# Expansion of the port in Ustka. Simulation of wave conditions

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This work is the result of the cooperation between the Gdańsk University of Technology, Faculty of Civil and Environmental Engineering and Norwegian University of Science and Technology completed with a MASTER THESIS (TBA4920 Marine Civil Engineering Spring 2016) for Wiktor Wickland and Hubert Konkol, entitled: "Expansion of the port in Ustka: simulation of wave conditions".

The purpose was to choose the best breakwater layout that will provide the best wave conditions inside harbour basin. In the same time, it has to be sufficient for the proper operation of the port and meet the standards. This master thesis concerns a new port in Ustka, which is located in the northern part of Poland.

The study was limited to issues that could be considered within the thesis related to the determination of selected parameters of analysed hydrotechnical constructions. These considerations were adapted to the breakwater systems and access parameters of waterways preliminary chosen together with the Maritime Office in Słupsk. In these analyses the optimization of the fairway parameters due to the size and type of vessels expected to service wind farms in Słupsk Bank was omitted. This subject requires separate examination. At the same time, the scope of work excluded the possibility of addressing the issue of the impact of the shape of breakwaters on the sediment transport and thus on the shape of the coast. For the south coast of the Baltic Sea and in particular the region of the Port in Ustka this topic is very important and requires further study.

There is a need for a new port to handle specialized vessels servicing the wind farms. In order to ensure that the new harbour fulfils all of its functions properly, tentative concepts have to be evaluated and the especially the waves conditions inside the harbour basin must be examined to guarantee minimal undesirable wave effects. To achieve this, numerical models will be prepared and run using diverse software. The present report was made on the basis of a thesis entitled: „Expansion of the port in Ustka. Simulation of wave conditions", made at Gdansk University of Technology in cooperation with the Norwegian Technical University in Trondheim.

The work was carried out using Mike 21 software provided by DHI. The study contains an analysis of wave climate within the port in Ustka and comparison of the 4 conceptual breakwaters layouts. The aim of the study was to determine which one provides wave conditions most favorable for carrying out cargo handling operations within the newly formed basins and prevents wave propagation inside the old port.

Full text of the thesis is available online at: https://brage.bibsys.no/xmlui/handle/11250/2412611.

## SITE OF INTEREST

A limited number of coastal areas attractive for industry forces investors to make investments in new locations where environmental conditions are often unknown or unfavorable, and prediction of environmental loads is much more complicated. Often, the best solution is to expand the existing ports. Such a situation occurs, among others, in Ustka, which is the subject of this study. In such cases, prediction and estimation of the wave loads or impact of a planned construction on the environment (eg. the sediment transport) using traditional computational techniques is often very tedious or impossible. Newest computer software, that allow to thoroughly analyse wave climate, currents and sediment transport, are often of great help. This software can also be used for the analysis of existing objects, eg. the assessment of effectiveness of breakwaters during storm surges, estimating the risk of a harbour oscillation or wave propagation inside the port.

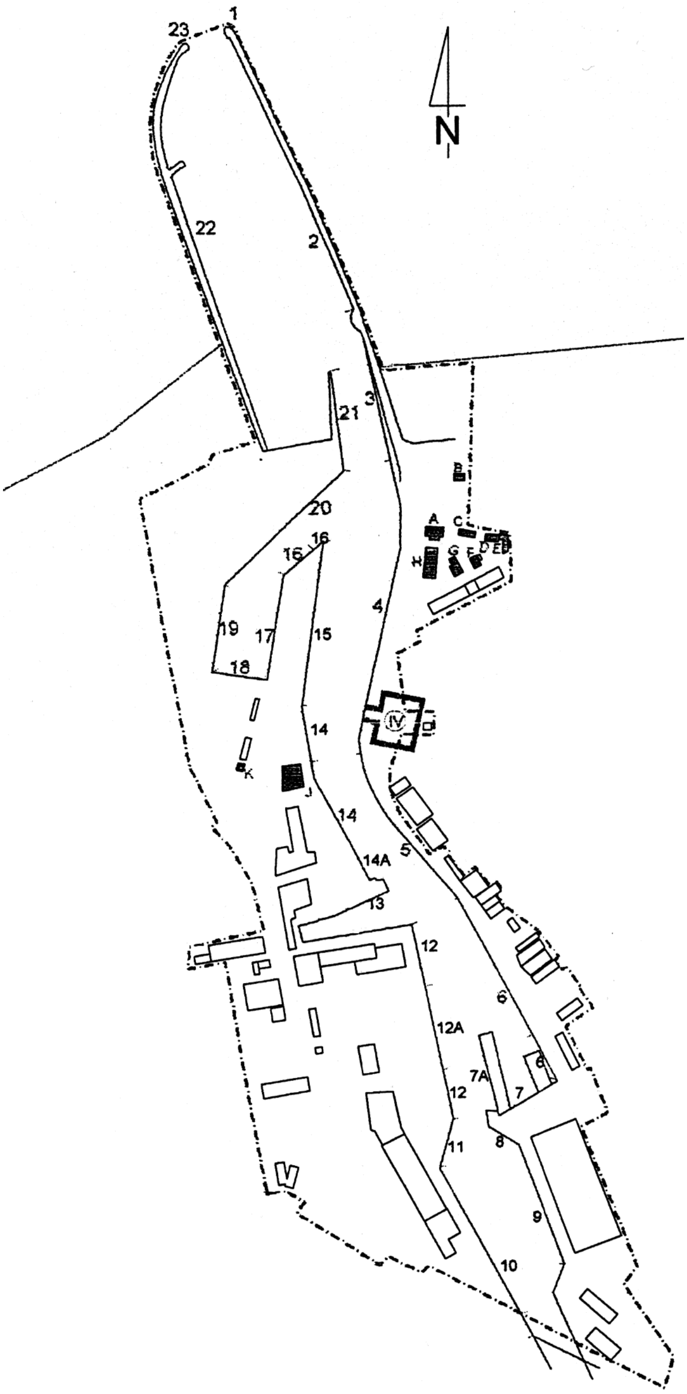


Fig. 1. Plan of the current port in Ustka

Ustka is a tourist destination located between Darłowo and Łeba, located in the central part of the Polish coastline. The town is located around the estuary of the Słupia river. A harbour, whose main objective is to handle small fishing and sailing boats can be found here. Its entrance is sheltered by two breakwaters: Eastern and Western. They deviate from the north about 24 degrees to the west. A plan of the site is shown in Fig. 1. Eastern breakwater has the shape of a concave arc and together with the Pilotowe quay (item no. 3 in Fig. 1) creates an extension of the river's mouth.

There are two main factors for the expansion of the existing port. The first factor is that the quays located near the mouth of the river are prone to failure and have stability problems because of intense filtration of the overtopping water. Second factor is the geometry of the harbour, which makes further development and handling larger vessels impossible. Dimensions of the existing entrance, basins and quays are insufficient for the current and target port usage. Because of the close proximity of the military areas and training grounds, expansion of the harbour will create opportunities for the Polish Navy to conduct trainings. The nearby Słupsk Bank, a shallow area of approximately 1000 km$^2$ with the depth varying from 8 to 20 m, is one of the areas proposed for installation of maritime wind farms, as shown in Fig. 2. This will create demand both for shelter for ships constructing and servicing the offshore wind farms and for storage place for parts of the wind turbines. The modernization of the port in Ustka will ensure the establishment of storage areas and quays, which will enable the realization of this project as well as improve the importance and industrial attractiveness of the whole region.

## APPROACH

After research and feasibility studies done by Maritime Office in Słupsk four different harbour layouts were proposed. The main criterion for the choice of the final solution was wave climate inside harbour basins and near its entrance. In order to determine the best configuration of the breakwaters it was necessary to perform a variety of numerical analyzes. Calculations were carried out using MIKE 21 software. MIKE by DHI is a powerful tool able to utilize flexible mesh and contains several modules designed for preparation of bathymetry data and calculating wave conditions at required time steps using both spectral (SW) and Boussinesq wave (BW) models.

Due to the lack of valuable wave data from the area of Ustka, which could be used for the calculation, the authors were forced to use nested approach. At first, the large-scale propagation was calculated, using Spectral Wave model. The input wave data (significant wave height, wave period and direction) was obtained from Swedish measuring buoys: Sodra Ostersjon (eastern boundary), Knolls Grund (northern) and German buoy FINO2 R (western). Data owners are the Swedish Meteorological and Hydrological Institute and the German National Institute of Hydrology. The exact location of the buoys is shown in Fig. 3.

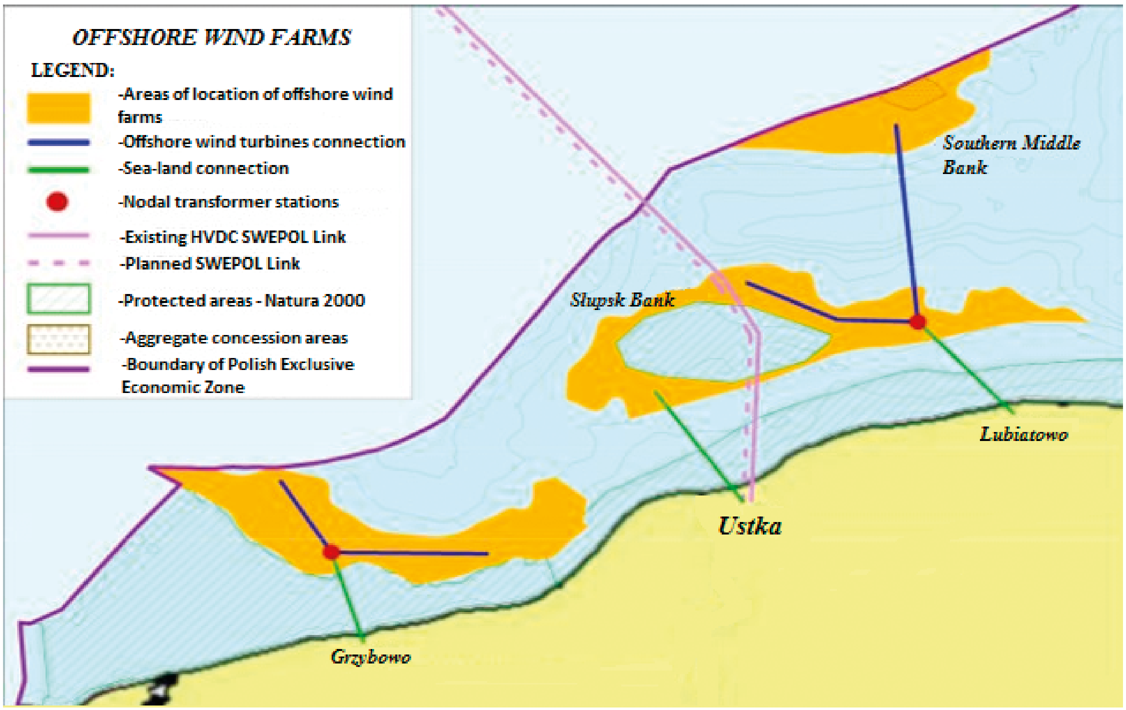


Fig. 2. Southern Baltic Sea areas proposed for installation of maritime wind farms (source: Renewable Energy)

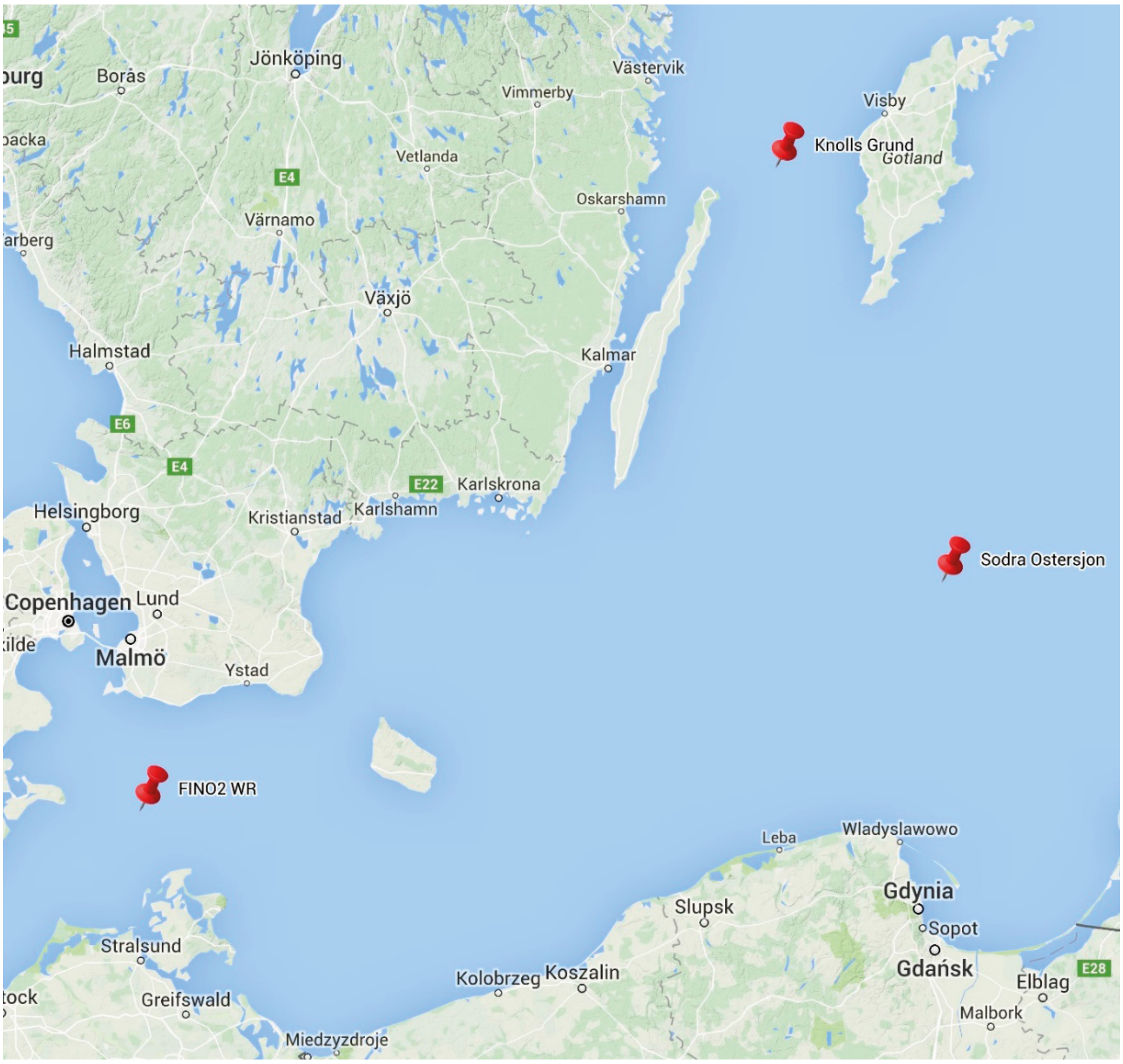


Fig. 3. Location of the measuring buoys (source: Google Maps)

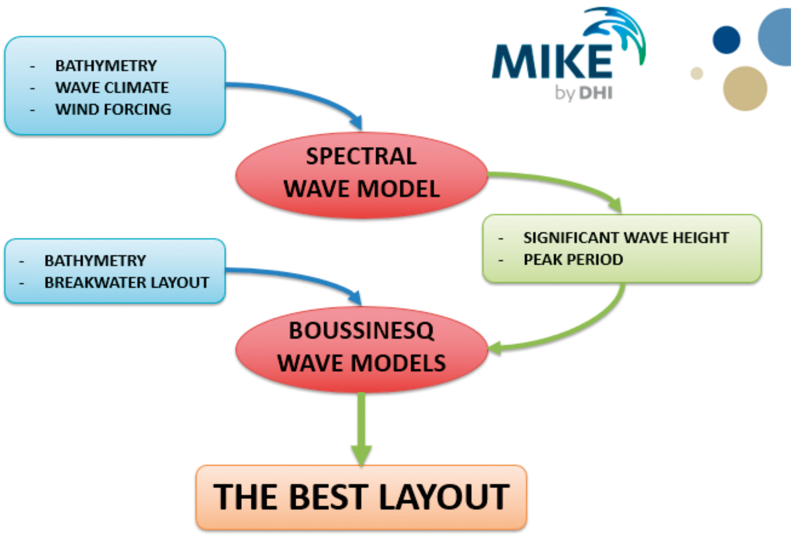


Fig. 4. Graph showing the relationship between the Boussinesq Model and Spectral Model. Medium grey boxes – the input data prepared prior to the simulation; dark grey – two different computational models, light grey – model results, which were used for further calculations

Time interval chosen for the analysis ranged from 00:00:00 on January 6 to 23:00:00 on February 28, 2015. This period was selected because of the occurrence of the storm surge coupled with a strong wave action that caused a failure of the Pilotowe quay.

SW is a global model, whose task was to provide information on the waves near the site of interest. Based on the results of the spectral calculation, a Boussinesq wave model, with much higher resolution, was prepared. At this stage different breakwater layouts were examined. Fig. 4 illustrates the chosen approach and gives the general overview on the data needed for the preparation of each model.

The Danish Straits make the Baltic Sea a relatively closed body of water, where influence of tides and currents is not observed. Wind direction and strength have therefore a significant share of water level fluctuations. In order to check the influence of tides and currents, the authors have prepared a spectral model in two configurations:

– ignoring impact of tides and currents (SW – Spectral Wave model only),
– taking into account the impact of tides and current (SW+HD – Spectral Wave + Hydrodynamic model).

In areas where tides can reach several meters, taking them into account in the simulation can be of great importance.

During high tide, temporarily raised water level can cause the appearance of waves with a much higher amplitude than at a low tide. Such a wave will be carrying much higher energy and hence its interaction with structures and conditions inside the port basins will be greater. The results of this analysis are shown further in this report.

As it is illustrated in Fig. 4, results obtained from the SW simulation are the input to the BW model. In case of Boussinesq wave model, the data preparation required different, more "individual" approach for each layout. This model takes into account the interaction between the waves and various phenomena such as diffraction, refraction and hence the model itself must be precisely prepared.

The model domain was narrowed down to the coastal area where the planned breakwaters were placed. Fig. 7 ÷ 10 show all four layouts proposed be Maritime Office in Słupsk. The main difference between the proposed layouts is the shape of the western breakwater. In the first layout it is more flattened. What is more, a detached breakwater has been placed at the entrance. Its purpose is to protect the entrance to the old port and to block the waves generated by the units coming into the new basin. In the other systems the geometry of the breakwater is changed. It has more rounded shape and place of the connection to the mainland varies.

Bathymetry files were obtained using one of the software's module, based on the results of soundings of the seabed. The minimum depth of the coastal zone has been set to 5 meters. This prevented wave breaking, which, due to the limited available computational power, could not be taken into account. During the test simulations, carried out without the corrected depth, a number of instabilities occurred which resulted in termination of the calculation. In every model there are three boundaries: east, west and north. In the case of the simulation of the highest wave (coming from the west, as obtained from SW calculations) eastern and western borders were open and at the northern a wave generator was imposed. Its task is to induce irregular waves of given spectral parameters. In the case of the simulation of wave coming from the most unfavorable direction (north east) only western border was open, and on the northern and eastern there was a wave generator. Otherwise generated waves would act only in a certain part of the domain, which would be contrary to the actual conditions.

Separate files, containing geometry of the harbour, described boundaries, definition of zones with different wave reflection and absorption coefficients, were prepared for each model. The reflection coefficient is crucial to model calibration. Therefore several zones allowing for the application of different reflection coefficients at different parts of the structure were defined. For example, the outer part of the breakwater, covered with rip-rap, absorbs some part of wave energy, while smooth, concrete wall of a harbour basin cause almost total reflection of the incoming

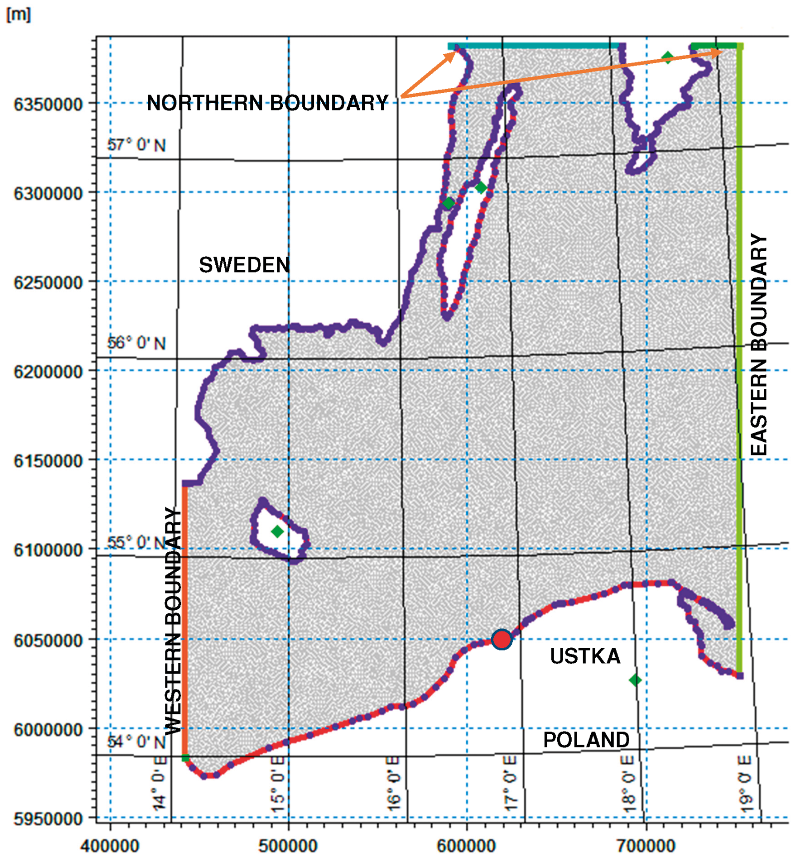


Fig. 5. SW model domain with marked boundaries and mesh

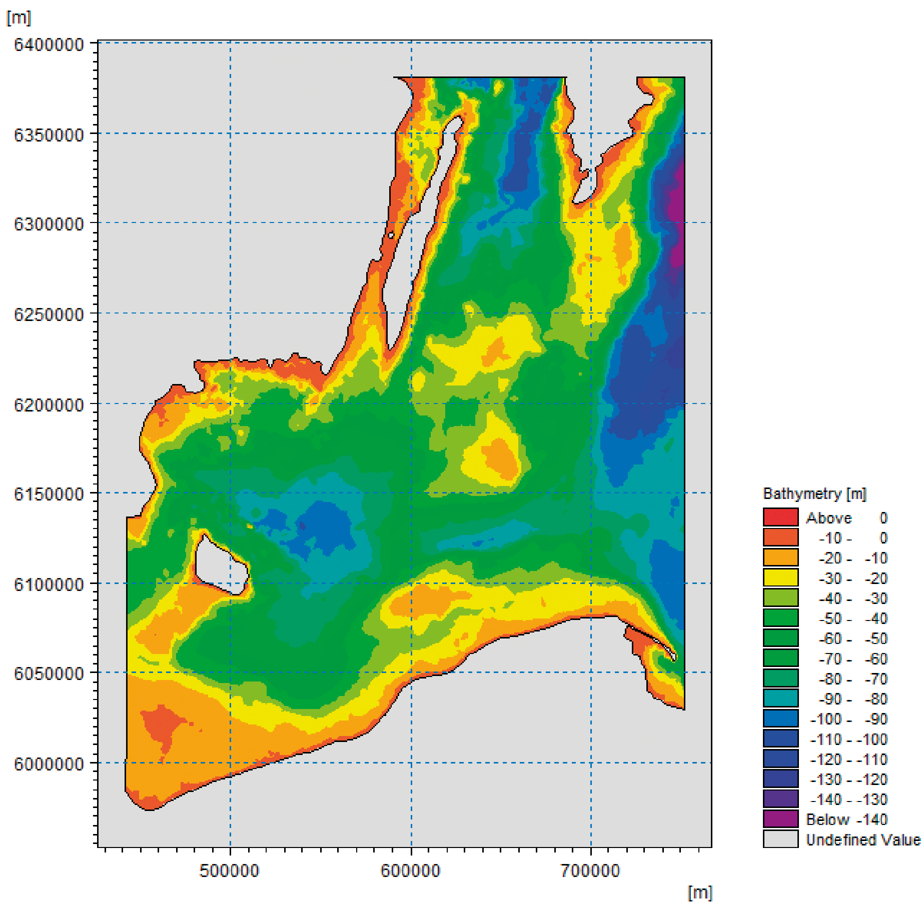


Fig. 6. Bathymetry of a fragment of the Baltic Sea that was studied in spectral model

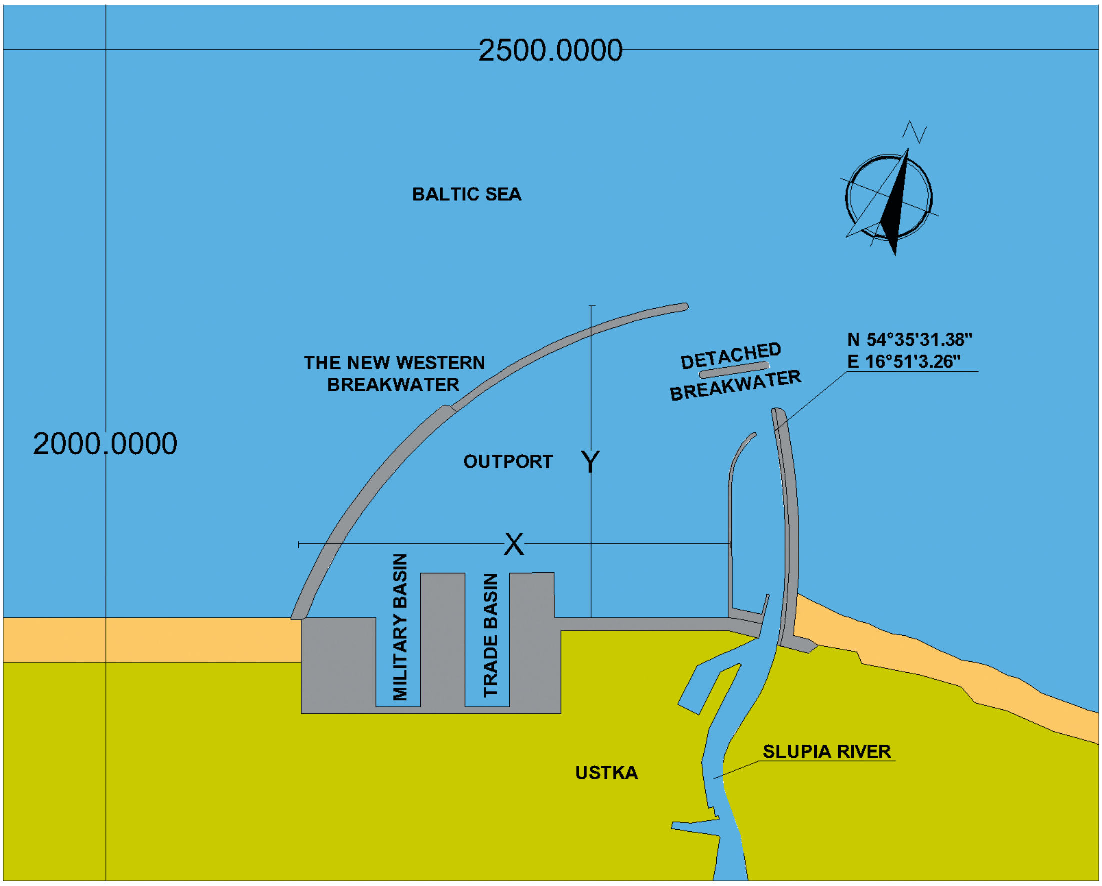


Fig. 7. First of the proposed layouts (source: Maritime Office in Słupsk; designer: Borodziuk A.)

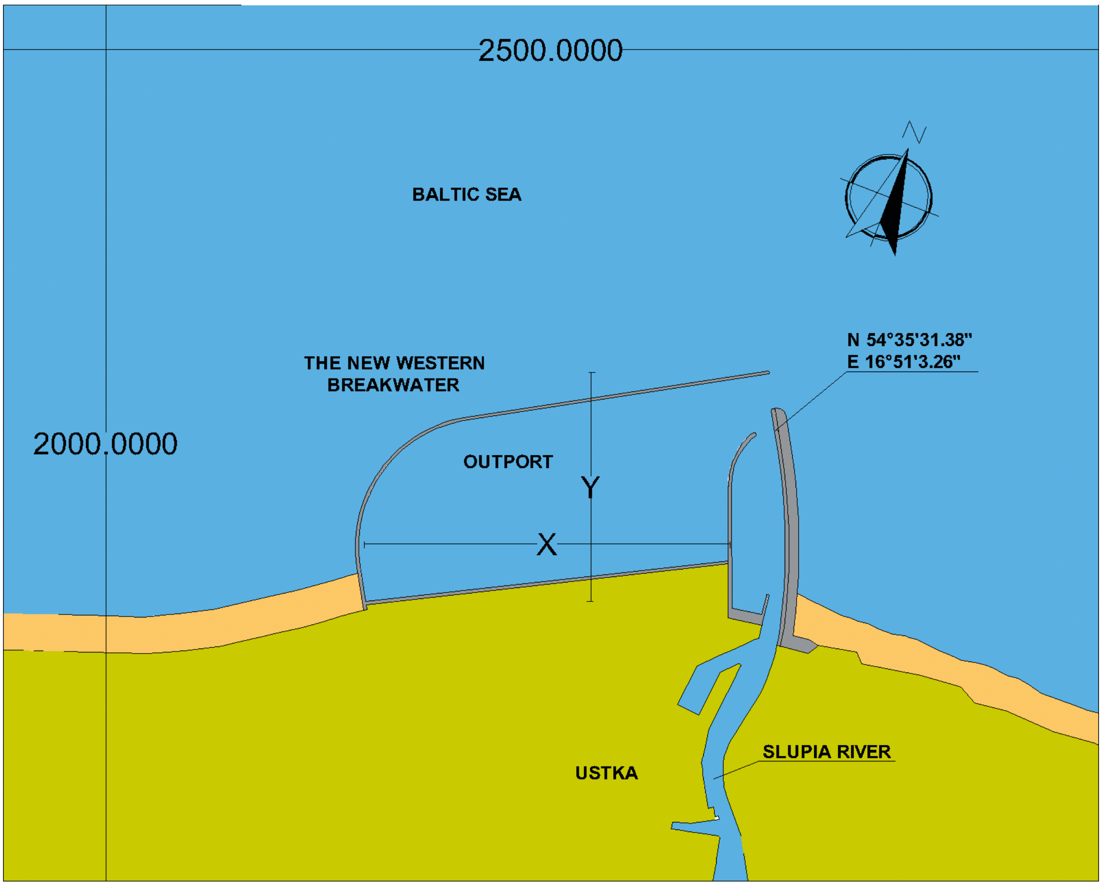


Fig. 8. Proposed layouts no 2 (source: Maritime Office in Słupsk; designer: Borodziuk A.)

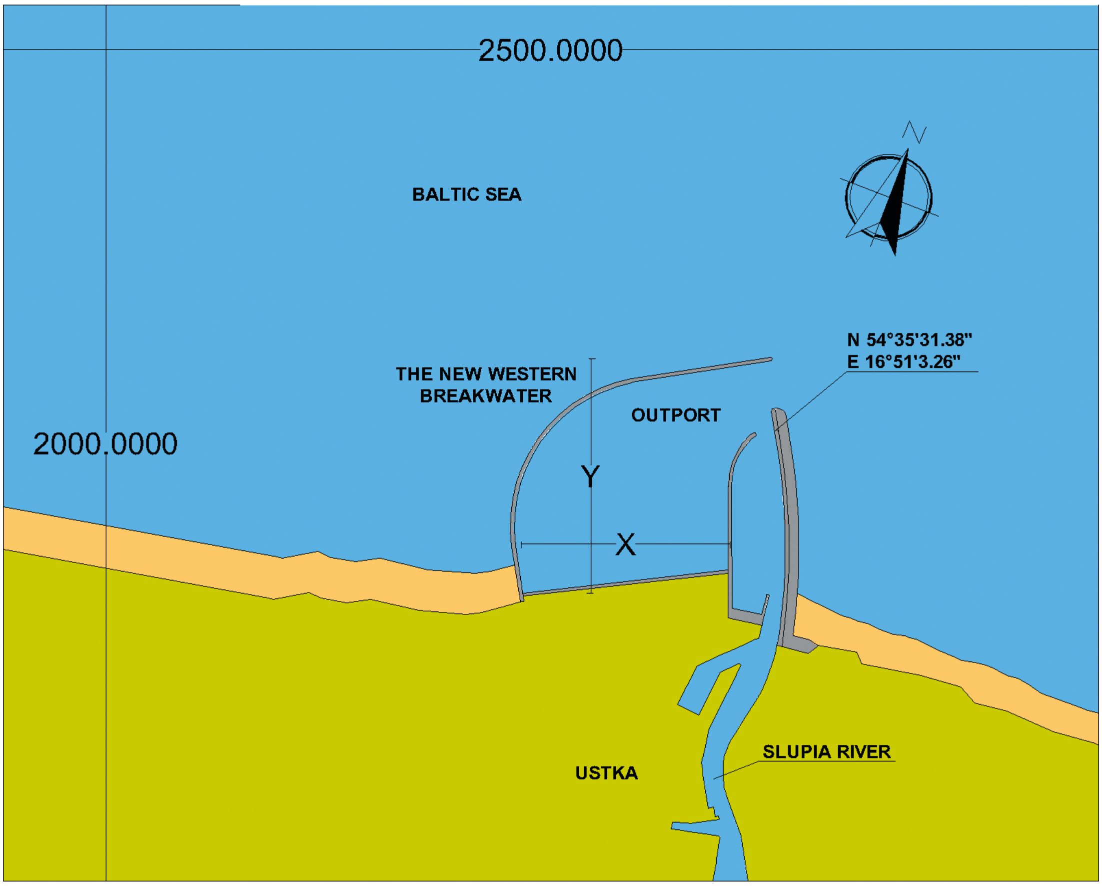


Fig. 9. Third proposed layout (source: Maritime Office in Słupsk; designer: Borodziuk A.)

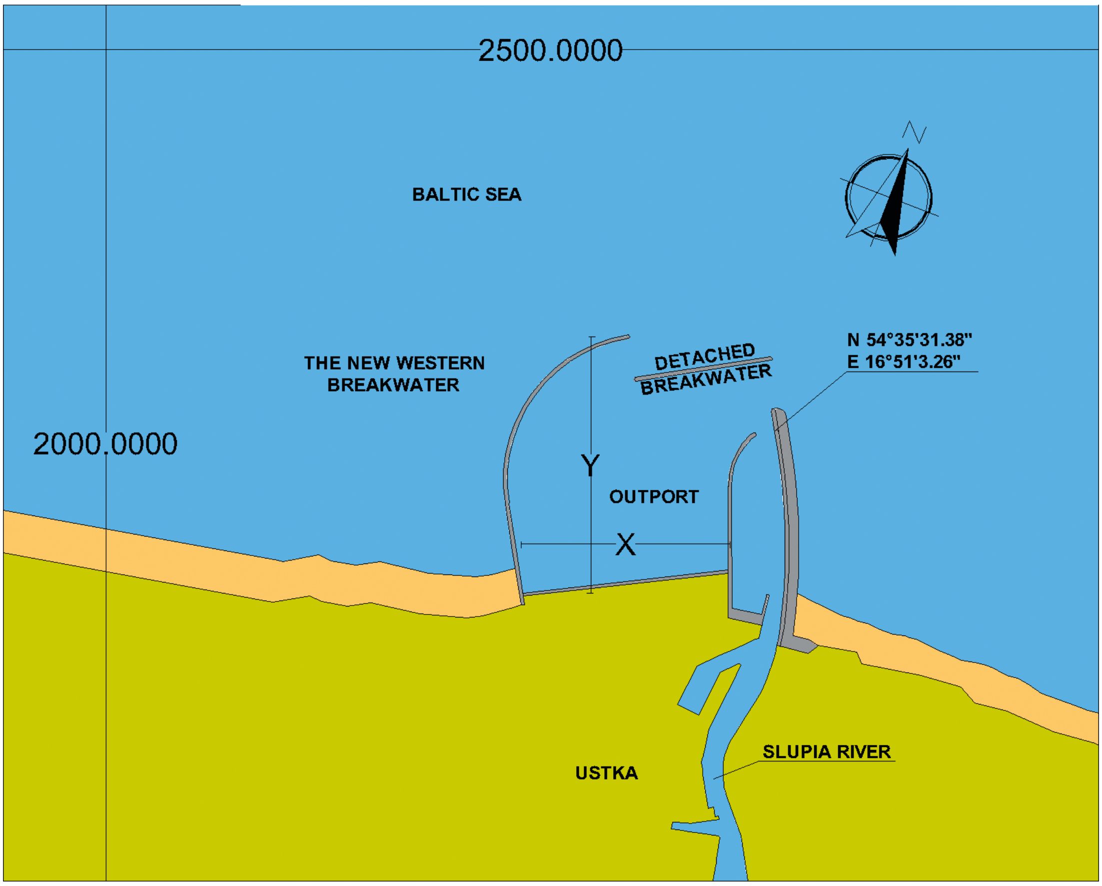


Fig. 10. Fourth proposed layout (source: Maritime Office in Słupsk; designer: Borodziuk A.)

wave. Numerical beaches that absorbs 100% of the wave energy were placed, besides the locations of actual beach, at the boundaries of the domain in order to prevent the reflection of the waves back into the area of calculation. Software providers ensure that effective absorption can be achieved when the thickness of the generated sponge is at least 1.5 wavelength. In the described case it was more than 2 wavelength thick. Fig. 11 and Fig. 12 show the different reflection zones, generated numerical beach and the location of the previously described wave generators.

Thus prepared models were ready for the calculations. The obtained results are described in the next section.

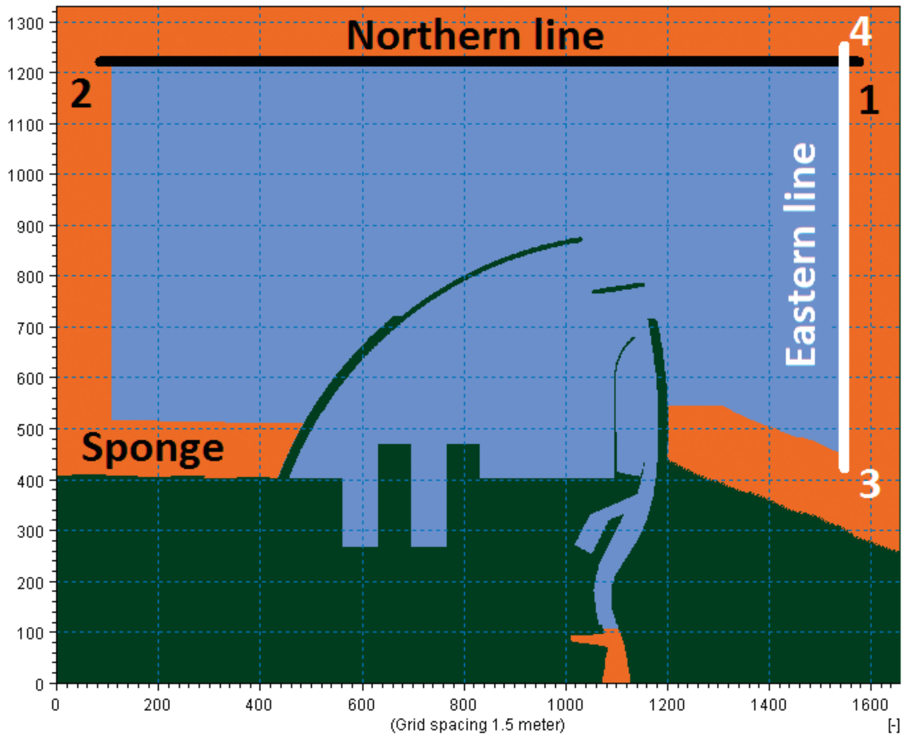


Fig. 11. Visualization of the sponge layer and wave generation lines. Generated by Mike Zero software.

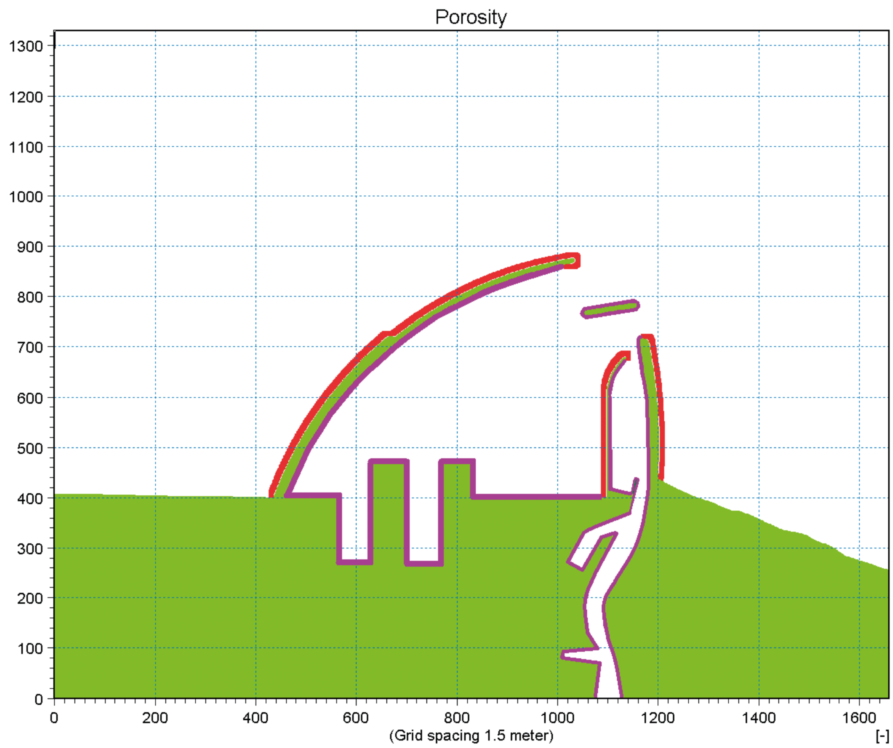


Fig. 12. Visualization of different reflective zones (purple – almost total reflection, red – partially reflective, rip-rap covered zones) Generated by Mike Zero software

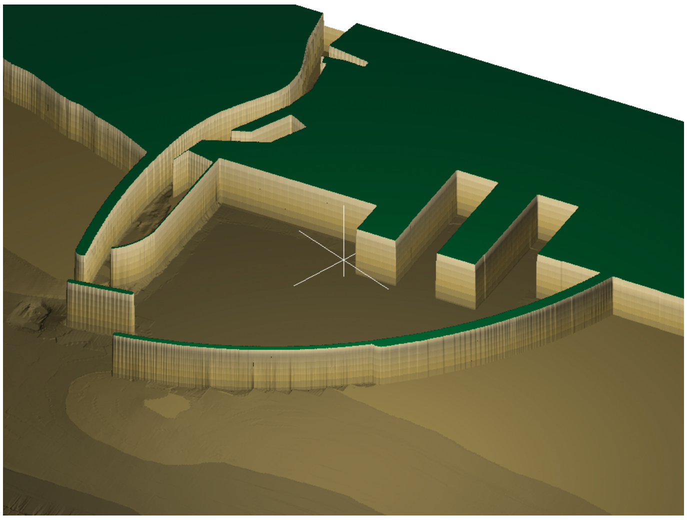

Fig. 13. Visualisation of the first layout

## RESULTS

Results obtained from spectral analysis confirmed the assumptions about the small impact of tidal and ocean currents. Wave parameters generated with tides and currents taken into account are insignificantly lower than without these phenomena. This applies to both a significant height, the maximum period and the peak period of wave. Compared results are listed in Table 1. Presented values are from 11th of January 2015 when the highest wave approached to the breakwater.

According to Czajewski (1988) during wind of 7-8 in Beaufort scale waves can reach height of 3-4 metres, occasionally reaching up to 7 metres. Such a sea state (Beaufort numbers 7-9) took place during the simulation. After analysis of wind and atmospheric pressure data used in the model it can be told that on the 10th January from the 12.00, due to low-pressure centre passing over the Baltic sea, wind speed grown from 18 m/s to the maximum of 21 m/s at 00:00 on the 11th January and decayed to 16.5 m/s during the same day. What is more, Paplińska (2000) found, using WAM4 model, that the main direction of wave propagation for polish coast is East to South-East, which is in very good consistence with wave direction obtained (see Fig. 14), and that the maximum value of the significant wave height can reach up to 5.94 m (1998-1999). Data presented in more detail in the references and mentioned above refers mainly to the area of southern Baltic sea in general, not precisely to the area in proximity to Ustka. Nevertheless, by comparing them with the results of the simulation it can be concluded that the calculated wave heights lie within the specified ranges. According to Jakusik (2006), the average wave period in the stormy season is 5.2 sec. The given value is little higher

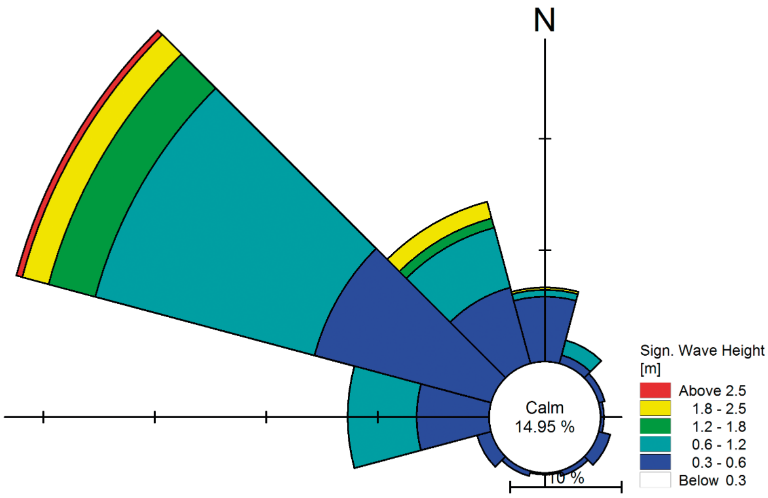


Fig. 14. The rose plot of the significant wave height at the proximity of Ustka (generated by: Mike Zero by DHI)

**Table 1. Comparison of the Spectral Wave models results**

| Model | Spectral (SW) | | | SW + HD | | |
|---|---|---|---|---|---|---|
| Date | 11-01-2015 03:00:00 | | | 11-01-2015 03:00:00 | | |
| Origin | Wind | Swell | Resultant | Wind | Swell | Resultant |
| Significant wave height [m] | 2.38 | 0.90 | 2.54 | 2.31 | 0.83 | 2.46 |
| Period $T_{01}$ [s] | 7.39 | 8.81 | 7.54 | 7.30 | 8.73 | 7.44 |
| Max. Wave height [m] | 4.54 | 1.69 | 4.84 | 4.42 | 1.57 | 4.69 |
| Peak period [s] | 9.80 | 10.15 | 9.85 | 9.75 | 10.20 | 9.80 |
| Mean direction [°] | 305.57 | 343.26 | 310.17 | 304.60 | 342.80 | 308.91 |

than obtained 4.1 s. This may be due to the fact that the simulation was made for the stormiest months – January and February, whereas the whole storm season lasts from October to March. The obtained values from the SW + HD simulation are slightly smaller than those without considering the influence of hydrodynamic processes. At the same time, compared with data from the literature, it can be assumed that they better reflect the actual situation. Therefore, they are used to carry out Boussinesq wave model simulation.

In addition, after analysis of the results in terms of the source of waves, it was found that the largest share in the sea state formation in the proximity of the Port in Ustka have waves generated locally by the wind. Waves from a distant storm (swell) have only slight impact. Fig. 15 and 16 present the relationship between the wind sea and the resultant sea state. It is clear from the figures, that extreme sea state is almost totally governed by waves locally generated by wind, whereas during relatively calmer periods it is swell that affects the sea state more.

In the windless period, the maximum swell wave height reached 0.7 m. This took place in the beginning of February.

Model domain with isolines showing significant wave height obtained from SW model is shown in Figure 17. Figure 18 presents close-up of the area of interest showing significant wave height and wave vectors. Refraction can be easily seen, as waves vectors approach the directions perpendicular to the shore.

In the Bousinesq model, each of the layouts has been analyzed for two main wave direction. The first one is obtained from SW – waves coming from the northwest. Bearing in mind that not always the most likely direction of the wave will be the most unfavorable, each layout was also tested against the maximum wave coming from north east.

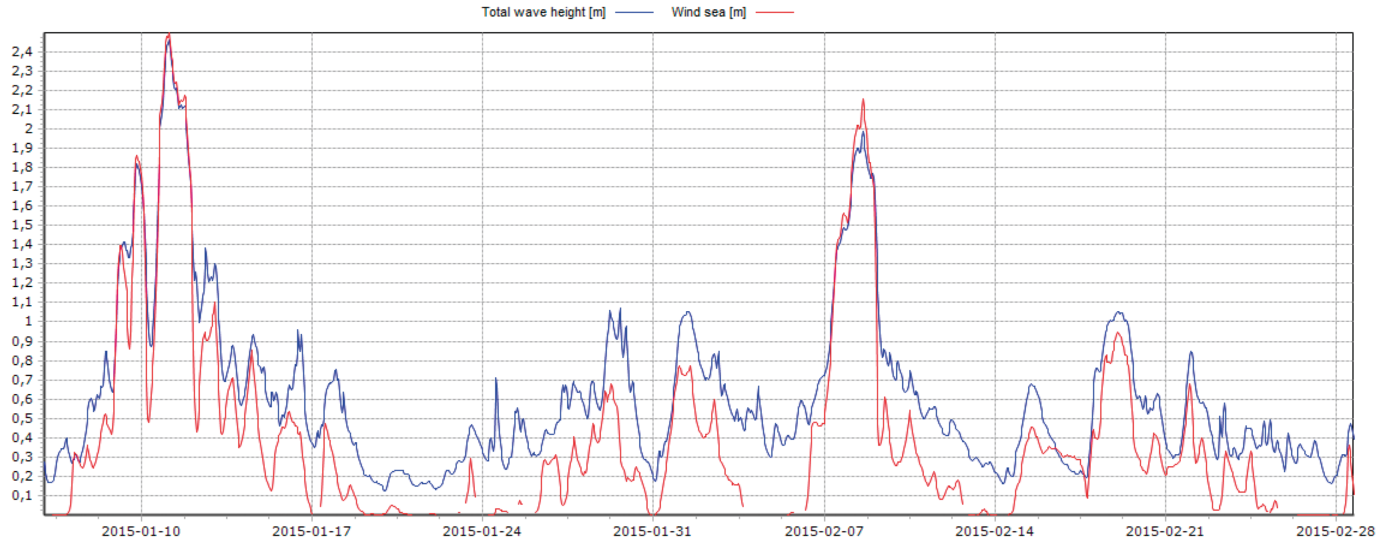


Fig. 15. The comparison of total wave height (blue) and wave height for wind sea (red) (generated by: Mike Zero by DHI)

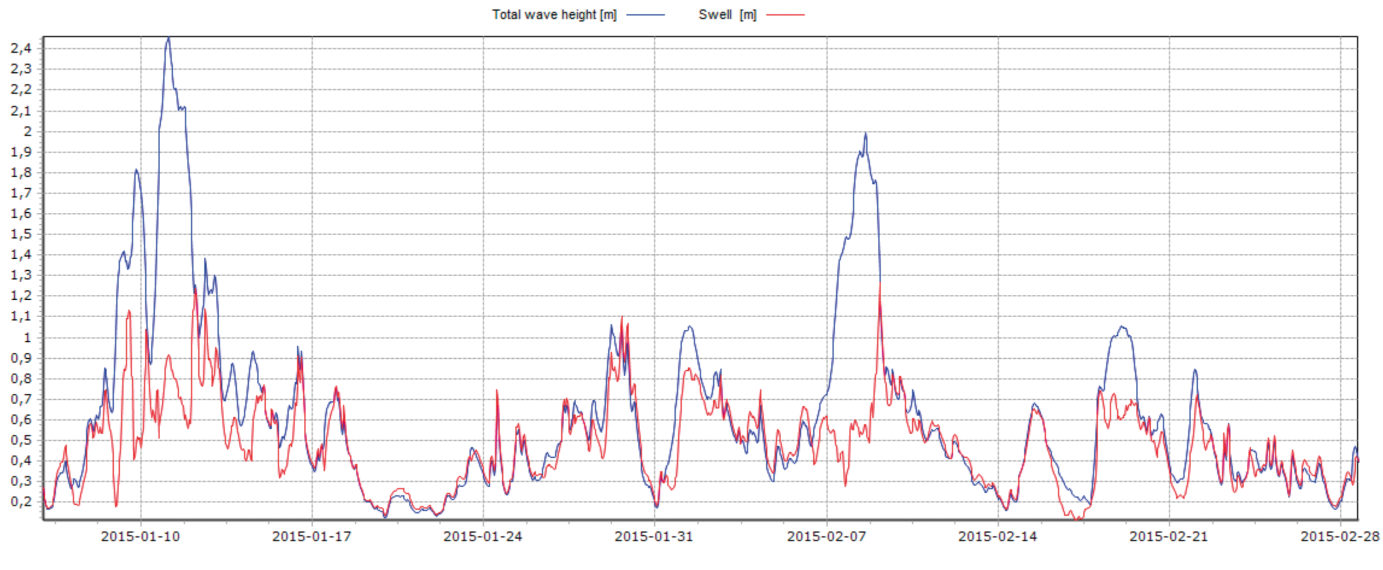


Fig. 16. The comparison of total wave height (blue) and wave height for swell (red). (generated by: Mike Zero by DHI)

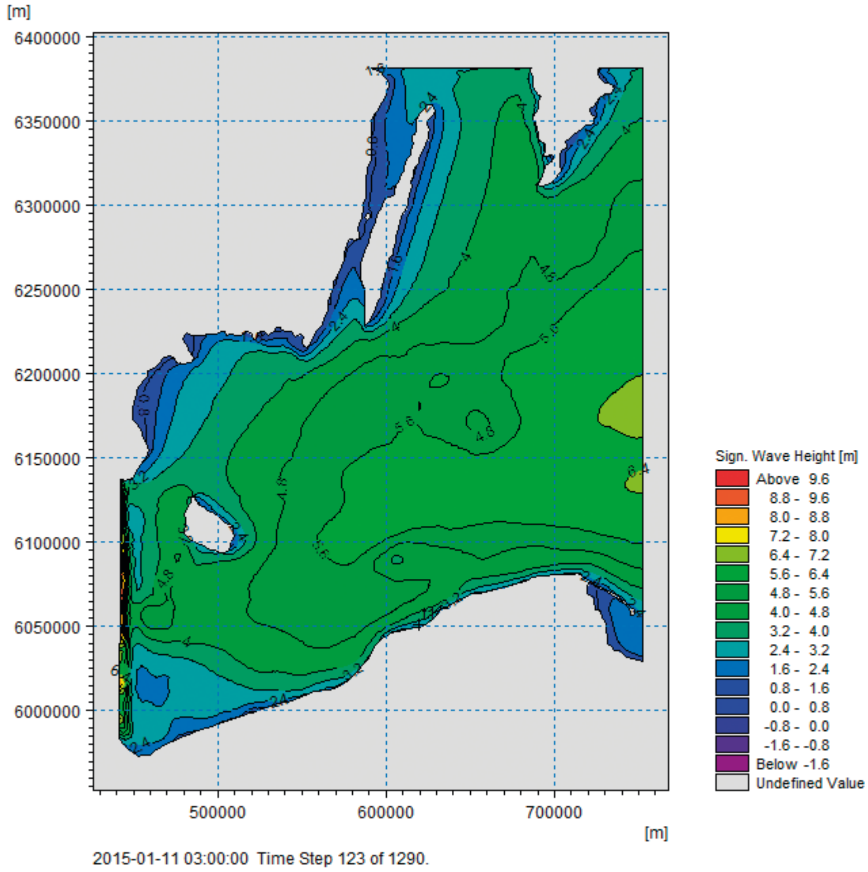


Fig. 17. Model domain showing isolines with significant wave height

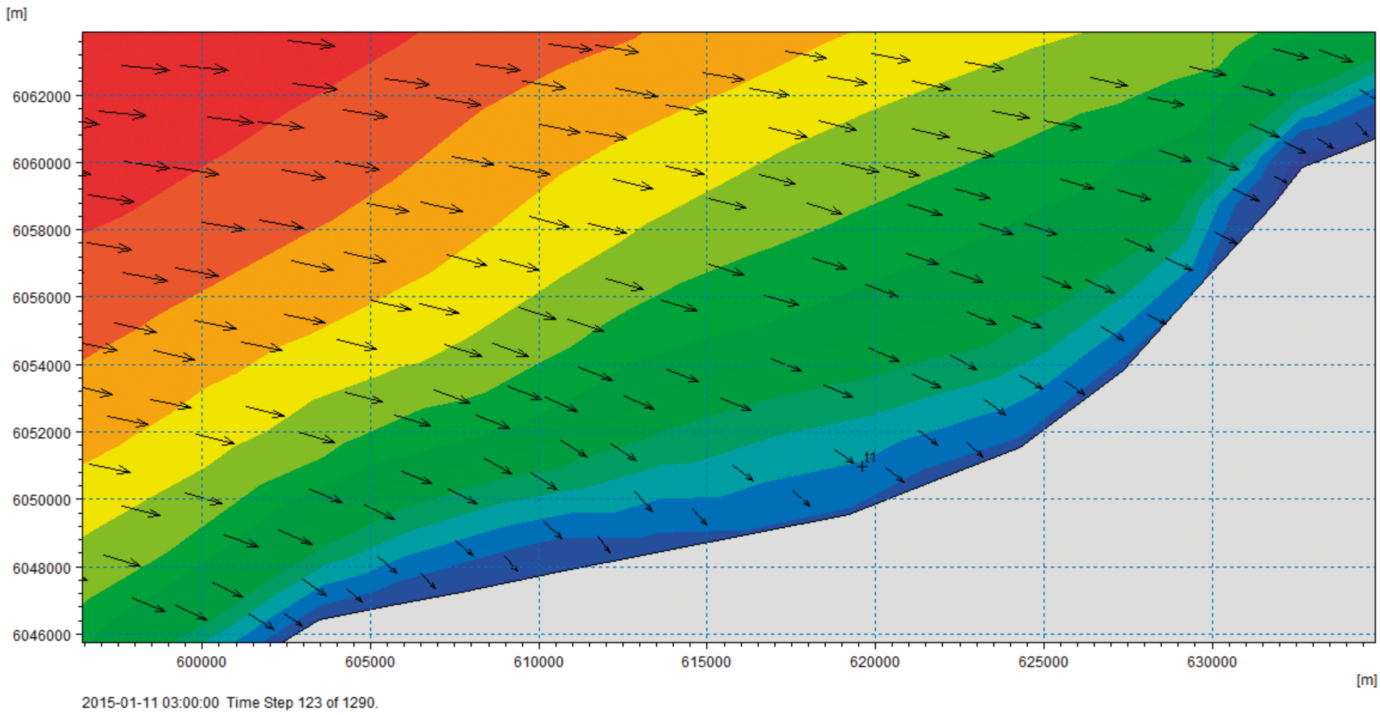


Fig. 18. Plot of the area of interest showing significant wave height and wave vectors

## COMPARISON AND DISCUSSION OF THE RESULTS

All layouts protect the basins from waves coming from north-east, which is the main direction of waves in this area. All proposed breakwater layouts create harbour entrances of different width, which affects the wave climate a lot. For layouts 1 and 4, which have two entrances separated by a detached breakwater waves can propagate into the harbour basins more easily than in cases 2 and 3, which have only one narrow entrance.

The next two figures, Fig. 19 and 20, show an example of the results obtained from BW simulation. Fig. 19 shows plot of the significant wave height. The second figure shows the 3D visualization of the waves. Wave generation line is marked with black line. The impact of numerical beach on the outer boundaries can be easily noticed.

Wave climate was checked at 6 characteristic points of each proposed breakwater layout. These are:

Point 1: In the middle point of the new breakwater;

Point 2: In the entrance to the old harbour;

Point 3: In the central point of the new basin;

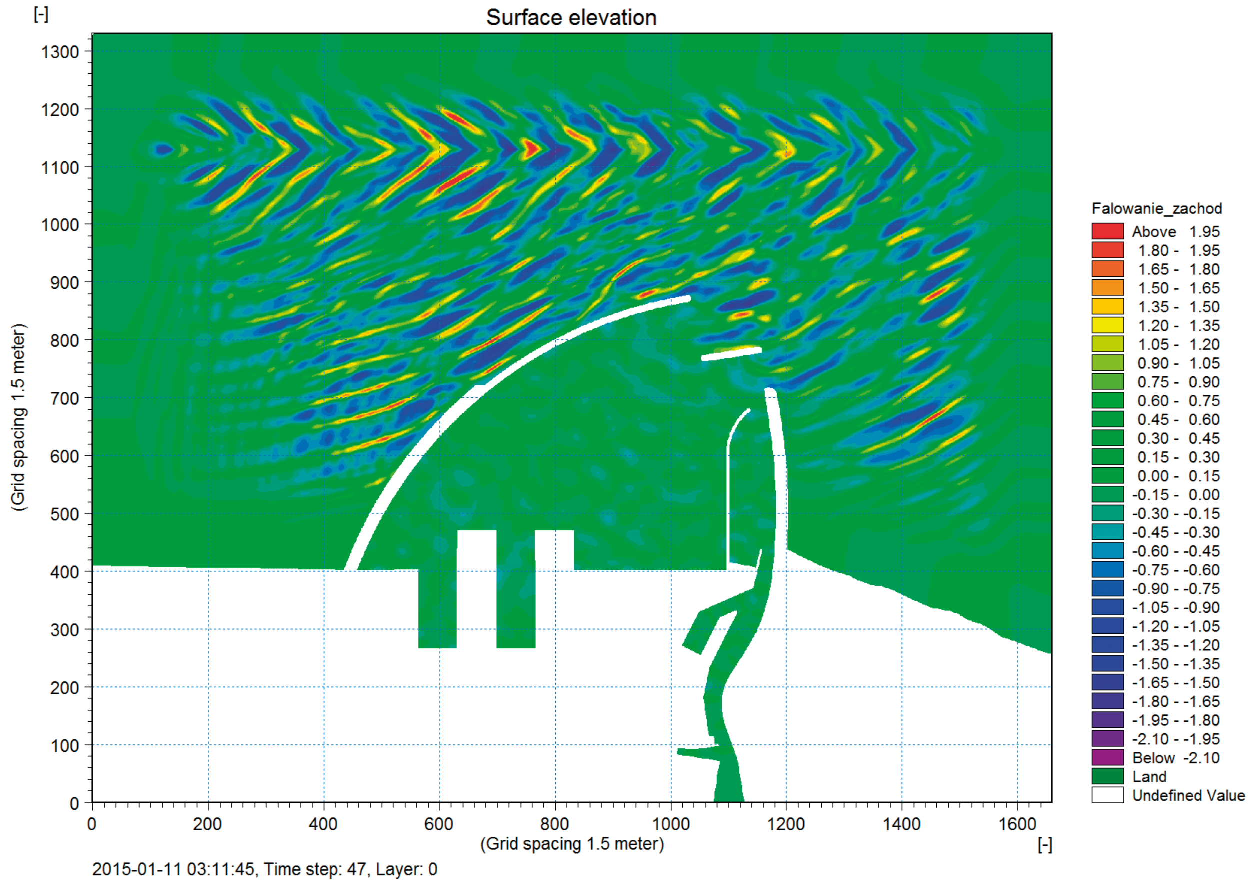


Fig. 19. First layout, random waves from north-west: Snapshot of propagating waves at the time of the occurrence of the highest waves at the harbour entrance

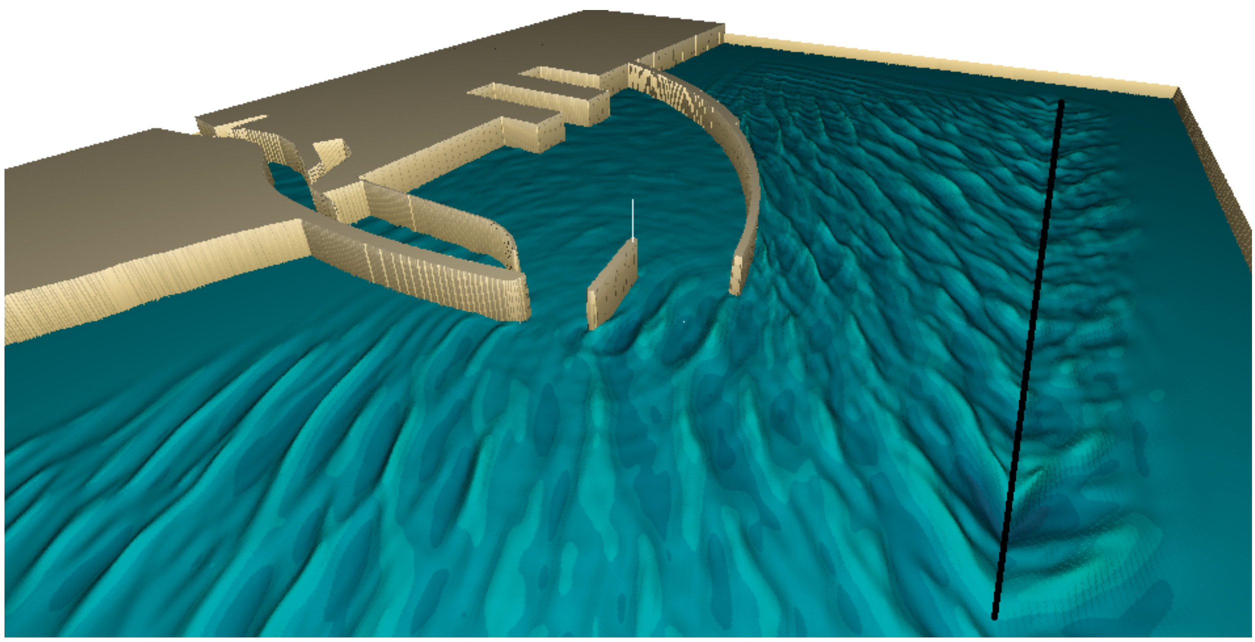

Fig. 20. Visualisation of the first layout. Snapshot taken at 47th time step when the highest wave occurs at the harbour entrance. Black line symbolize generation line

**Table 2. Summary of max. wave height obtained from simulation with random waves from north-west. Light grey colour symbolises the lowest value while dark grey – the highest values**

| Max. wave heights obtained from simulation with random waves from north-west | | | | |
|---|---|---|---|---|
| Location | Layout 1 | Layout 2 | Layout 3 | Layout 4 |
| Point 1 | 0.78 m | 1.04 m | 1.36 m | 0.78 m |
| Point 2 | 0.36 m | 0.20 m | 0.26 m | 0.15 m |
| Point 3 | 0.28 m | 0.09 m | 0.10 m | 0.22 m |
| Point 4 | 0.23 m | 0.11 m | 0.21 m | 0.35 m |
| Point 5 | 0.13 m | 0.14 m | 0.16 m | 0.14 m |
| Point 6 | 0.60 m | 0.35 m | 0.31 m | 0.60 m |

**Table 3. Summary of max. wave height obtained from simulation with random waves from north-east. Light grey colour symbolises the lowest value while dark grey – the highest values**

| Max. wave heights obtained from simulation with random waves from north-east | | | | |
|---|---|---|---|---|
| Location | Layout 1 | Layout 2 | Layout 3 | Layout 4 |
| Point 1 | 0.18 m | 0.12 m | 0.20 m | 0.63 m |
| Point 2 | 0.43 m | 0.29 m | 0.38 m | 0.55 m |
| Point 3 | 0.60 m | 0.26 m | 0.26 m | 0.49 m |
| Point 4 | 0.62 m | 0.21 m | 0.57 m | 0.56 m |
| Point 5 | 0.10 m | 0.08 m | 0.10 m | 0.10 m |
| Point 6 | 0.56 m | 0.54 m | 0.68 m | 0.72 m |

**Table 4. Summary of mean wave period obtained from LSA of random waves from north-west**

| Mean wave periods obtained from LSA with random waves from north-west | | | | |
|---|---|---|---|---|
| Location | Layout 1 | Layout 2 | Layout 3 | Layout 4 |
| Point 3 | 4.86 s | 4.94 s | 4.51 s | 4.66 s |
| Point 4 | 5.19 s | 4.59 s | 4.70 s | 4.83 s |
| Point 5 | 4.40 s | 5.90 s | 5.97 s | 5.63 s |

**Table 5. Summary of mean wave period obtained from LSA of random waves from north-east**

| Mean wave periods obtained from LSA with random waves from north-east | | | | |
|---|---|---|---|---|
| Location | Layout 1 | Layout 2 | Layout 3 | Layout 4 |
| Point 3 | 8.56 s | 6.98 s | 8.71 s | 6.95 s |
| Point 4 | 9.50 s | 9.54 s | 8.68 s | 5.89 s |
| Point 5 | 5.08 s | 7.08 s | 5.88 s | 7.45 s |

Point 4: In the proximity to the new quay in the new basin;

Point 5: In the entrance to the Coal basin in the old harbour;

Point 6: In the entrance to the new basin.

Wave heights have different values at the different locations inside the harbour, from the approximately 0.08 m inside the old harbour up to over 1.0 m at the detached breakwater. Despite the fact, that in the variant with waves coming from north-east imposed waves were significantly smaller ($H_s$ = 1.03 m instead 2.5 m for waves form north-west) the wave heights obtained at different points of the harbour are not so much smaller when compared to the previous variant. This is caused by the less favourable direction of wave propagation. Such direction of propagation makes it difficult to shelter the basins from the impact of incoming waves.

Maximum wave heights obtained from BW simulation are summarized in Table 2 and 3. In addition, mean wave periods $T_{01}$ are given in Table 4 and 5 for points 3,4,5, that is for the points which are located inside the harbour. In order to obtain information about wave periods Linear Spectral Analysis was used. As it can be easily seen in both variants of approaching wave directions the best results are given by the proposed layout 2. It provides the smaller waves in every point for waves coming from north-east and wave climate provide during wave incoming from north-west should also guarantee undisturbed berthing and cargo handling inside harbour. The worst solution seems to be layout 4. In almost every point obtained wave height exceed the threshold values of safe wave heights for yachts or small fishing boats.

Despite the fact that waves obtained in layout have quite large mean wave period (4.5 ÷ 9.5 seconds), that can influence both small and larger vessels, the wave height are small enough to assume, that it will not affect port operations.

To obtain wave period from results obtained from BW simulation a Linear Spectra Analysis was performed with default setup values. Log files from those analyses are located at Appendices.

## CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Planning and designing the harbour layout is very complex task, dependent on wide range of factors, such us technical, environmental or economic aspects. As the main task for harbour structures is to ensure safe conditions for berthing and cargo handling operations, the wave climate provided by the geometry and construction solutions have to be thoroughly investigated. Numerical simulations are of great help with this task. With growing computational power of computers they are growing in popularity as are cheap and efficient way of checking proposed solutions, optimising and making more reliable and durable constructions. To prepare a model that will give credible and reliable information is also a demanding and difficult process. One have to take into account a large variety of phenomena that take place in deep water and near the coastline. Numerous parameters have to be chosen wisely as they can significantly alter the results.

Obtaining representative input data is of highest importance, but is often quite troublesome, as measuring station are located far away from each other or do not take measurements at the same time. This was also the case in this study.

In spite of such difficulties effective analysis was conducted. Results from prepared numerical simulations of wave conditions provided by four different given concepts of new breakwater layouts indicate that the calmest wave climate is provided by the layout that was marked as Layout 2, that is the one without the detached breakwater and with large new oblong basin. For the two main wave directions checked, it gave the smallest wave heights inside the harbour basins and at the entrance to the harbour.

Prepared model has some shortcomings that could be easily corrected, given more time and with additional data and resources available. First of all, it lacks validation. This can be done in two ways. A scale model testing can be useful to check whether obtained wave patterns are realistic. This requires a facility with a wave basin and is quite expensive. Other method involves taking wave measurements inside the existing harbour and running additional numerical model with current geometry in order to calibrate all the parameters used in target models. This was impossible to prepare due to lack of input data for SW simulation from recent time.

The other drawback of the prepared model are simplifications used in order to make the model calculable on regular, not so powerful, personal computers. With more powerful processors complex phenomena such as wave breaking could be taken into account.

Conducted analysis verified only the basic criterion, that is the wave climate inside the harbour. In order to make sure, that no additional unfavourable phenomena take place, prepared models should be extended by additional features. Due to the fact that old Ustka harbour is located at the river mouth and river flow connected with storm surge was causing quay stability problems, information about hydrodynamics (currents, river flow, storm surge) should be included into numerical model. This would give valuable information about the impact of new structures on the conditions inside the harbour during such adverse conditions.

Harbour oscillations and seiches can be also causing unfavourable effects, especially on mooring systems. This phenomenon should be investigated as well to make sure that water oscillations induced by pressure changes or long waves entering the harbour do not have similar frequencies to the natural frequencies of water masses inside harbour basins.

Coastal structures affect natural processes that take place nearshore. This refers mainly to the sediment transport, that can be significantly disturbed by structures and induce disastrous effects and should be investigated additionally.

One last issue should also be noted. The research focused only on choosing the best layout out of four different concepts given by Maritime Office in Słupsk. Re-examination of the problem could possible reveal another harbour layout, that will provide even better wave climate inside as well as meet other criteria not included in this study.

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