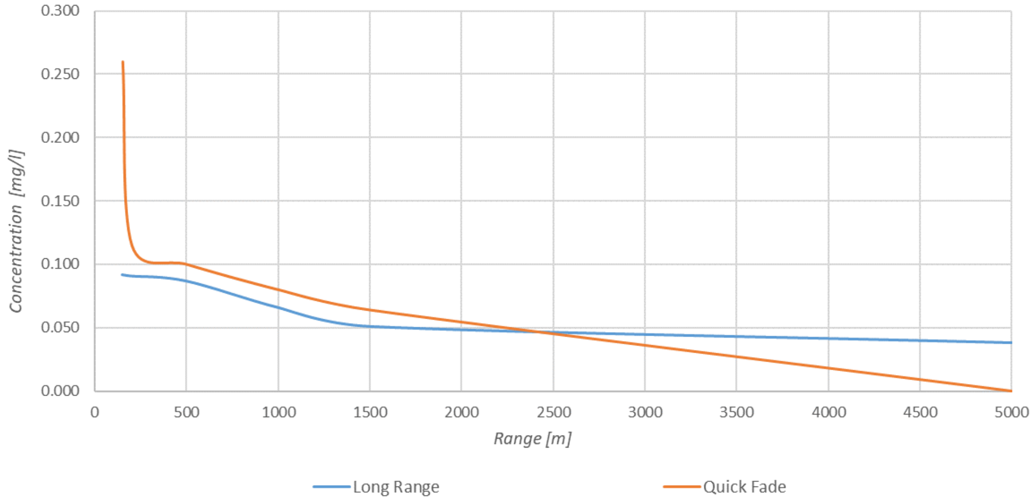


Figure 5.65. *The concentration distribution of suspended solids during the performance of two simultaneous works (the dredging of the seabed substrate for the vessel spud cans)*

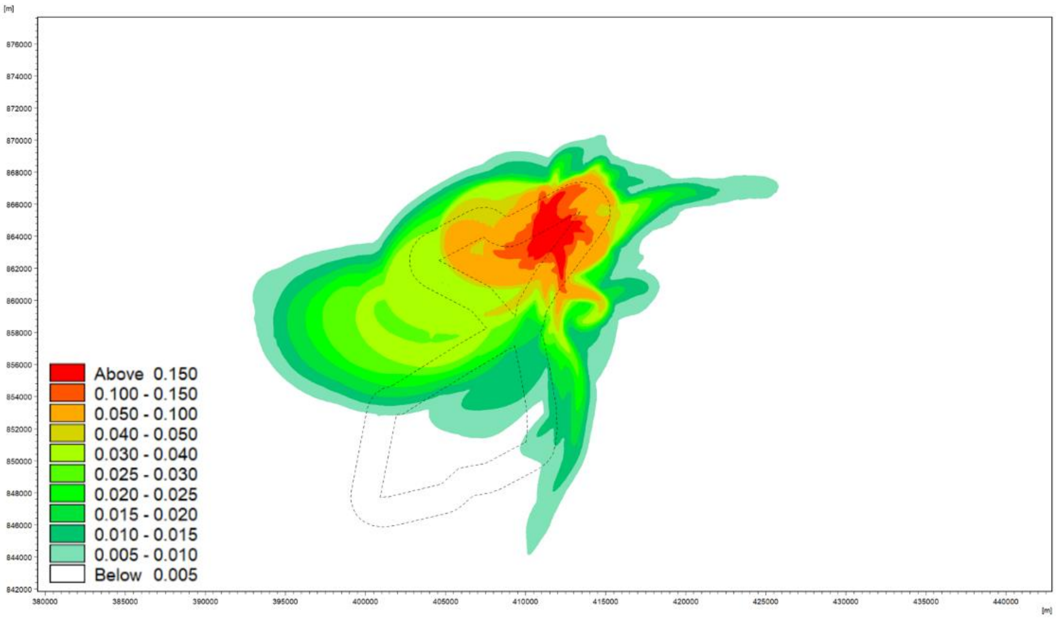


Figure 5.66. *The maximum concentration values [g·l^{-1}] in the form of an envelope encompassing events from the entire calculation cycle, during the performance of two simultaneous works (the dredging of the seabed substrate for the vessel spud cans) in the Baltica-1 OWF field*

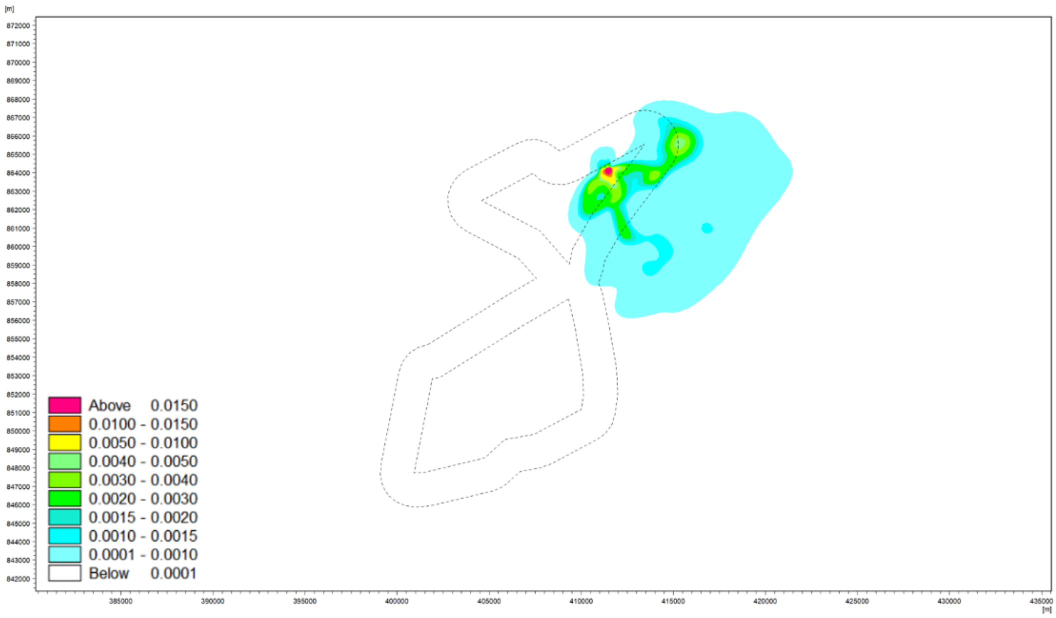


Figure 5.67. The sediment layer thickness distribution [m] after the completion of two simultaneous works (the dredging of the seabed substrate for the vessel spud cans) in the Baltica-1 OWF field

5.3 The analysis of the potential cumulation of suspended solid impacts

The cumulated impacts of suspended solids can occur when various underwater works responsible for the emission of suspended solids are conducted close to each other, creating specific sequences of events. These sequences cover relatively short periods when certain types of work are performed simultaneously or directly one after another. The potential cumulation of the impact of suspended solids disturbed by works carried out simultaneously on various investment projects includes:

- works related to the extraction of aggregates on the neighbouring concession carried out simultaneously with work carried out within the Baltica-1 OWF;
- works on the neighbouring Bałtyk I wind farm carried out simultaneously with construction work on the Baltica-1 OWF area.

In the first of the cases considered, it should be taken into account that the seabed in the concession area consists of non-cohesive soils (sands, gravels) used for construction purposes, i.e. soils that release significantly smaller amounts of suspended solids during dredging work than cohesive soils. Works carried out in the concession area are limited to the extraction of aggregates and loading them into the holds of vessels transporting the material to the unloading sites. In connection with the above, it is estimated that the emission of suspended solids from this area will be very low. In turn, the area of the Baltica-1 OWF adjacent to the extraction concession area, in particular, the western strip of the northern sub-area and the entire southern sub-area, is also covered with sandy sediments. In such soils, the works responsible for generating the largest amount of suspended solids (preparing the ground for the installation of gravity-based structures), in compliance with the calculations made for the least favourable meteorological and hydrodynamic conditions, may generate a cloud of suspended solids that will be characterised by a concentration of approximately 10 $mg \cdot l^{-1}$ at a distance of approx. 400 m from the worksite performed and 5 $mg \cdot l^{-1}$ at a distance of 5 km. In connection with the above, the cumulation of suspended solids impacts from the analysed works in the case of their simultaneous performance cannot be ruled out, however, this impact can be described as very small and due to the nature of the works carried out on the offshore wind farm, also short-term.

In the second case considered, the impact of suspended solids agitated by construction works at the Bałtyk I offshore wind farm may potentially be amplified (cumulated) with the impact of suspended solids generated during works on the Baltica-1 OWF. Of course, it should be emphasised that the directions of the spread of both dispersion clouds resulting from the impact of the wind will be similar and will not be directed towards each other. The boundary of the Bałtyk I OWF area is located approx. 950 m from the boundary of the Baltica-1 OWF area (the southern subarea), while, notably, the boundaries of development areas of both of these farms are located approx. 2 km away. In both analysed areas, sands are deposited on the seabed, generating low parameters of disturbance to the marine environment with suspended solids. The results of calculations carried out for underwater works performed in sandy soils indicated that dispersion clouds at distances of 2 km from the worksites can reach very low concentrations, approximately 5 $mg \cdot l^{-1}$, and consequently be responsible for the sedimentation of suspended solids into a layer with a thickness equal fractions of millimetres. To sum up, in the case under consideration, the impacts will probably coexist (accumulate) in a specific area, but this effect should be estimated as very small, practically negligible.

6 SUMMARY AND CONCLUSIONS

The calculations conducted were intended to determine the parameters of the impact on the marine environment of suspended solids generated by the anthropogenic activity related to the construction of the Baltica-1 OWF. Using numerical simulations, the parameters of the disturbance to the marine environment with suspended solids agitated by works related to the setting of WTG foundations and the laying and embedding of power cables in the seabed of the offshore wind farm area were analysed. The presented results illustrate the dispersion of suspended solids, their concentration in the water depth and sedimentation on the seabed. The analysis included both works related to preparing the seabed for the installation of gravity-based structures and methods much less invasive in terms of suspended solids agitation related to the foundation of support structures with the use of piles (monopiles and jack-ups). The work related to cable-laying, which includes stone and boulder clearance along the cable routes, as well as the actual embedding of cables into the seabed, causes the smallest soil fractions to become suspended in the water column, creating dispersion clouds. Numerical simulations were also carried out for these works to determine the parameters of disturbance to the marine environment.

The main impact parameters include the concentration of suspended solids which may be formed in the marine environment and their impact ranges and durations, as well as the thickness of sediments that are generated in the suspended solids sedimentation phase.

For all the numerical simulations conducted, the calculated parameters of environmental disturbance have been presented in the form of tables. The following table [Table 6.1] presents the concentration ranges of suspended solids during underwater works.

Table 6.1. The maximum concentration ranges for all considered underwater works based on the analysis of instantaneous events in the area of the offshore wind farm

Method	Concentration range [km]				
	Duration	**5 mg·l^{-1}**	**10 mg·l^{-1}**	**30 mg·l^{-1}**	**100 mg·l^{-1}**
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil	t_1	8.20	2.00	0.16	-
	t_2	0.50	0.45	0.40	0.20
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil	t_1	5.00	0.36	-	-
	t_2	0.46	0.41	0.29	0.11
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil	t_1	6.40	0.40	-	-
	t_2	0.48	0.42	0.30	0.15
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil	t_1	3.15	0.06	-	-
	t_2	0.44	0.40	0.27	0.04
Driving a Ø 12 m pile into the seabed consisting of cohesive soil	$t_1 = t_2$	0.1	-	-	-
Boulder clearance (300 m·h^{-1})	t_1	5.80	0.60	-	-

Method	**Concentration range [km]**				
	Duration	**5 mg·l^{-1}**	**10 mg·l^{-1}**	**30 mg·l^{-1}**	**100 mg·l^{-1}**
	t_2	0.65	0.46	0.14	0.05
Cable embedment using the jetting method, 200 m·h^{-1}, in cohesive soil	t_1	6.80	0.90	-	-
	t_2	0.81	0.73	0.59	0.11
Cable embedment using the jetting method, 200 m·h^{-1}, in non-cohesive soil	t_1	2.70	0.45	-	-
	t_2	0.68	0.36	0.14	-
Cable embedment using the ploughing method, 300 m·h^{-1}, in cohesive soil	t_1	6.40	0.70	-	-
	t_2	0.80	0.60	0.21	0.09
Cable embedment using the ploughing method, 300 m·h^{-1}, in non-cohesive soil	t_1	4.60	0.35	-	-
	t_2	0.78	0.58	0.15	-
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures in cohesive soil in both locations	t_1	13.50	6.20	0.10	-
	t_2	0.80	0.65	0.40	0.30
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures with cohesive soil in one location and non-cohesive soil in the second location	t_1	13.4	3.00	0.10	-
	t_2	0.50	0.45	0.40	0.20
Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil and cable embedment using the jetting method at a speed of 200 m·h^{-1} in cohesive soil	t_1	8.80	1.60	0.20	-
	t_2	0.50	0.45	0.40	0.20
Dredging works in the place intended for the resting of the vessel spud cans and deposition of material via a pipeline within the OWF area	t_1	12.0	11.5	8.1	-
	t_2	3.5	3.3	3.0	0.8

The table below [Table 6.2] contains information on suspended solids concentrations: the maximum instantaneous concentrations at places of underwater work performance within the Baltica-1 OWF area, at the distances of 150 m and 500 m from the worksites, and the concentration ranges in the majority of the sea basin affected by the disturbance.

Table 6.2. The maximum concentrations during the work performance based on the envelope analysis

Method	The highest instantaneous concentration envelopes at a distance of 150 m from the worksite [$mg \cdot l^{-1}$]	The highest instantaneous concentration envelopes at a distance of 500 m from the worksite [$mg \cdot l^{-1}$]	The concentration range in a major part of the area affected by the disturbance [$mg \cdot l^{-1}$]
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil	250	95	6–20
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil	195	58	6–15
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil	220	75	6–20
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil	160	45	6–15
Driving a Ø 12 m monopile into a cohesive soil	6	3	4–6
Boulder clearance (300 $m \cdot h^{-1}$)	88	46	7–20
Cable embedment using the jetting method, 200 $m \cdot h^{-1}$, in cohesive soil	160	65	7–25
Cable embedment using the jetting method, 200 $m \cdot h^{-1}$, in non-cohesive soil	52	21	5–15
Cable embedment using the ploughing method, 300 $m \cdot h^{-1}$, in cohesive soil	115	51	5–25
Cable embedment using the ploughing method, 300 $m \cdot h^{-1}$, in non-cohesive soil	85	42	5–20
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures in cohesive soil in both locations	270	139	6–20
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures with cohesive soil in one location and non-cohesive soil in the second location	250	98	6–20
Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil and cable embedment using the jetting method at a speed of 200 $m \cdot h^{-1}$ in cohesive soil	250	99	6–20
Dredging works in the place intended for the resting of the vessel spud cans and deposition of material via a pipeline within the OWF area	1500	850	10–60

The table below [Table 6.3] presents the remaining parameters of the marine environment disturbance caused by the works carried out in the seabed of the Baltica-1 OWF area. These include the thickness of the sediment newly formed in the suspension sedimentation process. The maximum distances over which a layer of sediment with a thickness exceeding 1 mm from the worksite may spread, and the largest calculated thickness values at the distances of 150 m and 500 m from the sites of works performed for the purposes of the Baltica-1 OWF are presented here.

Table 6.3. The thickness of the newly formed sediment layer at specific distances from the underwater worksite

Method	**The maximum spread of a 1-mm sediment layer from the worksite [km]**	**The maximum thickness at a distance of 150 m from the worksite [mm]**	**The maximum thickness at a distance of 500 m from the worksite [mm]**
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil	2.500	5.6	2.4
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil	0.750	3.4	1.7
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil	2.100	4.1	1.9
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil	0.600	2.6	1.2
Driving a Ø 12 m monopile into a cohesive soil	-	0.1	-
Boulder clearance (300 $m \cdot h^{-1}$)	-	0.9	0.3
Cable embedment using the jetting method, 200 $m \cdot h^{-1}$, in cohesive soil	0.220	1.0	0.8
Cable embedment using the jetting method, 200 $m \cdot h^{-1}$, in non-cohesive soil	-	0.6	0.4
Cable embedment using the ploughing method, 300 $m \cdot h^{-1}$, in cohesive soil	0.220	1.0	0.4
Cable embedment using the ploughing method, 300 $m \cdot h^{-1}$, in non-cohesive soil	-	0.4	0.3
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures in cohesive soil in both locations	2.600	5.9	3.1
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures with cohesive soil in one location and non-cohesive soil in the second location	2.100	5.7	2.9
Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil and cable embedment using the jetting method at a speed of 200 $m \cdot h^{-1}$ in cohesive soil	2.100	5.7	2.9
Dredging works in the place intended for the resting of the vessel spud cans and deposition of material via a pipeline within the OWF area	6.300	35	9

For all works analysed to determine the level of disturbance to the marine environment caused by suspended solids, it should be assumed that the time of suspended solids remaining in the water in a concentration exceeding 5 mg·l^{-1} will not exceed 21 hours for works involving a moving source of sediment agitation in a specific location and 24 hours for works performed in one place after these works are finished, while in the case of cumulative impacts, these periods will be extended to 31 and 41 hours, respectively [Table 6.4].

Table 6.4. The time of suspended solids remaining agitated in the marine environment in a concentration exceeding 5 mg·l^{-1}

Method	The maximum span of a dispersion cloud with the concentration of 5 mg·l^{-1} from the moment the work is completed [h]
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in cohesive soil	24
Preparation of the substrate for the installation of a Ø 55 m gravity-based structure in non-cohesive soil	16
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in cohesive soil	16
Preparation of the substrate for the installation of a Ø 45 m gravity-based structure in non-cohesive soil	13
Driving a Ø 12 m monopile into a cohesive soil	2
Boulder clearance (300 m·h^{-1})	15
Cable embedment using the jetting method, 200 m·h^{-1}, in cohesive soil	21
Cable embedment using the jetting method, 200 m·h^{-1}, in non-cohesive soil	7
Cable embedment using the ploughing method, 300 m·h^{-1}, in cohesive soil	19
Cable embedment using the ploughing method, 300 m·h^{-1}, in non-cohesive soil	10
Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil in both locations	41
Two underwater works carried out at the same time: the substrate preparation for the installation of Ø 55 gravity-based structures with cohesive soil in one location and well non-cohesive soil in the second location	40
Two underwater works carried out at the same time: the substrate preparation for the installation of a Ø 55 gravity-based structure in cohesive soil and cable embedment using the jetting method at a speed of 200 m·h^{-1} in cohesive soil	31
Dredging works in the place intended for the resting of the vessel spuds and deposition of material via a pipeline within the OWF area	72

The calculation results obtained from the numerical model with various forcing conditions (wind, currents) taken into account, allowed analysis of how these conditions affect specific parameters of the suspended solids' impact (concentration value, spread range, retention time in the water column, sediment thickness). The calculation and result interpretation methods applied made it possible to select impacts of suspended solids agitated by the construction works on the Baltica-1 OWF that are the least beneficial for the environment, i.e. have the most substantial impact on the marine environment. The results of the numerical simulations performed lead to the following conclusions:

- with a weaker environmental forcing, i.e. at low wind speeds responsible for generating currents with the lowest speeds (in the order of a few $cm \cdot s^{-1}$) or with rapidly changing wind and current directions generating current fields with highly random (chaotic) circulation with small velocities, the concentrations of suspended solids reach the highest values locally;
- the impact of suspended solids has the largest range at moderate winds, the direction of which is determined in the period of underwater works, causing the agitation of small fractions of soil into a state of suspension in the water column (i.e. the works associated with the setting of gravity-based foundations, power cable embedment in the seabed with the use of the jetting method, during the impact cumulation);
- higher concentrations of suspended solids (from 30 to over 100 $mg \cdot l^{-1}$) have a local scope in relation to the underwater worksite, and the range of their impact does not exceed a distance of 600 m, also in the case of the analysed cumulative impacts (data obtained from the analysis of instantaneous events within the wind farm area [Table 6.4]); the only exception is the discharge of dredged material via a suction pipe in the area of the farm during works related to the soil reinforcement under the spuds the installation vessel, where a dispersion cloud with concentrations higher than 30 $mg \cdot l^{-1}$ may spread to a distance of up to 8.1 km, and a cloud with concentrations of 100 $mg \cdot l^{-1}$ – up to 800 m;
- the maximum range of impact of suspended solids with a concentration of 10 $mg \cdot l^{-1}$ was 2.0 km from the place of work related to seabed preparation for the installation of a gravity-based structure in cohesive soil, 6.2 km in the case of cumulated impacts from two works consisting in replacing soil for gravity-based structures carried out at the same time, and 11.5 km in the case of works related to replacing cohesive soil under the vessel spuds and its discharge using a suction dredger;
- the effect of accumulation of suspended solids concentrations may occur for various types of underwater works making sediments suspended in the water column, carried out at a distance of approximately 1000 m from each other, however, the increase in suspended solids concentration is insignificant and the maximum time of suspended solids' remaining in the water column with a low concentration of 5 $mg \cdot l^{-1}$ does not exceed 41 hours after completion of these works, and in the case of deposition of liquefied soil material, it is up to 72 hours;
- avoiding the cumulative effect resulting in an increase in suspended solids concentration when underwater works are carried out at the same time is associated with the introduction of restrictions on the possibility of simultaneous work in locations less than 2.0 km apart;
- the largest thickness of sediments newly formed by sedimenting suspended solids in the least favourable cases (sea current systems, work carried out in cohesive soils) at a distance of 150 m from the worksite does not exceed 35 mm in the case of soil replacement for the installation vessel spuds together with its local deposition, 6 mm in the case of work related to the preparation of the seabed for the installation of a gravity-based structure and 1 mm in the case of embedding of a cable using the jetting method. In the case of cumulative impacts from two works conducted simultaneously approx. 1 km apart, the maximum thickness of the newly formed sediment layer does not exceed 6 mm;

- the maximum thickness of sediments newly formed (from sedimenting suspended solids) at a distance of 500 m from the worksite may locally reach the values of 9 mm for the soil replacement under the vessel spud cans, 2.4 mm for works preparing the seabed for the gravity-based structure installation, while for other underwater works, it will not exceed 1 mm;
- the effect of the accumulation of sediments newly formed as a result of various anthropogenic activities conducted during the construction phase (foundation works and works related to the installation of the cable network) is possible, but the cumulative impacts will be local and short-term. The natural processes of sediment re-suspension caused by storm phenomena (an increased velocity of near-seabed currents) will be responsible for the changes in sediment thickness in the Baltica-1 OWF area and beyond during the wind farm operation phase;
- in the least favourable scenario, the impact of suspended solids on the marine environment lasts no longer than 110 hours (with the work implementation time of 38 hours and the time of solids remaining suspended of 72 hours) counted from the commencement of a seabed intervention work consisting in soil replacement to reinforce the substrate under the vessel spuds, 36 hours – counted from the commencement of a seabed intervention work consisting in setting of a single foundation – and no longer than 53 hours in the case of cumulative impacts (this condition is determined by the moment of achieving a negligible concentration of less than 5 $mg \cdot l^{-1}$);
- the results of calculations for the considered technologies of underwater works in the area of Baltica-1 OWF indicate that the method interfering with the marine environment to the highest extent will be the water jetting in cohesive soil during works related to the movement of cable embedding devices, while during quasi-stationary works, it will be soil replacement and its local deposition in the course of works related to the reinforcement of the substrate in places where the installation vessel spud cans are to rest, also in cohesive soil (because the environmental impact of suspended solids is greater when underwater works are carried out in cohesive soils of soft and plastic consistency than in the case of non-cohesive soils);
- in each underwater work carried out, the sediments mobilised will be natural and local sediments; preliminary studies of the sediment chemistry have shown that these are not contaminated sediments.

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