

УДК 627.52

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MODELING OF HYDRODYNAMIC AND LITHODYNAMIC COASTAL PROCESSES IN THE HARBOUR AREA

Received 27.04.2022, Revised 05.07.2022, Accepted 18.10.2022

Abstract

One of the problems in the design of ports is the assessment of coastal sediment movements near structures. The article presents materials for assessing the impact of port facilities on the processes of coastal erosion/accumulations in the area of Gelendzhik Bay (Black Sea). All the main processes of interaction of waves, currents and sediment movement occur in the coastal zone, therefore, the study presents the possibilities of complex application of hydrodynamic and lithodynamic models. In this work, the wind wave models Wave Watch III and SWAN were used. As the initial data, the data of the NCEP/NCAR reanalysis of wind fields in the period from 1989 to 2012 were used. To simulate currents, sediment transport and lithodynamic processes, a model of two-dimensional COASTOX–CUR currents generated by waves and wind, COASTOX–SED sediment transport together with the COASTOX–MORPHO bottom reshaping model was used. In the simulation scenario, a sequence of the 5 strongest storms from the period under consideration was considered. Analysis of washout zones/accumulations have shown that areas of intensive bottom reshaping are associated with the most intense currents. It is shown that the construction of the port facilities will not have a significant impact on the lithodynamic processes in the Gelendzhik bay.

Keywords: Port facilities, Black Sea, Gelendzhik Bay, numerical modeling, waves, current, lithodynamic processes

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МОДЕЛИРОВАНИЕ ГИДРОДИНАМИЧЕСКИХ И ЛИТОДИНАМИЧЕСКИХ БЕРЕГОВЫХ ПРОЦЕССОВ В РАЙОНЕ МОРСКОГО ПОРТА

Статья поступила в редакцию 27.04.2022, после доработки 05.07.2022, принята в печать 18.10.2022

Аннотация

Одной из проблем при проектировании портов является оценка перемещений береговых наносов вблизи сооружений. В статье приведены материалы оценки влияния сооружений порта на процессы береговой эрозии/аккумуляции в районе бухты Геленджик (Черное море). Все основные процессы взаимодействия волн, течений и движения наносов происходят в прибрежной зоне, поэтому в исследовании представлены возможности комплексного применения гидродинамических и литодинамических моделей. В данной работе использовались модели ветрового волнения Wave Watch III и SWAN. В качестве исходных данных использовались данные реанализа NCEP/NCAR полей ветра в период с 1989 по 2012 г. Для моделирования течений, переноса наносов и литодинамических процессов использовалась модель генерируемых волнами и ветром двумерных течений COASTOX–CUR, транспорта наносов COASTOX–SED совместно с моделью переформирования дна COASTOX–MORPHO. В сценарии моделирования рассматривалась последовательность 5-ти самых сильных штормов из рассматриваемого периода. Анализ зон размывов/аккумуляции показал, что участки интенсивного переформирования дна связаны с наиболее интенсивными течениями. Показано, что строительство сооружений порта не окажет существенного влияния на литодинамические процессы в Геленджикской бухте.

Ключевые слова: сооружения порта, Черное море, Геленджикская бухта, численное моделирование, волны, течения, литодинамические процессы

Ссылка для цитирования: Аншаков А.С. Моделирование гидродинамических и литодинамических береговых процессов в районе морского порта // Фундаментальная и прикладная гидрофизика. 2022. Т. 15, № 4. С. 101–108. doi:10.48612/fpg/xhaz-46hz-kk62

For citation: Anshakov A.S. Modeling of Hydrodynamic and Lithodynamic Coastal Processes in the Harbour Area. *Fundamental and Applied Hydrophysics*. 2022, 15, 4, 101–108. doi:10.48612/fpg/xhaz-46hz-kk62

1. Introduction

Assessment of the impact of seaport construction in the Gelendzhik Bay on currents and associated sediment transport distribution is included in a set of necessary measures to study the impact of this construction on coastal processes in the bay. Usually such estimates are made on the basis of observations of lithodynamic processes in the design area [1], but there are studies performed on the basis of numerical modeling [2]. Comprehensive numerical modeling of wind waves, hydrodynamics, sediment transport and lithodynamics provides the basis for conducting such a study. The key consideration was to compare changes in bottom bathymetry after series of design storms in today's conditions and after construction of port facilities.

The area of the projected port is located in Gelendzhik Bay on the northeastern shore of the Black Sea. Gelendzhik Bay juts into the shore for 3 km between Cape Tonky and Cape Tolstyy (Fig. 1). The depth at the entrance to the bay reaches 18 m, in the center of the bay — about 10 m and gradually decreases towards the shores. The shore of the bay in the construction area is abrasive, the height of the abrasive ledge is 1.5–2.0 m, and near the entrance capes the shores are rocky. There are practically no natural beaches (their width does not exceed 2 m).

Wind waves were modeled using the Wave Watch III and SWAN models [1–3]. To simulate currents, sediment transport and lithodynamics, we used the COASTOX–CUR model of two-dimensional currents generated by waves and wind, COASTOX–SED sediment transport together with the COASTOX–MORPHO seabed reshaping model [4–7].

2. Methods

Wave fields inside the Gelendzhik Bay, necessary for modeling currents and seabed reshaping, were calculated by the Wave Watch III (deep-water zone) and SWAN (coastal zone) models based on the NCEP/NCAR [8–10] reanalysis of wind fields in the period from 1989 to 2012. The same unstructured grids were used to model wind waves, as for lithodynamic modeling. Thus, errors arising from re-interpolation of fields from one grid to another were excluded.

COASTOX–CUR is a model for modeling of coastal currents generated under joint impact of wind, gradient currents of the deep-water zone, tides and wind waves. The numerical module solves two-dimensional shallow water equations using the finite volume method on unstructured grids, which include terms describing the effects of bottom friction, wave radiation stresses, and horizontal turbulent mixing. Due to the universal structure of model equations, they can, in addition to coastal currents, by appropriate boundary conditions and switched off function of



Fig. 1. Satellite image of the Gelendzhik Bay

wave radiation stresses, describe various long-wave processes — river currents, transformation of tidal waves, storm surges, tsunami waves. Algorithms for parallelizing computations on multiprocessor and/or multicore systems are also implemented.

The COASTOX current module is based on a two-dimensional system of equations time-averaged on scales significantly exceeding the period of “short” waves (storm waves, swell), in the long-wave (hydrostatic) approximation. These equations explicitly describe the tides and water level fluctuations associated with wind surges. The effect of short waves on currents and changes in the mean level is parameterized in the equations by wave stresses. The corresponding system of equations, in which the time-averaged currents in the coastal zone are determined by the balance between the wind shear stress τ_w , the bottom shear stress τ_b , the vertical averaged turbulent horizontal exchange tensor T_{ij} , the radiation stress tensor S_{ij} , and the force due to the free surface elevation gradient $\partial \xi / \partial x_i$, has the following form:

$$\frac{\partial h}{\partial t} + \frac{\partial q_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial q_i}{\partial t} + \frac{\partial}{\partial x_j} (u_j q_i) + g h \frac{\partial \xi}{\partial x_i} = \frac{\partial}{\partial x_j} \left(D_j \frac{\partial q_i}{\partial x_j} \right) - \tau_{bi} + \tau_{wi} + \tau_{si}, \quad (2)$$

where t — time, x_i — spatial coordinates, $h = \xi - \zeta$ — flow depth, u_i — current speed in i -direction; q_i — discharge in i -direction; $\zeta(x, y, t)$ — function of water surface; g — acceleration of gravity; τ_{si} — wave stress in i -direction; τ_{wi} — surface wind shear stress; D_j — horizontal turbulent viscosity coefficient (is a function of wave characteristics).

The bottom shear stress consists of two components. The first is determined by the quasi-stationary flow, and the other — by the bottom orbital motion of water particles induced by waves. After averaging of the bottom stress over the wave period, we obtain the following formula for the bottom stress due to the action of waves and currents:

$$\tau_{b1} = c_b \left\{ \left(U_{wc} + \frac{\omega_b^2}{U_{wc}} \cos^2 \alpha \right) u_1 + \left(\frac{\omega_b^2}{U_{wc}} \sin \alpha \cos \alpha \right) u_2 \right\}, \quad (3)$$

$$\tau_{b2} = c_b \left\{ \left(\frac{\omega_b^2}{U_{wc}} \sin \alpha \cos \alpha \right) u_1 + \left(U_{wc} + \frac{\omega_b^2}{U_{wc}} \sin^2 \alpha \right) u_2 \right\}, \quad (4)$$

where α — direction of wave propagation to coastline relatively to coordinate line x_1 .

$$U_{wc} = \frac{1}{2} \left\{ \sqrt{u_1^2 + u_2^2 + \omega_b^2 + 2(u_1 \cos \alpha + u_2 \sin \alpha) \omega_b} + \sqrt{u_1^2 + u_2^2 + \omega_b^2 - 2(u_1 \cos \alpha + u_2 \sin \alpha) \omega_b} \right\}, \quad (5)$$

$$\omega_b = \frac{\sigma H_w}{\pi \sinh[kh]}. \quad (6)$$

Here σ — wave angular frequency; H_w — wave height; k — wave number.

Wave stresses can be calculated by the formula:

$$\tau_{si} = -\frac{1}{\rho_w} \frac{\partial S_{ij}}{\partial x_j}, \quad (7)$$

where S_{ij} — wave-generated radiation stresses. At depths less than 0.35 m, radiation stresses are given by the ratio:

$$\tau'_s = \tau_s \frac{h}{0.35}. \quad (8)$$

The COASTOX-SED model is based on the numerical solution of the equations of advective-diffusion sediment transport by the finite volume method. The local intensity of sedimentation and erosion processes is taken to be proportional to the difference between the instantaneous and equilibrium sediment concentration in each grid node. To calculate this intensity, set of known formulas of the modern theory of coastal sediment transport is used. At the same time, the Van Rijn formulation [11–13] is recommended as the main one for non-cohesive sandy sediments and fractions close to them in size, and the Camenen-Larsen [14] formulation is recommended for pebble sediments.

The COASTOX-MORPHO model is based on a two-dimensional equation of the mass balance of seabed sediments in the coastal zone (Exner's equation), which is numerically implemented on the same computational grid as the COASTOX-CUR and COASTOX-SED models.

The wind wave modeling was carried out on four nested rectangular grids. The first grid covered the entire Black Sea, the number of grid nodes was 288×117 , the grid cell size was 3 minutes, or approximately 5.5 km. The second grid covered the North-Eastern part of the Black Sea — 267×169 points, cell size — 0.6 min or 1.1 km. The third grid covers the coastal zone of the sea opposite the bay — 239×88 points, cell size 0.15 min, or 275 m. The fourth grid covered the water area of the Gelendzhik Bay. When constructing the grid, the projected port facilities were taken into account. The number of grid nodes is 238×168 , the cell size is about 27.5 m. The bathymetry for the computational grids was interpolated to the nodes from the GEBCO topographic publicly available data on a 30-second grid, as well as for the coastal zone from Kerch to the eastern border of Turkey from the digitized graphic sea maps C-Map v93.2. For the coastal part of the Gelendzhik port, depths from construction drawings, measured with an echo sounder, were used [15].

To model hydrodynamic and lithodynamic processes, two computational grids were constructed. One for the bathymetry of Gelendzhik Bay in the today's conditions, the other — taking into account the design facilities of the port and dredging zones.

The grid size in the first case is 47625 nodes, 94414 elements, in the second — 54383 nodes, 107532 elements. The linear size of the grid cells varies from 100 m in the east of the bay to 5 m in the port area (Fig. 2).

Taking into account the assumption that main seabed reshaping is usually caused by strong storms, the 5 strongest storms were selected from the period under consideration, for which currents, suspended sediments concentrations and the final picture of bed level changing were then calculated.

The table shows the simulated storms. The average duration of the storms was 8 days, and the total duration of the simulation period was 41 days.

Based on field data of seabed soils in the Gelendzhik Bay, the sediments were considered as non-cohesive sediments (sand) with the following characteristics: density — 2650 kg/m^3 ; particle size distribution — $D_{50} = 0.1 \text{ mm}$, $D_{90} = 0.3 \text{ mm}$. The soil porosity was taken equal to 0.33.

To calculate sediment transport in conditions of waves and currents action, the Van Rijn model was used. In this model, direction of sediment transport coincides with flow direction.

Table

Duration and characteristics of simulated storms

№	Dates of storm	Duration of storm, days	Significant wave height at entrance to the bay, m
1	03.12.1989–09.12.1989	6	5.80
2	16.01.1993–27.01.1993	11	5.51
3	25.12.2001–31.12.2001	6	5.44
4	30.01.2003–06.02.2003	7	5.85
5	05.11.2007–16.11.2007	11	6.18

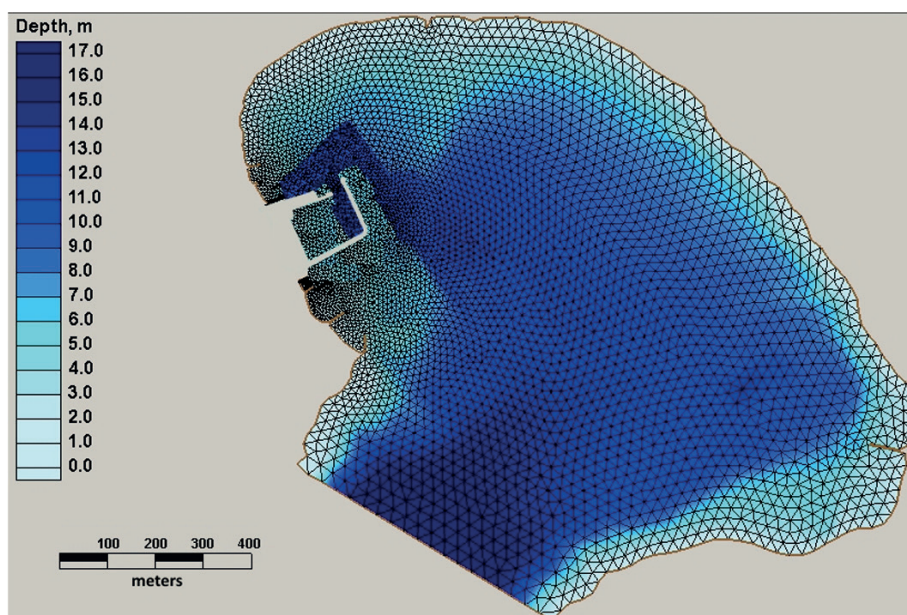


Fig. 2. Unstructured grid of SWAN and COASTOX models

3. Results and Discussion

For the selected extreme storms, with a wind force more than 10 m/s, the prevailing directions were the directions of approaching waves in the segment from south to west. The strongest winds were observed for the west and southwest directions. Wind speed from southwest reached values of 20–24 m/s. The distribution of currents in the Gelendjik Bay and in the area of the designed port during the extreme storm from 05.11.2007 to 16.11.2007 is shown in Fig. 3, 4 separates for today's conditions and after construction of port facilities.

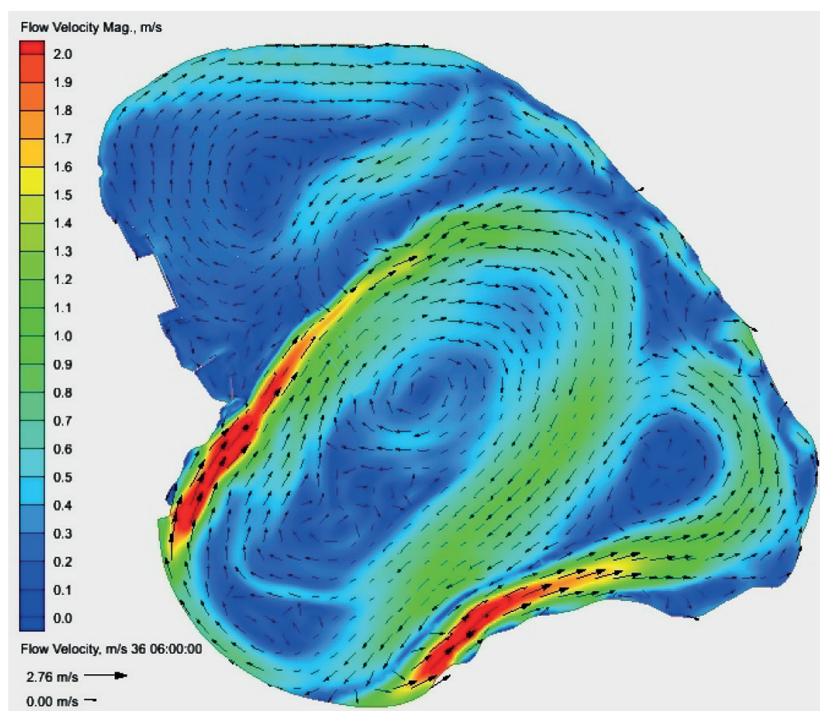


Fig. 3. Currents in the Gelendjik Bay in today's conditions

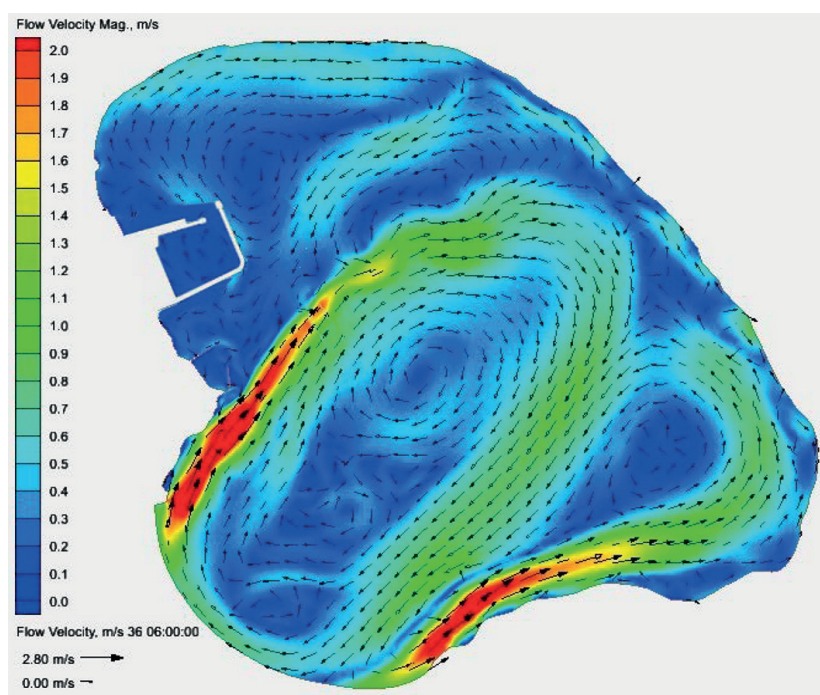


Fig. 4. Currents in the Gelendjik Bay after construction of port facilities

The construction of the Gelendjik port has practically no effect on the distribution of currents in the southeastern part of the Gelendjik Bay.

The currents in the central part of the bay are influenced by the port facilities. However, the general distribution of the currents after construction does not change. The main change is due to the fact that currents coming from the Cape Tonkyy becomes more unstable after the port construction and may deviate somewhat more to the west or east than before construction.

In addition, the distribution of currents in the northwestern part of the bay changes the most after the construction of the port. First, the form of vortices changes significantly. Their number may also change. There are also no strong alongshore currents, north of the existing pier, they are blocked by the port.

The final bed level change in the Gelendjik Bay and in the port area is shown in Fig. 5, 6.

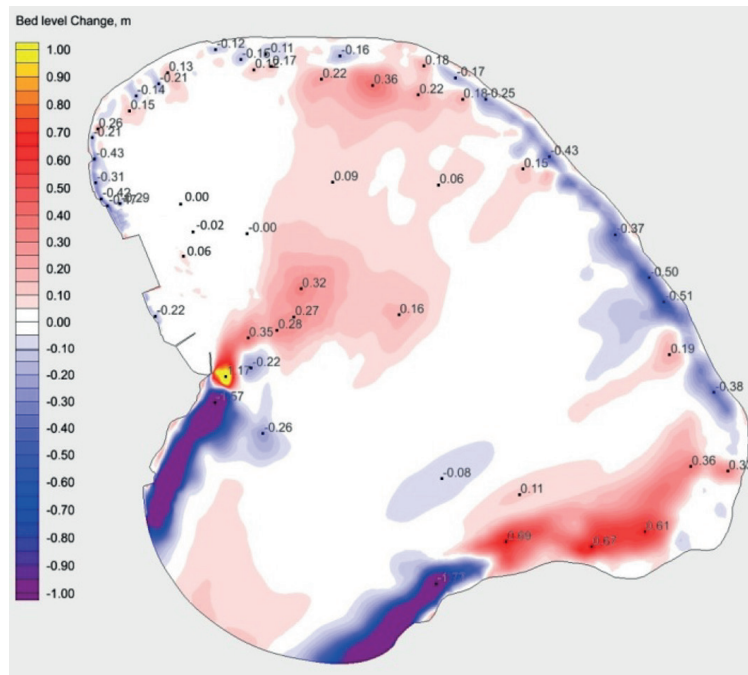


Fig. 5. Final bed level change in the Gelendjik Bay after the set of five extreme storms in today's conditions

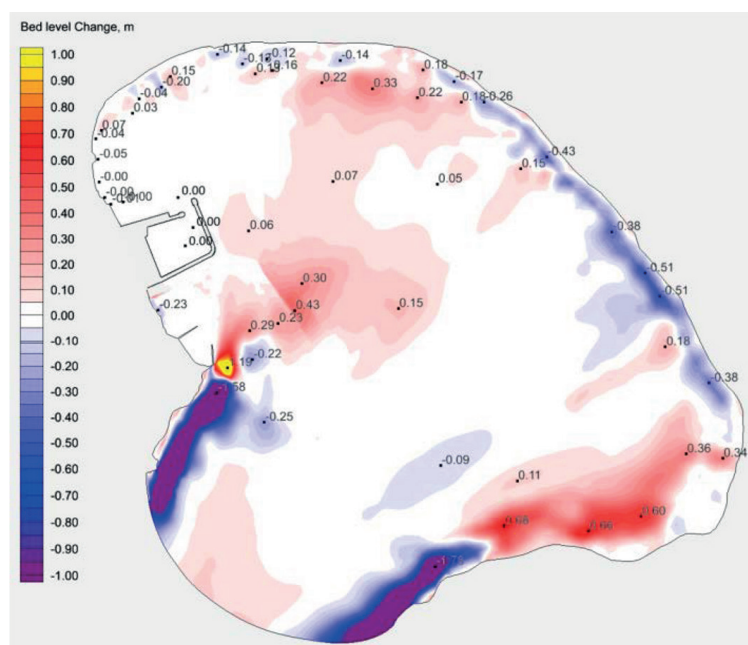


Fig. 6. Final bed level change in the Gelendjik Bay after the set of five extreme storms after construction of port facilities

Based on the analysis results of erosion/accumulation in today's conditions, it can be concluded, that the areas of the strongest bed level changes in the Gelendjik Bay are associated with the most intense currents. Thus, the largest erosion in the bay is observed in areas of strong currents near the capes that limit the entrance to the bay. The value of the maximum erosion is observed near the capes and is about 1.8 m. The eroded material is carried away by currents from the capes and is settled where the currents slow down.

In the eastern part of the bay, sediment accumulation zones of about 0.7 m in size are formed. Accumulation zones of lower values is formed in the western part of the bay, along the current course from the cape to the north, the value of accumulation thickness layer is about 0.3 m.

Significant bed level change is also observed along the coastline in the northeastern and central parts of the bay. In the northeastern part, the values of erosion are about 0.4–0.5 m. In the central part — about 0.15–0.4 m. There is also an accumulation zone of about 0.2–0.3 m in front of the erosion zone in the central part.

In the port facilities area, bed level changes are insignificant. At a distance of about 100 m southeast of the southern breakwater, there is a small accumulation zone with layer thickness of about 0.1 m.

4. Conclusions

The construction of the port in the Gelendjik Bay has no significant effect on the distribution of erosion/accumulation zones in the bay in its eastern and northern parts and along the coast in the northeast. The construction of the port caused the disappearance of the erosion zone along the coastline to the north of the constructed berth, which is due to the blocking of the currents observed here.

For the technical water areas of the port, the following can be concluded. The areas of the Gelendjik Bay, which belong to the technical water areas of the designed port, are not subject to significant sediment accumulation or erosion. Also, the dredging area to the north-east of the port generally does not tend to accumulation. In the protected port water area, the processes of bed level changing do not take place.

Acknowledgements

The author is grateful to Professor E.N. Pelinovsky for consultations during the preparation of this paper.

Funding

This study was initiated particularly in the framework of the grant of the President of the Russian Federation (MK -3792.2021.4).

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