UDC 519.6 10.23947/2587-8999-2021-1-1-36-43

HYDRODYNAMIC WAVE PROCESSES NUMERICAL MODELING IN THE COASTAL RECREATIONAL ZONE OF THE TSIMLYANSK RESERVOIR *

A.I. Sukhinov[1], V.V. Sidoryakina[2], E.A. Protsenko[2]

[1] Don State Technical University, Rostov-on-Don, Russia

[2] Taganrog Institute after A.P. Chekhov (branch) of RSUE, Taganrog, Russia

✉ sukhinov@gmail.com, cvv9@mail.ru, eapros@rambler.ru

This paper presents the results of wave regime hydrophysical characteristics calculations in the area of the accumulative shore of the Tsimlyansky reservoir northwestern part. Wave hydrodynamics model based on 3D mathematical model that includes three Navier-Stokes motion equations, the continuity equations for an incompressible fluid was used. The discretization of the hydrodynamic equations was performed using the pressure correction method. Numerical algorithms and the software package implementing them are used to determine the pressure field, the water medium velocity vector field and to plot the pressure a given section of the reservoir water area. The results of the study can be used in the study of hydrophysical processes, assessment of the hydrodynamic impact on the formation of the coast-line and the bottom relief of large plain-type reservoirs in the Southern Russia.

Keywords: modeling of hydrodynamic processes, wave processes, large reservoirs, aquatic ecosystem, coastal recreational zone, parallel algorithms.

Introduction. Reservoirs play an important role in the water management complex of Russia. The creation of these water bodies is aimed at ensuring the regulation and redistribution of river flow over time, guaranteed water supply to the population, meeting the needs of the population for energy resources, protecting territories from floods, etc. Together with canals and other water supply facilities, water storage facilities serve as the basis for the versatile and integrated use of water resources [1-4].

In Southern Russia, where there is an acute shortage of water resources, especially in the spring and summer period, the development and implementation of measures aimed at preserving and improving the hydroecological state of water reserves is extremely important. One of the main waterways of the Southern Russia is the Don River. The only reservoir on the Don River is the Tsimlyansk reservoir, located in the Volgograd and Rostov regions. The reservoir was built in 1948-1952, by creating a dam near the modern city of Tsimlyansk. The Tsimlyansk reservoir belongs to the category of large ones. The total volume of the reservoir is 23.8 km^3. The reservoir serves to meet the needs of the population in fresh water, irrigation, energy resources, convenient transport routes, is one of the attractive places for recreation and fishing.

The high economic development of the Tsimlyansky reservoir in recent decades contributes to the growth of external load on it, the consequence of which is the complication of the hydrological

* The reported study was funded by RFBR according to the research project № 19-01-00701.

situation and the deterioration of the state of ecosystems. Thus, the destruction of the banks has a significant impact on the infrastructure of the reservoir. The rather large size of the Tsimlyansky reservoir (the mirror area is 2702 km^2) allows wind waves up to 4-5 m high to form, which conduct their destructive work. In connection with the above, one can imagine how great scientific and practical importance the objective study of this water body has.

The most effective research methods in this area are based on determining the parameters of wave action, since they have a significant impact on all elements of the hydrological regime of reservoirs. To date, limnology has already accumulated some experience in hydrodynamic modeling of wave processes. When modeling, it is possible to take into account the features of natural processes characteristic of large reservoirs, such as their significant spatial and temporal variability, multidimensionality, non-linearity of processes and the different scale of dynamic phenomena [5-8].

In this paper, for the water area of the Tsimlyansky reservoir, the results of the study and parallel numerical implementation of a nonlinear 3D model of wave hydrodynamic processes are presented. The developed algorithms for solving model problems and their numerical implementation in the form of a problem-oriented software package have a wide practical application for studying wave processes of coastal systems of the same type of water bodies and their hydrodynamic impact on the territory of the coast. A private object of modeling is the north-western coast of the Tsimlyansk reservoir, located near Tsimlyansk, the territory of which includes the city beach. For the selected local area, studies of the hydrodynamic characteristics of the wave effect on the coastal recreational zone, such as the pressure field, the field of the velocity vector of the water medium, were carried out and pressure plots were constructed for different phases of the wave.

Mathematical model of three-dimensional wave hydrodynamics. The developed model for calculating 3D velocity vector of the aquatic environment movement based on is hydrodynamics mathematical model of shallow water bodies [9, 10]:

– the equation of motion in three coordinate directions (system of Navier-Stokes equations)

$$u'_t + uu'_x + vu'_y + wu'_z = -\frac{1}{\rho}P'_x + \left(\mu u'_x\right)'_x + \left(\mu u'_y\right)'_y + \left(\nu u'_z\right)'_z, \tag{1}$$

$$v'_t + uv'_x + vv'_y + wv'_z = -\frac{1}{\rho}P'_y + \left(\mu v'_x\right)'_x + \left(\mu v'_y\right)'_y + \left(\nu v'_z\right)'_z, \tag{2}$$

$$w'_t + uw'_x + vw'_y + ww'_z = -\frac{1}{\rho}P'_z + \left(\mu w'_x\right)'_x + \left(\mu w'_y\right)'_y + \left(\nu w'_z\right)'_z + g, \tag{3}$$

– continuity equation (mass conservation law)

$$\rho'_t + (\rho u)'_x + (\rho v)'_y + (\rho w)'_z = 0, \tag{4}$$

where $\mathbf{V} = \{u, v, w\}$ is the water flow of shallow water body velocity vector; P is the hydrodynamic pressure; ρ is the aquatic environment density; μ, ν are turbulent exchange coefficients in the horizontal and vertical directions; g is the gravity acceleration.

The system of equations for the movement of the aquatic environment in mouth areas (1) - (4) is considered under the following initial condition

$$\mathbf{V} = \mathbf{V}_0 \tag{5}$$

and boundary conditions:

–entrance (incoming streams from the sea and in the riverbed)

$$\mathbf{V} = \mathbf{V}_0, \ P'_{\mathbf{n}} = 0, \tag{6}$$

– lateral and lower water-bottom boundary

$$\rho_v \mu (\mathbf{V}_\tau)'_{\mathbf{n}} = -\boldsymbol{\tau}, \ \mathbf{V}_{\mathbf{n}} = 0, \ P'_{\mathbf{n}} = 0, \tag{7}$$

– lateral “water-water” boundary

$$(\mathbf{V}_\tau)'_{\mathbf{n}} = 0, \ \mathbf{V}'_{\mathbf{n}} = 0, \ P'_{\mathbf{n}} = 0, \tag{8}$$

– water surface (“water-air” boundary)

$$\rho_v \mu (\mathbf{V}_\tau)'_{\mathbf{n}} = -\boldsymbol{\tau}, \ \ w = -P'_t / \rho g, \ P'_{\mathbf{n}} = 0, \tag{9}$$

where $\mathbf{V}_{\mathbf{n}}, \mathbf{V}_\tau$ are the velocity vector normal and tangential component; $\mathbf{n}$ is the normal vector; $\boldsymbol{\tau} = \{\tau_x, \tau_y, \tau_z\}$ is the tangential stress vector; ρ_v is suspension density.

On the free surface of a water body, the tangential stress is calculated as follows

$$\boldsymbol{\tau} = \rho_a C d_s |\mathbf{w}| \mathbf{w} \tag{10}$$

where $\mathbf{w}$ is the wind velocity relative to water; ρ_a is the atmosphere density; $Cd_s = 0.0026$ is the dimensionless surface resistance coefficient, which depends on wind speed [11].

At the water body’s bottom, the tangential stress has the form

$$\boldsymbol{\tau} = \rho C d_b |\mathbf{V}| \mathbf{V},$$

where $Cd_b = gk^2 / h^{1/3}$, $k = 0.025$ is the group roughness coefficient in Manning's formula; h is the distance from free surface to bottom.

To discretize the model (1)-(10), we apply the pressure correction method, according to which the solution process is divided into three problems [15-16]. Discrete analogs are solved by an adaptive modified alternating-triangular method of variational type [21, 22].

Numerical experiments. After the development of the software package, a series of numerical experiments was performed. The selected site for conducting numerical experiments is located in the northwestern part of the Tsimlyansk reservoir near the city of Tsimlyansk. The local modeling area has a size of $5\times10^3 \times 5\times10^3$ m and a maximum depth of 18 m, the peak point rises 2 m above sea level. The source of the disturbances is set at a certain distance from the shore line. At the initial moment of time, the liquid is at rest.

In order to prepare the input data, digital model area is constructed that displays depths map of the calculated area and the contour of the bottom surface and the coastline depths (Fig. 1, 2). The model area is characterized by geometrically complex coastline configuration.

For the calculated area, a uniform grid with dimensions of 100 × 100 × 40 is constructed, which corresponds to the size of cells of the order of 50 m in horizontal directions and 0.2 m in vertical directions. The input data on the depth readings of the water body were interpolated to this grid.

In order to be able to talk about the adequacy of the hydrodynamic wave model, an initial set of information is required, including information about the pressure field and the velocity vector field of the aqueous medium. Fig. 2 shows the calculations results of these characteristics.

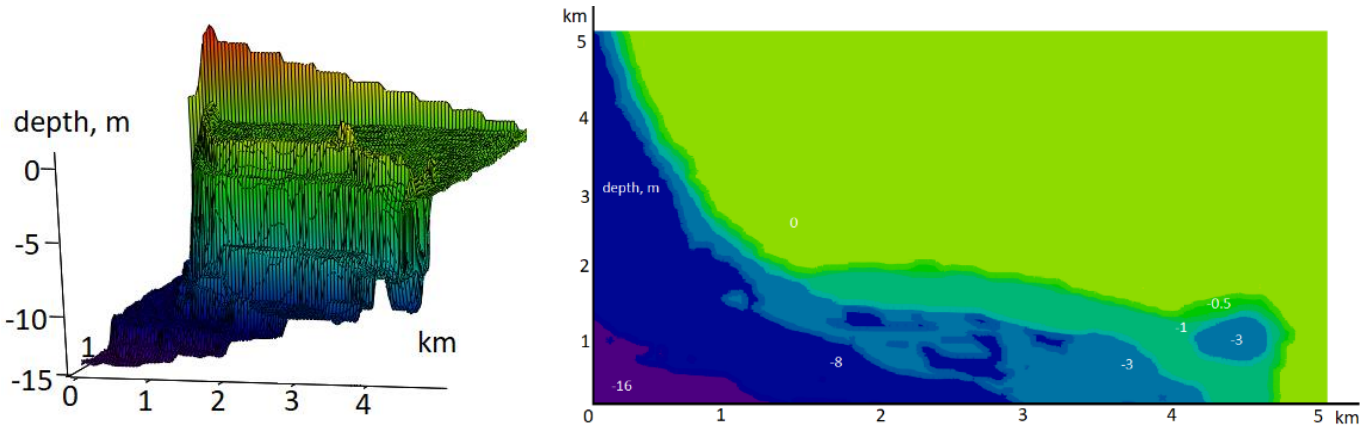

Fig. 1. Isolines and depth map of the calculated area

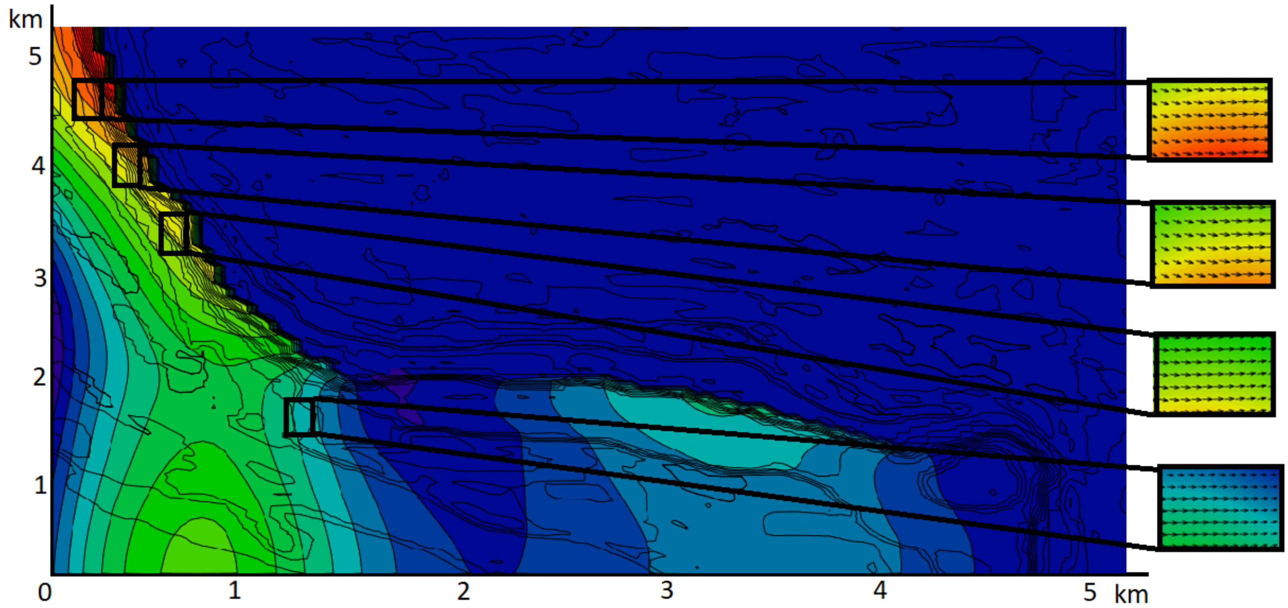

Fig. 2. The pressure field and the velocity vector field of the water medium

The geometric heterogeneity of the site significantly affects the kinematic structure of the water flow. The change in the patterns of the velocity vector field when the wave rolls onto the coastline is clearly visible.

On the section of the calculated area corresponding to the territory of the city beach, the function of the elevation of the level changes dynamically, flooding and shallowing zones are formed. To the left of the beach area, a vortex formation is emerging against the background of wave microturbulent exchange. In order to fully represent the picture of the velocity field, the calculated profiles of the horizontal velocity of the water medium in various sections of the calculated region by the *Oxz* plane passing through the beginning of the cut are given. Fig. 4. shows pressure diagrams for different phases of oncoming waves.

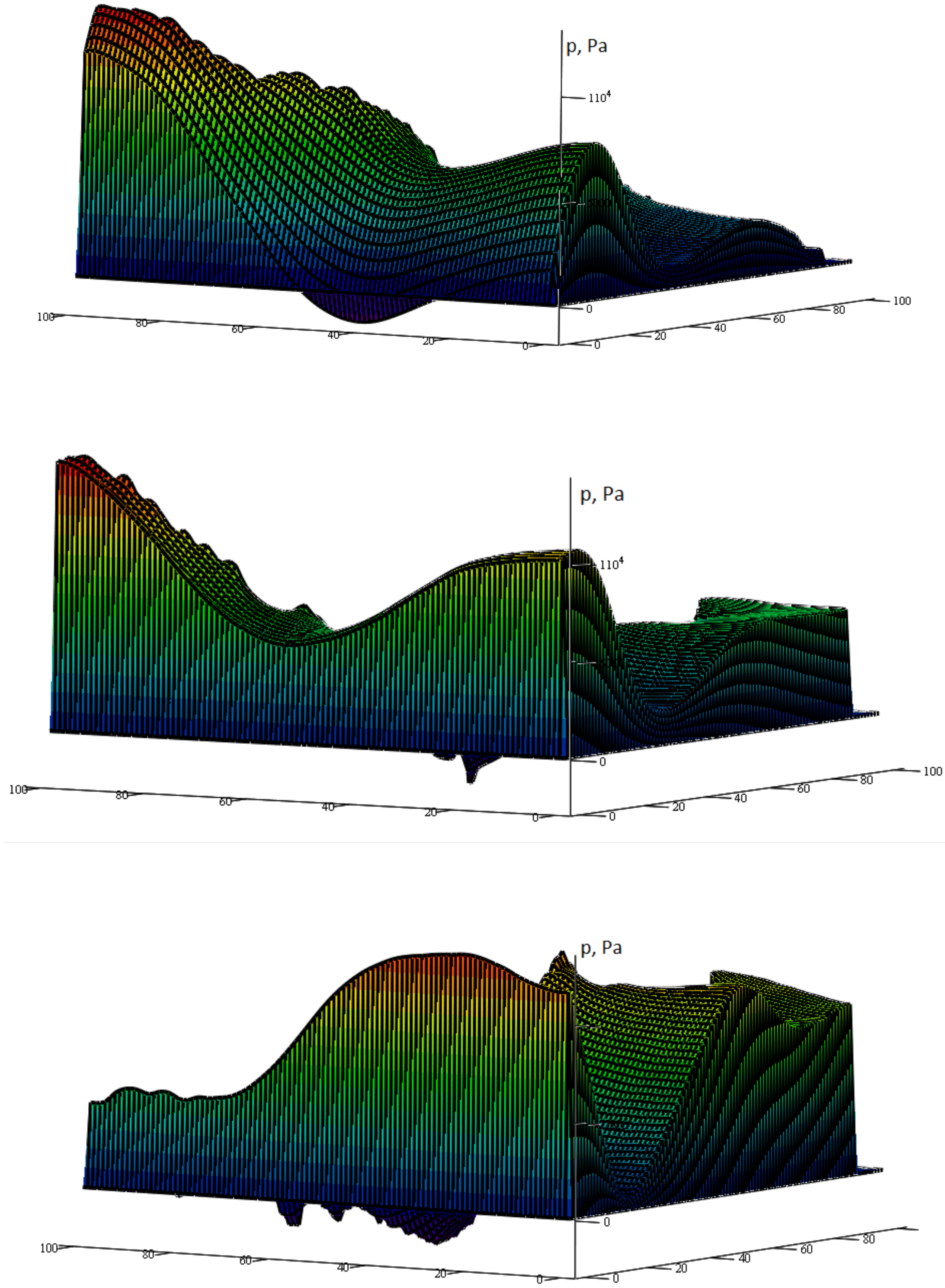

Fig. 3. Pressure diagrams for different phases of oncoming waves

Conclusion. The problem of assessing the hydrodynamic characteristics of wave processes is important in solving many economic problems. Calculations of these characteristics are one of the most important elements that determine the safety of the coastal infrastructure. In addition, their consideration is necessary when predicting the state of the surface of a water object and for compiling its regime and climatic characteristics. A lot of attention is currently being paid to the disturbance regime of the Tsimlyansky reservoir. However, despite this, the available material is not complete and sufficient to solve various practical problems, including the problems of calculating the transformation of the shores. The model of three-dimensional hydrodynamic wave processes developed by the authors takes into account, along with generally accepted factors, such as wind stress on a free surface, friction on the bottom, etc., also evaporation and precipitation not only in the continuity equation, but also in the equations of motion of the aquatic environment, which is essential for the waters of large reservoirs. Numerical algorithms and a set of programs that implement them have been developed for the proposed model, which made it possible to calculate the hydrodynamic characteristics of wave processes in natural conditions in the coastal recreational zone of the reservoir. The results of numerical experiments are presented.

References

1. Vakhitov R.R., Karimova L.Z. Some aspects of the impact of reservoirs on the geoecological environment // Problems of life support for large cities. - Naberezhnye Chelny. – 2002. – P. 360-361 (in Russian).
2. Usmanov B., Nicu I.C., Gainullin I., Khomyakov P.V. Monitoring and assessing the destruction of archaeological sites from Kuibyshev reservoir coastline. Tatarstan Republic, Russian Federation. A case study // Journal of Coastal Conservation. – 2018. – Vol. 22, № 2. – P. 417–429. DOI:10.1007/s11852-017-0590-9.
3. Vuglinsky V.S. Water resources and water balance of large reservoirs of the USSR // Moscow: Gidrometeoizdat. – 1991, p. 222.
4. Su X., Nilsson C., Pilotto F., Liu S., Shi S., Zeng B. Soil erosion and deposition in the new shorelines of the Three Gorges Reservoir // Sci. Total Environ. – 2017, 599 –600. – P. 1485–1492. DOI: 10.1016/j.scitotenv.2017.05.001.
5. Nikanorov A.M., Horuzhaya T.A., Minina L.I., Martysheva N.A. The danger of "blooming" of the Tsimlyansk reservoir // Vodoochistka. Water treatment. Water supply. – 2011. – Vol. 2, № 38. – P. 70–74.
6. Khoruzhaya T.A., Minina L.I. Assessment of the ecological state of the Tsimlyanskoye, Proletarskoye and Veselovskoye reservoirs // Meteorology and Hydrology. – 2017. – Vol. 5. – P. 117–122.
7. Bakaeva E.N., Ignatova N.Akh. Water quality in the dam part of the Tsimlyansk Vodoksranilish under conditions of the color of blue-green microalgae // Global nuclear safety. – 2013. – Vol. 1, № 6. – P. 23-28.
8. Lobchenko E.E., Minina L.I., Nichiporova I.P., Pervysheva O.A. Dynamics of water quality in the Tsimlyansk reservoir (for the period from 1979 to 2014) // Water management of Russia: problems, technologies, management. – 2016. – Vol. 6. – P. 74-92.
9. Monin A.S. Turbulence and microstructure in the ocean // Physics-Uspekhi. – 1973. – Vol. 109, № 2. – P. 333-354.
10. Shokin Yu.I., Chubarov L.B., Marchuk An.G., Simonov K.V. Vychislitelnyi eksperiment v probleme tsunami // Novosibirsk: Nauka. Sib. otd. – 1989, – p 164.
11. Belotserkovskiy O.M. Turbulentnost: novye podkhody // M.: Nauka. – 2003, p 286.
12. Belotserkovskii O.M., Gushchin V.A., Shchennikov V.V. Use of the splitting method to solve problems of the dynamics of a viscous incompressible fluid USSR // Computational Mathematics and Mathematical Physics. – 1975. – Vol. 15, № 1. – P. 190-200. DOI:10.1016/ 0041-5553(75)90146-9.
13. Belotserkovskiy O.M., Gushchin V.A., Kon'shin V.N. The splitting method for investigating flows of a stratified liquid with a free surface // USSR Computational Mathematics and Mathematical Physics. – 1987. – Vol. 27, № 2. – P. 181-191.

14. Sukhinov A.I., Chistyakov A.E., Protsenko E.A., Sidoryakina V.V., Protsenko S.V. Accounting method of filling cells for the hydrodynamics problems solution with complex geometry of the computational domain // Matem. Mod. – 2019. – Vol. 31, № 8. – P. 79–100. DOI: https://doi.org/10.1134/S0234087919080057.

15. Sukhinov A.I., Chistyakov A.E., Protsenko E.A., Sidoryakina V.V., Protsenko S.V. Set of coupled suspended matter transport models including three-dimensional hydrodynamic processes in the coastal zone // Matem. Mod. – 2020. – Vol. 32, № 2. – P. 3–23. DOI: https://doi.org/10.20948/mm-2020-02-01.

16. Sukhinov A.I., Chistyakov A.E., Protsenko E.A., Sidoryakina V.V., Protsenko S.V. Parallel algorithms for solving the problem of coastal bottom relief dynamics // Num. Meth. Prog. – 2020. – Vol. 21, № 3. – P. 196–206. DOI: https://doi.org/10.26089/NumMet.v21r318.

17. Sukhinov A.I., Chistyakov A.Ye., Fomenko N.A. Metodika postroyeniia raznostnykh skhem dlia resheniia zadach diffuzii-konvektsii- reaktsii, uchityvaiushchikh stepen zapolnennosti kontrolnykh yacheek // Izvestiia YUFU. Tekhnicheskie nauki. – 2013. – Vol. 4, № 141. – P. 87-98.

18. Sidoryakina V.V., Sukhinov A.I. Well-posedness analysis and numerical implementation of a linearized two-dimensional bottom sediment transport problem // Comput. Math. Math. Phys. – 2017. – Vol. 57, № 6. – P. 978–994. DOI:https://doi.org/10.1134/S0965542517060124.

19. Sukhinov A.I., Sukhinov A.A. 3D Model of Diffusion-Advection-Aggregation Suspensions in Water Basins and Its Parallel Realization // Parallel Computational Fluid Dynamics, Multidisciplinary Applications, Proceedings of Parallel CFD 2004 Conference, Las Palmas de Gran Canaria, Spain, ELSEVIER, Amsterdam-Berlin-London-New York-Tokyo. – 2005. – P. 223-230.

20. Samarskii A.A. The Theory of Difference Schemes // New York, Basel, Marcel Dekker Inc. – 2001, p. 761.

21. Samarskiy A.A., Nikolayev Ye.S. Metody resheniia setochnykh uravnenii // M.: Nauka. – 1978, p. 592.

22. Sukhinov A.I., Chistyakov A.E. Adaptive Modified Alternating Triangular Iterative Method for Solving Grid Equations with a Non-Self-Adjoint Operator // Mathematical Models and Computer Simulations. – 2012. – Vol. 4, № 4. – P. 398-409.

Authors:

Sukhinov Alexander, Don State Technical University (1st Gagarin Square, Rostov-on-Don, Russian Federation), corresponding Member of the Russian Academy of Sciences, Doctor of Science in Physics and Maths, Professor

Sidoryakina Valentina, Taganrog Institute of A.P. Chekhov (branch) RSUE (Initiative Street, Taganrog, Russian Federation), Candidate of Science in Physics and Maths, Associate professor

Protsenko Elena, Taganrog Institute of A.P. Chekhov (branch) RSUE (Initiative Street, Taganrog, Russian Federation), Candidate of Science in Physics and Maths, Associate professor

УДК 519.6 10.23947/2587-8999-2021-1-1-36-43

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ГИДРОДИНАМИЧЕСКИХ ВОЛНОВЫХ ПРОЦЕССОВ В ПРИБРЕЖНОЙ РЕКРЕАЦИОННОЙ ЗОНЕ ЦИМЛЯНСКОГО ВОДОХРАНИЛИЩА*

А.И. Сухинов[1], В.В. Сидорякина[2], Е. А. Проценко[2]

Донской государственный технический университет, Ростов-на-Дону, Российская Федерация
Таганрогский институт им. А.П. Чехова (филиал) РГЭУ (РИНЭ), Таганрог, Российская Федерация

✉ sukhinov@gmail.com, cvv9@mail.ru, eapros@rambler.ru

В настоящей работе представлены результаты расчетов гидрофизических характеристик волнового режима в районе аккумулятивного берега северо-западной части Цимлянского водохранилища. Для проведения расчетов использовалась, разработанная в авторском коллективе, гидродинамическая модель волновых процессов, базирующаяся на 3D математической модели, включающей три уравнения движения Навье-Стокса, уравнения неразрывности для несжимаемой жидкости. Дискретизация уравнений гидродинамики выполнена при использовании метода поправки к давлению. Численные алгоритмы и реализующий их комплекс программ использованы для определения поля давления, поля вектора скорости водной среды и построения эпюры давления при разных фазах волнения для заданного участка акватории водохранилища. Результаты исследования могут быть использованы при исследовании гидрофизических процессов, оценки гидродинамического воздействия на формирование береговой линии и рельефа дна крупных водохранилищ Юга России равнинного типа.

Ключевые слова: моделирование гидродинамических процессов, волновые процессы, крупные водохранилища, водная экосистема, прибрежная рекреационная зона, параллельные алгоритмы

Авторы:

Сухинов Александр Иванович, Донской государственный технический университет (344000 Ростов-на-Дону, пл. Гагарина, д. 1), член-корреспондент РАН, доктор физико-математических наук, профессор

Сидорякина Валентина Владимировна, Таганрогский институт им. А.П. Чехова (филиал) РГЭУ (РИНХ) (347936 Таганрог, улица Инициативная, д. 48), кандидат физико-математических наук, доцент

Проценко Елена Анатольевна, Таганрогский институт им. А.П. Чехова (филиал) РГЭУ (РИНХ) (347936 Таганрог, улица Инициативная, д. 48), кандидат физико-математических наук

* Исследование выполнено при финансовой поддержке РФФИ в рамках научного проекта № 19-01-00701.