Composite Modelling in Port Engineering

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Abstract. An introduction and review of the composite modelling, defined as the combining of physical and numerical models, are presented in this paper. Although the composite modelling is still in its infancy in the hydraulic community, in MSUCE it has been applied in many coastal projects, which will be described in this paper. The strengths and weaknesses of numerical and physical models for each case studies, are described. The optimal methodologies and guidelines on how to decide if the composite modelling is beneficial and how to set up a composite modelling experiment, are given. Finally, it was concluded that despite the challenges and difficulties, there is a growing trend toward applying the composite modelling as an effective tool in the field of coastal engineering.

1. Introduction

For the design of port facilities, it is necessary to correctly determine the design loads on the structures for the actual conditions of the design site and taking into account the proposed layouts and design of structures. Among external loads for port facilities, loads from wind waves, currents and wind are often decisive.

The calculated values of the parameters of wind waves, currents and wind, and their interaction with structures should be determined for the hydrometeorological conditions of a particular construction site. Four methods can be used for this: field measurements, physical modeling (laboratory studies in hydro wave basins and trays), calculation methods and mathematical modeling (numerical studies). Each of these methods has its advantages and disadvantages.

Field measurements of waves, currents and wind on the proposed construction site allow us to obtain actual values, but do not allow to obtain long-term statistics. Physical modeling allows us to explore the interaction of waves and wind with structures, taking into account the structural features of structures. However, physical modeling is limited by the scale of laboratory facilities and the need to ensure similarity criteria. For the physical modeling, it is not available to model the development and transformation of wind waves at considerable distances. The methods of calculation allow you to quickly obtain basic estimates, however, these methods are based on simplified solutions and they give unpredictable errors. Numerical methods make it possible to take into account the real hydrometeorological and topographic features of a particular region, but often it is necessary to use solutions that are not strict in terms of computational mathematics. Therefore, the right is to use all four methods when studying an object.

Currently, an integrated approach to the study of wave processes provides a hybrid or composite modeling, which is a combined use of numerical and physical models. Using numerical modeling, the characteristics of the wave regime and the wave parameters immediately in the front of the structure...
are determined, which are necessary to study the interaction of waves with structure. For immediate studies of the interaction of waves with structures, experiments on physical models are conducted in hydrodynamic laboratories. Using physical modeling, we can obtain many required parameters for the mathematical modeling of wave regime. As the reflection coefficients of waves from structures.

This article discusses an example of composite modeling for the structures of the designed dry cargo area of the Taman Sea Port (Russian Federation), Fig. 1. As a part of the research, numerical and physical modeling was carried out, in which the issues of determining wave effects on the port facilities were considered. The tests on the physical models in wave basins, performed by various teams of authors are described in detail. The results of numerical modeling were compared with laboratory experiments. The study was performed for regular and irregular waves. The advantages and disadvantages of using physical and numerical models are noted.

The research work was carried out by Witteveen + Bos in collaboration with Delft and Deltares (Netherlands) and MSUCE (Russian Federation).

![Figure 1. Project of the dry cargo area of the Taman Sea Port [1]](image)

2. **Set-up of the models**

2.1. **Physical model setup**

Physical modeling is one of the main methods for solving engineering problems. This method is effectively used in the design of hydraulic structures, when obtaining reliable theoretical results is associated with significant difficulties, due to the complexity of the processes. According to the theory of similarity, to study the process of wave action on structures on a hydraulic model, we must ensure geometric similarity of the model to a full-scale object, similarity of the wave regime and similarity of surface and volume forces, i.e., it is necessary to ensure that all defining similarity criteria are met. In the general case, it is impossible to achieve all these conditions at the same time. In particular, if we used fluid is the same in the model and in the natural conditions, so it is impossible to simultaneously ensure similarity by Froude (Fr) and Reynolds numbers (Re). However, for a number of tasks with
important practical significance, similarity in both parameters is not required. When the influence of viscosity is small, so during the wave motion or the impact of non-collapsed or collapsed waves on hydraulic structures, the dynamic similarity of model and natural processes is determined by the equality of the Froude numbers.

For physical modeling, the section of the designed port water area, which includes the location area of the heads of breakwaters and the approach channel, was selected. The approach channel has a length of 10.4 km, a width of 250 m (at the entrance to the port) and 170 m (at a distance from the port gate), the channel depth is 21.3 m. The scale of the physical model in the Deltares wave basin was chosen 1:60 (Fig. 2a) [2,3]. In MSUCE, the experiments were carried out in the laboratory of the Scientific and Educational Center "Hydrotechnics", two physical models were constructed at the scales of 1:52 (Fig. 2b) and 1:60 (Fig. 2c). As the main criterion for similarity, the Froude criterion was chosen. In the physical model in the wave basin, the length of waves was more than 0.7 m, therefore, the effect of surface tension and molecular viscosity of the liquid on the results was insignificant. Thus, the studied processes on physical models were dynamically similar to natural ones.

Figure 2 shows the location of wave sensors on physical models of Deltares and MSUCE. The direction of the wave approach in the Deltares experiments was 184 °, but in the MSUCE experiments was 190 °. It should be noted that the approach channel for Deltares model almost twice longer than for MSUCE model. Behind the model there is a damping beach for damping wave energy and preventing wave re-reflection. The process of the physical model construction in the wave basin of MSUCE is shown in Fig. 3.

Figure 2. Physical Model Plan: a - Deltares, M 1:60; b - MSUCE, M 1:52; c - MSUCE, M 1:60

In Deltares experiments, a generator of random multidirectional waves was used, but in MSUCE experiments, a generator of unidirectional waves was used. Both wave generators were equipped with active wave absorption, which allows to avoid the repeated reflection of waves from the shield of the wave producer.
2.2. Numerical model setup
A numerical model of a physical experiment in the Deltares wave basin, was created [2,3]. The authors used the following numerical models: SWAN [4], PHAROS [5], and SWASH [6]. Similar work was performed in MSUCE, by using SWAN and ARTEMIS models [7]. The bathymetry of the physical model has been transferred to the numerical. The SWAN, PHAROS, and SWASH models are spectral and use the well-known JONSWAP spectrum. Regular waves were used in the ARTEMIS numerical model.

To study the influence of the side walls of the MSUCE physical model (Fig.2b and Fig.2c), two computational domains were created in the ARTEMIS numerical model. Figure 4a shows the computational domain of the ARTEMIS model excluding the reflection from the side walls, and Fig. 4b shows the computational domain with reflection.

In Fig. 4, the wave-generating boundary is shown in blue, in yellow - freely releasing waves (with reflection coefficient \( kr = 0.0 \)), green - reflecting waves (\( kr = 1.0 \)), red - reflecting (\( kr = 0.52 \)) and
brown - reflecting border (kr = 0.9); reflection coefficients from port facilities are shown. The reflection coefficients from the port facilities were determined by a special series of experiments in the wave tray.

In the SWASH model, the wave-absorbing layer was specified as a damping beach. The diffraction module in SWAN was not used, because it could lead to an underestimation of the wave heights in the region of the approach channel and breakwaters.

2.3. Test conditions
In the SWAN, PHAROS, and SWASH numerical models, as well as in the Deltares physical model, the wave-generating boundaries are specified in the form of two-dimensional wave spectra with a wave propagation direction of 20°. Unidirectional waves are specified in the numerical model of ARTEMIS and on the physical model of MSUCE. Table 1 summarizes the boundary conditions for physical and numerical experiments conducted by Deltares and MSUCE. These wave characteristics were determined by the results of numerical simulation of SWAN; this is described in more detail in [8].

| Scenarios  | H_{m0}, m | T_p, s |
|------------|-----------|--------|
| Deltares   | 4.8       | 14.10  |
| MSUCE      | 4.7       | 14.45  |

In table 1: H_{m0} – significant wave height (m), T_p – peak wave period (s).

3. Results and comparative analysis
The results of numerical and physical modeling performed by Deltares and MSUCE are presented. In the first series of experiments on the MSUCE model with a scale of 1:52, the fastening slopes of the heads of breakwaters was made of tetrapods 13 tons weight. Based on the results of physical modeling, it was found that the stability of the head fastening elements to the influence of the design wave is not ensured - there was a multiple displacement of tetrapods, located in the zone of variable water level, and washout of the underlying layer of sorted stone - Fig. 5a. The selection of the mass of tetrapods that are resistant to the design waves was recommended to be carried out by the two-dimensional modeling in the wave tray of MSUCE. Using special series of experiments in the wave tray, it was found that the mass of tetrapods for fastening slopes of the heads of breakwaters must be increased to 20 tons, which ensures the stability of the protective fastening (Fig. 5b). Therefore, for the second series of experimental studies in the wave basin, the model was rebuilt at a new scale of 1:60, and the mass of tetrapods was increased to 20 tons.

Figure 5. Experiments in the wave basin and tray of MSUCE
The obtained wave fields for the conditions of physical modeling of the MSUCE in the numerical model of ARTEMIS are shown in Fig. 6a excluding the reflection from the side walls, in Fig. 6b with
the reflection. Figure 7 shows a comparison of the results of numerical and physical modeling for 8 points located at the port gate, where $H_{m0}$ is a significant wave height (m). The measured wave heights for physical modeling at points 2 and 6 have good agreement, but at point 3 the difference reaches 0.4 m. This discrepancy in the results can be explained by the reflection of waves from the side walls of the physical model. In the experiments conducted by MSUCE, the measurement point No. 3 is located quite close to the side wall, which affected the value of the wave height. As noted earlier, the Deltares model is geometrically twice larger than the MSUCE model and the measurement points are quite far from the side walls.

Figure 6. ARTEMIS wave fields: a - excluding reflection from side walls; b - with the reflection

Figure 7. The comparison of the results of numerical and physical modeling

The wave heights obtained by the ARTEMIS model excluding the side walls are in satisfactory agreement with the data of physical modeling of Deltares and MSUCE. Considering the reflection of waves from the side walls leads to an increase in wave heights, as shown in Fig. 6,7. This trend was partially shown in a physical experiment, as in MSUCE experiments, wave heights were measured only at three points No. 2; 3; 6. Taking into account the reflection from walls leads to the concentration of wave energy at points No. 5, 7, however, according to the physical modeling data of Deltares (Fig. 7) and MSUCE (Fig. 8), a decrease in wave heights is observed at these points. It can be concluded that the side walls in a physical experiment do not affect the measured wave heights, but considering reflection from the walls in the numerical model leads to an overestimation of the wave heights.
Each series of experiments in the MSUCE wave basin was repeated many times under constant conditions, but the wave height measurements at points were not stable. The discrepancy between the minimum and maximum values reached 10%; therefore in Fig. 7 the average wave heights are given. The results were also affected by the impossibility of accurate transmission of bathymetry from the physical model to the numerical one, which is one of the main problems of composite modeling.

![Experiments in the wave basin of MSUCE, M 1:60](image)

Figure 8. Experiments in the wave basin of MSUCE, M 1:60

Similar problems were identified in this work where, for comparison with the physical modeling data, the numerical models SWAN, PHAROS, and SWASH were used, Fig. 9. In these research works, the discrepancy between the results reached 20%. It is noted that the reasons are the reflection of waves from a navigation channel approaching the port. And scale effects that affect the results of physical experiments. The effects of wave reflection are not considered in this article, they are described in many studies [2, 3, 9].

In Fig. 9, a comparative analysis of the numerical modeling results performed by various teams of authors is carried out for points No. 4; 5; 6 (Fig. 7). The data of the physical experiment performed by Deltares was taken as a reference. Also, Fig. 10 shows wave fields in the port gate area. Figure 10a shows the SWAN and SWASH performed by Deltares. Figure 10b shows the SWAN performed by MSUCE.

![Comparative analysis of the numerical modeling results](image)

Figure 9. Comparative analysis of the numerical modeling results
The wave fields in Fig. 6a and Fig. 10 have a similar structure. They reflect the concentration of wave energy on the windward side of the channel, as well as its gradual damping in the area behind the channel. Comparing the simulation results showed that the SWAN model underestimates the value of wave heights at points № 5 and 6. This is due to the fact that the diffraction processes in SWAN are considered approximately. The ARTEMIS model also gives significant discrepancies, but they are caused by the approach of unidirectional regular waves. The results of the spectral models PHAROS and SWASH have the best convergence among the listed models.

4. Conclusions
This research shows the integrated use of the methods of numerical and physical modeling to obtain characteristics of wave loads and impacts on designed port hydraulic structures. The correctness of their definition is necessary for the development of effective and economical design solutions, as well as to ensure appropriate technologies during construction and operation.

The resulting economic effect from the use of composite modeling is determined individually for each port facility project. In all cases, it is associated with prevented damage from possible destruction of structures, the need for their reconstruction or repair, and losses during the period of inactivity. In addition, for large-scale modern projects, the described approach is the only possible, scientifically substantiated way to determine the design characteristics of loads on structures.

For the project of the dry cargo area of the Taman seaport (Russian Federation) for the sloping protection of the heads of the breakwaters, the designers proposed to use curly arrays - tetrapods with a mass of 13 tons. Experiments in the wave basin showed that such a protective coating is unstable, and to ensure stability it is necessary to increase the mass of tetrapods to 20 tons.

Numerical modeling of the waves made it possible to explain the increase in the height of the design waves in front of the breakwater head. This effect is associated with the concentration of waves on the edges of the approach channel. The increase in wave height leads to an increase in the load on the protective structures of the breakwater head.

The example shows the advantages and disadvantages of physical and numerical models. The disadvantages of the physical model include: scale and model effects; multiple instrumental measurements at a separate point and multiple repetitions of measurements do not give stability; the high labor input of physical models, as well as the need for special equipment. Advantages of the physical model: generally accepted modeling technology; its results are often used as a reference. The disadvantages of the numerical model: not all processes can be correctly described; high needs of computing power; inapplicability of numerical models for some problems creates the potential for
errors. Advantages of the numerical model: flexibility of models; adequate representation of various physical processes; data can be obtained in any point of the model and at any time.

The composite modeling technology, considered by the authors has shown its effectiveness, which allowed to obtain the necessary characteristics for design, construction and operation. Therefore, this integrated approach is the only possible and correct way for solving such tasks.

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