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Original article

Testing of a Piled (Permeable) Breakwater Made of Composite Material for Coastal Protection. Part 1: Installation Conditions and Stability Assessment

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Abstract

The article discusses the results of an experiment (03 October 2021–30 April 2023) to test a “Grebenka” breakwater (breakwater of a through structure, or wave-breaking piled wall) made of composite material. The purpose of the study is to prove or disprove the hypothesis that the structures under study are sufficiently resistant to natural effects of the marine environment and can be considered as an alternative to existing coastal protection methods and means. The test breakwater in the form of five 12-meter modules, four of which were arranged in a line, was installed on the northern shore of the Sambia Peninsula (Baltic Sea, Kaliningrad Oblast’). The state of the breakwater was registered by various methods, including underwater and aerial photography. The results of the study showed that the installation of modules on the unprepared bottom caused their shear and tilt as a result of wave action. In order to improve the resistance of the “Grebenka” breakwater to such impact, it is necessary to prepare the bottom by flushing out the sand cover up to the consolidated layer level. Despite the fact that one of the breakwater modules split into two parts following the longitudinal fracture of its base (due to a violation of installation technology), all vertical pipe-piles forming the wave-dampening pile rows with cantilevered sealing at the base and free upper ends did not break off or corrode. This indicates that the composite material is strong enough for use in marine conditions with wave and ice loads. Algae biofouling has demonstrated the friendliness of the composite material to the biota.

Keywords: breakwater, coastal protection, composite material, Baltic Sea, natural experiment

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Испытание свайного (проницаемого) волнолома из композитного материала для берегоукрепления. Часть 1. Условия установки и оценка устойчивости

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Аннотация

Рассмотрены итоги испытания (03.10.2021–30.04.2023) волнолома «Гребенка» (волнолома сквозной конструкции, или волногасящей проницаемой стенки) из композитного стеклобазальтопластика. Цель исследования – доказать или опровергнуть гипотезу о том, что исследуемые конструкции достаточно устойчивы к естественным воздействиям морской среды и могут быть рассмотрены в качестве альтернативы традиционным берегозащитным средствам. Тестовый волнолом в виде пяти 12-метровых модулей, четыре из которых были расположены в один ряд, установили на северном побережье Самбийского полуострова (Балтийское море, Калининградская область). Состояние волнолома фиксировали разными способами, включая подводную съемку и аэросъемку. Результаты показали, что установка модулей на неподготовленное дно спровоцировала их сдвиг и наклон вследствие волнового воздействия. Для повышения устойчивости волнолома «Гребенка» к таким воздействиям необходимо подготавливать грунт путем размыва песчаного чехла до уровня консолидированного слоя. Несмотря на то, что один из модулей волнолома разделился на две части при продольном разломе его основания (из-за нарушения технологии монтажа), все вертикальные трубы-сваи, образующие волногасящие свайные ряды с консольной заделкой в основании и свободными верхними концами, не обломились и не подверглись коррозии. Это говорит о достаточной прочности композитного материала для использования в морских условиях с волновыми и ледовыми нагрузками. Биообрастание водорослями свидетельствует о дружественности материала к биоте.

Ключевые слова: волнолом, берегоукрепление, композитный материал, Балтийское море, натурный эксперимент

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Introduction

The concept of the Kaliningrad Oblast' coastal protection [1] involves the application of several methods of coastline reinforcement, as well as their testing before implementation. Modern materials based on natural or man-made polymers, such as geosynthetics [2, 3], are used in the construction of coastal protection structures to increase the reliability of the soil or construction materials [4]. Such a material is glass-basalt-plastic [5], of which the "Grebenka" breakwater considered in this article is made.

In [6], it was demonstrated that the installation of a 300 m long breakwater at a distance of 250 m from the shore resulted in beach growth and coastline extension of up to 40 m per year.

The practice and rules for the utilisation of breakwaters for the purpose of coastal protection are defined by Regulations 277.1325800.2016 [1)]. In [7], it was demonstrated that the efficiency of permeable structures depended on the ratio of the area of openings to the total area of the structure.

The present study concerns a natural experiment designed to assess the feasibility of utilising the "Grebenka" breakwaters. It is presumed that such breakwaters are capable of dampening waves effectively, resistant to severe storm damage and safe for people and natural environment. Furthermore, it has been demonstrated that the "Grebenka" breakwaters exhibit superior technical performance in comparison to both concrete and wooden breakwaters [8]. The site where the experiment was conducted is located in the South-Eastern Baltic on the northern coast of the Sambia Peninsula (Kaliningrad Oblast', the Russian Federation) west of the city of Zelenogradsk (Fig. 1, *a*).

The objective of this article is to analyse the results of the natural experiment, to evaluate the resistance of the "Grebenka" breakwater to destructive environmental impacts and to propose recommendations for optimising the technology of its installation.

As the first part of the description, this article presents the initial findings of the experiment, with a particular focus on the technical aspects of breakwater installation, its resistance to natural storm loads and other external factors. The results of the data analysis examining the impact of the breakwater on the shoreline, gathered during the experiment, are extensive and will be presented in the second part.

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1) JSC TsNIITS, 2017. *Book of Rules СП 277.13258000.2016. Coastal protection constructions. Design rules*. Moscow, 91 p. (in Russian).

Materials and methods of study

The five-module "Grebenka" breakwater was installed (Fig. 1, *b*, *c*) opposite the last inter-groin pocket at the eastern end of the site with old, partially collapsed groins (Fig. 1, *c*). Depths at the experimental site ranged from 1.2 m near the shore to more than 2.5 m at the point where the modules were installed. The estimated closure depth for this area varies considerably, with figures ranging from 7.5 m [9] to 8.4 m [10]. As indicated in [11], the wave collapse zone in the vicinity of the breakwater installation commences at a distance of over 200 m from the shore.

In contrast to traditional through pile breakwaters [2)], a special feature of the "Grebenka" breakwater design is the use of pipes (hollow piles) of different diameters. The pipes are made of glass-basalt-plastic – a corrosion-resistant composite

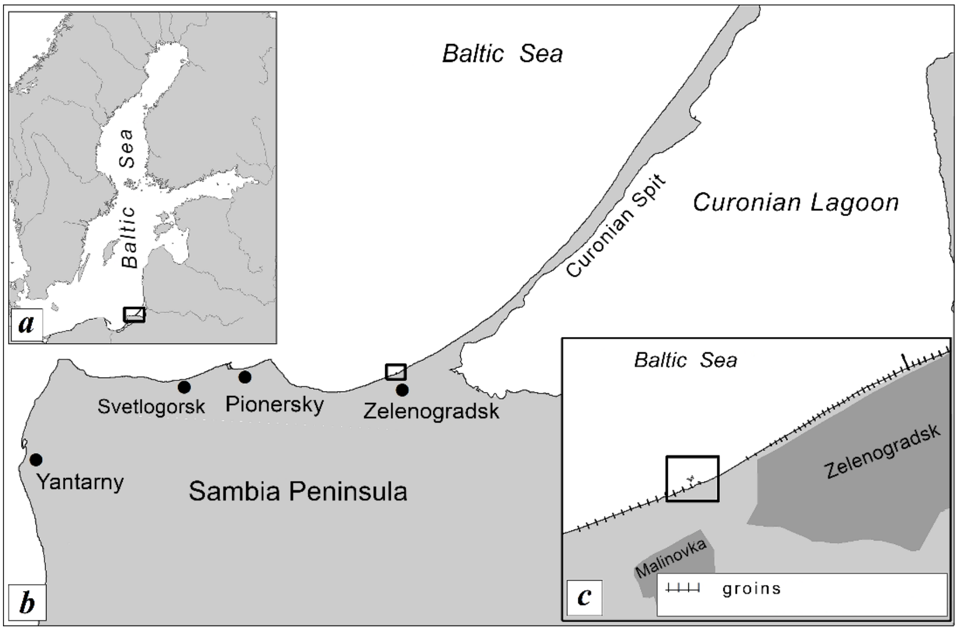


Fig. 1. Place of the experiment: *a* – the Baltic Sea; *b* – the northern shore of the Sambia Peninsula, Kaliningrad Oblast'; *c* – a section of the shore adjacent from the west to the Zelenogradsk city beach. From left to right: old groins (dashes on the shore line), a breakwater in the sea (the breakwater and four old groins are highlighted by a rectangle), a group of new groins and a pier protruding into the sea

2) Sedrisev, D.N. and Rubinskaya, A.V., 2011. [*Fundamentals of Design of Hydraulic Structures, Woodyards and Log Receiving Ports: Training Manual*]. Krasnoyarsk: SibGTU, 119 p. (in Russian).

material that has already been adopted on a wide scale in numerous sectors of the construction industry [5]. The primary benefits of glass-basalt plastic, along with the findings from testing a set of pipes in a wave flume, are presented in comprehensive detail in [8].

A modular breakwater design [3)] was selected with a maximum length per module of 12 m (based on the ability to transport materials to the installation site) and a width of 3 m. The breakwater module (Fig. 2) consisted of a grid base (three horizontal rows of parallel 12 m long, 0.5 m diameter base pipes and an additional pipe at 0.5 m distance, connected by 3 m long, 0.25 m diameter cross pipes) served as a bottom-mounted base. All base pipes were filled with concrete. Vertically installed pipe-piles with diameters of 0.2 and 0.1 m were inserted into the main pipes of the grid base and formed a comb (*grebenka*) of three rows – the analogue of a pile row. The vertical pipes were 3 m high in three modules and 2.5 m high in two modules (*4* and *5*). An additional horizontal pipe (located seaward) at the base was without piles and functioned as a ballast pipe (visible in Fig. 2, *a*) to increase the module resistance to shear and overturning. The weight of the module after filling the horizontal base pipes with concrete was about 28 t. The modules were installed in a line parallel to the shore.

In order to achieve the most effective wave dampening, it is recommended that the relative open area of a row of vertical pipes should be no more than 30–40 %. Furthermore, it is advised that the relative open area should decrease from row to row towards the shore, in accordance with the recommendations set forth by “Central Scientific Research Institute of Construction” JSC.

The most effective scheme, as determined through testing at “Sea Coasts” Research and Development Centre, exhibited a relative open area of 30–20–10 %. To assess the resistance of the vertical rows to storm conditions, the structure was tested with a relative open area of 40–30–20 %. The reflection coefficient, as determined by wave flume tests, was found to be 0.2 [8].

a

b

F i g . 2 . The module (with pontoons) on the shore (*a*), a line of modules (*1–4*) and a number of installation slips in May 2021 (*b*)

[3)] Efremova, M.V., 2019. Utility Model Patent 187014 U1 Russian Federation. МПК E02B 3/06. [*Breakwater*]: 2018137512. Applied 23.10.2018, published 13.02.2019. 10 p. (in Russian).

From the point of view of functional application, the "Grebenka" wave-dampening piled structure can be considered as a type of through breakwater or wave-dampening permeable wall.

Traditionally, piled breakwaters and other piled barrier structures are constructed on piles that are pounded, hammered, screwed into undrained dense soil, which does not correspond to the "Grebenka" installation technology. On the other hand, Annex A of Regulations 24.13330.2021 mentions a post pile that transmits the load to the foundation only through a heel (in the case of the "Grebenka", this heel is the grid base of the structure). The investigated structure also contains elements of the piled breakwater mentioned in Regulations 277.1325800.2016 "Marine Coastal Protection Structures. Design Rules." What is new in the design of the "Grebenka" breakwater compared to traditional through breakwaters is the composite cover, modularity and mobility of assembly and installation.

Regulations 277.1325800.2016 recommend that for sandy beaches, underwater breakwaters should be installed at least 100 m from the shore line. As the tested breakwater is permeable, the designers decided to reduce this distance.

With a total module line length of 60 m and a distance from the shore of 75–80 m, the ratio of the length of the structure to its distance from the shore was between 0.75 and 0.8, which could result in either material accumulation and extension of the shore towards the structure, or even a tombolo.

The modules were assembled from prefabricated sets, then the base was poured with concrete onshore. Vertical pipe-piles were fixed in the base pipes simultaneously with concrete pouring. The assembly of five modules took two days in addition to 3–4 days for the concrete to harden and gain transport strength.

The modules were launched and transported to the sea using inflatable pontoons (Fig. 2, *a*, *b*) with a carrying capacity of 8 t (4 pieces per module). From the sea, the modules with pontoons were towed by the boat through 33 m long prefabricated slips (Fig. 2, *c*).

The modules were placed on the bottom without bedding preparation. Module *5* was placed at a depth of 1.5 m at a distance of 35 m from the shore at the level of the middle of the visible part of the easternmost destroyed old groin. Other four modules (*1–4*) were placed at a depth of 2.5 m at a distance of 75–80 m from the shore (in line with a slight curve, distance between modules 1.5–2 m (Fig. 3)). Module *5* was installed in one day in October 2020 and other four modules were installed in two days in May 2021.

After installation, module *5* (2.5 m high pipe-piles) protruded 1 m above the water and modules *1–3* (3 m high pipe-piles) – 0.5 m above the water. Module *4* (2.5 m high pipe-piles) did not protrude much from the water and the tops of the piles were in the near-surface layer.

The tests of the "Grebenka" breakwater were carried out from 03 October 2021 to 30 April 2023. Expedition surveys were carried out by the manufacturers (LLC Trading House Basalt Pipes), the employees of the Atlantic Branch of Shirshov Institute of Oceanology of RAS, Immanuel Kant Baltic Federal University and GBU KO Baltberegozashhita.

Changes in the location and characteristics of the modules were recorded during visual and tactile inspections and photography, which made it possible to assess the degree of mechanical damage and corrosion, as well as the degree of immersion of the base of the modules in the sand and their position relative to sea level. Photographs from the shore were taken 2–4 times a month throughout the experiment.

Satellite images from the Google and Yandex open sources were used to assess the change in position of the breakwater modules, as in [3]. The coordinates of stationary reference points on the site were used to georeference the satellite images. The accuracy of the module coordinates was improved by GPS georeferencing. The final error was up to 2.7 m.

Aerial visual observations were carried out using an unmanned aerial vehicle (UAV – DJI Mini2) during the 2022 autumn–summer period and during the 2023 winter–spring period. The flight altitude was limited to 120 m taking into account necessary safety measures and the requirements of flight regulations. Similar examples of aerial visual observation are presented for the Black Sea and the Sea of Azov in [12], for the Tsimlyansk Reservoir in [13] and for the rivers of the Yamalo-Nenets Autonomous Okrug in [14].

Underwater photography of the structures using an SJCAM 5000 action camera was conducted on 07 September 2022 and 12 April 2023. Photographs of each module of the structure were taken from a distance of approximately 1 m, with a clockwise traverse of the structure from the west corner off the sea or west side of the module. A bottom-to-surface depth scale was applied to the photographs that showed the bottom.

Results and their discussion

At the time of studying the main morphological parameters during the 2022 summer season, the position of the modules of the "Grebenka" breakwater became relatively stable. The composite material used proved its durability under storm conditions. The "Grebenka" breakwater withstood ice loads successfully during the 2020–2021 winter.

A series of heavy storms during the 2020–2021 winter period disrupted the linear arrangement of modules *1–4* (Fig. 3): three out of five modules were displaced or rotated. From the second year of the experiment, the disturbed linear array of modules acted as a disjointed set of modules and did not provide the expected wave-dampening effect.

Photographs of the underwater section of the breakwater modules and measurements provided an indication of the extent to which the base of the modules was submerged in sand, the tilt of the structures, their integrity and algae fouling.

The most complete survey of the structure was carried out on 07 September 2022 (Figs. 3–5). Module *1* was 1.5 m above the ground, had not been destroyed or overturned and was almost completely covered by water, although it was 0.5 m above the water level when installed; the top 2/3 of the unsanded part of the piles were covered with filamentous algae. Segment *2a* of module *2* was 1 m above the ground,

F i g . 3 . Initial and final location of the “Grebenka” breakwater modules: *a* – initial (red lines) and final (blue lines) location of the modules (Google Maps image, 2021. https://www.google.ru/maps); *b* – location of the “Grebenka” breakwater modules on 12 April 2023

tilted westwards towards the shore and was completely covered by water. The entire visible part of the piles was covered with algae. The depth at the location of module *3* was 1.2 m. It was not destroyed or overturned. Some of the piles were 0.1–0.3 m above the water. The piles were covered with algae along the entire length of the underwater section. Module *4* was up to 0.5 m above the bottom, tilting to the west and completely covered by water. The western part of the module was almost completely hidden by the sand, with only the upper eastern, unsanded part up to 1/3 of its height covered with algae. Fig. 3, *b* shows that the module split into two parts following the longitudinal fracture of its base, as its eastern third is clearly outside the unified line of the first two thirds.

The repeated photography of all modules was carried out from the UAV on 12 April 2023 (Fig. 3, *b*). It uncovered module *2*, which was not visible in the UAV photography dated 07 September 2022 because it was under the sand layer of the underwater berm. The tops of the vertical piles rose 0.4–1.0 m above the bottom and tilted towards the sea. Module *2* appeared to be split into two parts. Probably, the splitting of the module into several parts occurred due to the violation of installation technology of the structure. The reason for this will be definitively determined when the module is dismantled. The most probable explanation is that the connecting cross pipes of the module grid base, which were not cast in concrete, fell onto an uneven part of the bottom under the layer of sand causing the module to break when the sand was eroded.

There was no algae fouling on the piles of module *2* as they were hidden by the sandy underwater berm for most of the time. The fact that it became bare and was observed during the photography on 12 April 2023 is a consequence of the deformation of the berm and the increase in depth at the module site.

In Fig. 3, the dark colour of the piles is associated with algae fouling (except for module *2* (Fig. 3, *b*), which was entirely under sand); part *2a*, separated from module *2*, was not completely covered, so its piles were partially covered with algae.

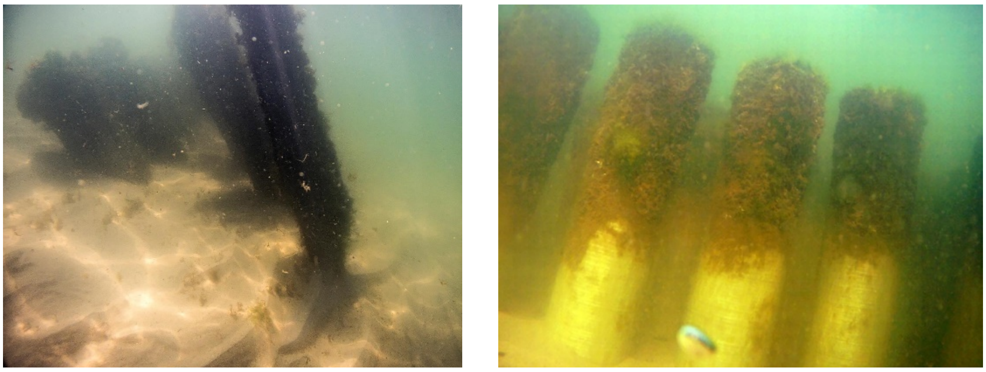
The upper parts of the piles of all the modules (which were in the water) were covered with algae, indicating a certain friendliness of the glass-basalt-plastic to biota and its ability to form the basis of an underwater reef. If the lower part of the piles was free of vegetation, this meant that it had been covered by sand during the growing season up to the time of the survey. During the resurvey on 12.04.2023, an increase in the lower bare part of all modules was recorded, indicating that sand had been partially washed away from the underwater slope.

The location of the breakwater did not take into account the fact that the breakwater was in the zone of influence of an extensive longshore berm and several types of currents. The migration of the underwater berm ensured that the base of all the modules was covered with sand.

Prior to the installation of the "Grebenka" breakwater modules, necessary engineering survey of the bottom area was not carried out, in particular, the height of the sand layer above the compacted bottom was not established. The modules were not only sanded up, but also subsided by 0.5 m or more (Fig. 5). To avoid such subsidence, it is necessary to place the modules on a hard bottom. This can be achieved, for example, by flushing out the sand at the installation site to the moraine bed, which is much cheaper than preparing a rock bed under stationary stone-concrete breakwaters.

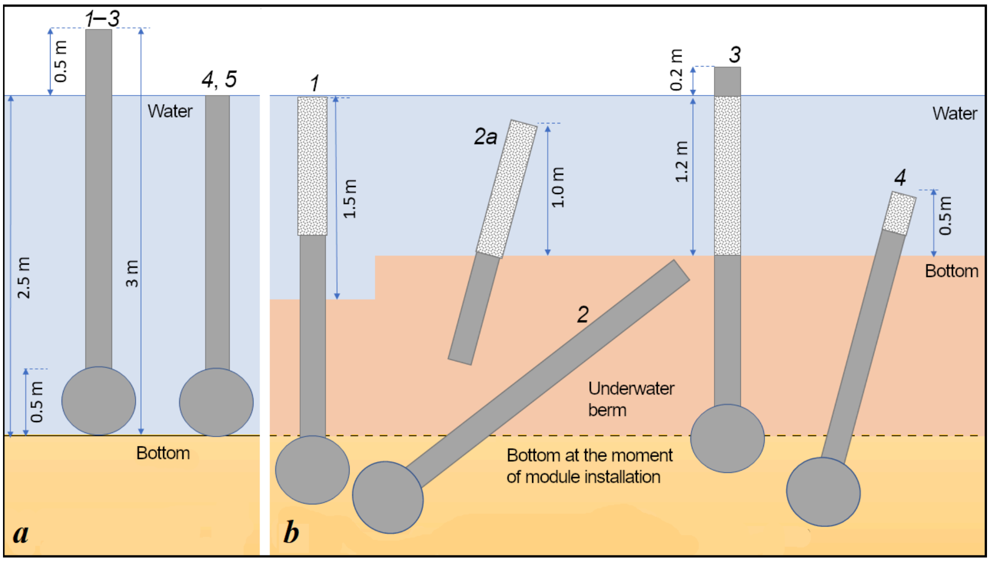
It was assumed that subsidence of the breakwater would increase the shear stability of the modules during storms. In the first year of the experiment, this dynamic was observed, but then the modules tilted during heavier storms.

Since storm wave lengths ranged from 120–140 m, a structure of four modules exposed along a single line provided only the minimum acceptable ratio of wave-dampening structure length to wavelength, i.e. approximately 1:2. Initially, the organisers of the experiment understood that the local impact of the structure could



a ***b***

F i g . 4 . State of the “Grebenka” breakwater modules: *a* – algae fouling and tilt of the structure (survey on 7 September 2022); *b* – post-storm partial exposure of the wave-damping piles from under sand (survey on April 12, 2023)



F i g . 5 . Schematic initial position of the modules (*1*–*5*) during installation in May 2021 (*a*) and their final position during the survey on 07.09.2022 (*b*). The parts fouled with algae are highlighted in light gray. The diagram shows the subsidence of modules and their sanding up, deviations from the vertical axis, and changes in the height of the surface part only occur within the inter-groin pocket blocked by the structure. At this stage, based on the results of the experiment, the organisers admit that a mistake was made in the location of the structure: with its short length, it was too far from the shore. This experience will have to be taken into account when building similar structures in the future.

The modules are preferably orientated so that the additional horizontal pipe at the base is on the shore side, providing support against wave action and preventing overturning. In this installation, the modules were orientated the other way round.

Conclusions

Five 12-metre modules were installed on the northern shore of the Sambia Peninsula (Baltic Sea, Kaliningrad Oblast') during the "Grebenka" breakwater (a breakwater of through construction, or wave-dampening permeable wall) natural experiment. The technology of module assembly on shore, their transport and submersion to the bottom was worked out. For a year and a half (03 October 2021–30 April 2023) the investigated structures were exposed to wave and ice loads.

The preparation of the breakwater site is important for the safety of structures exposed to wave action. Initially it was assumed that no bottom preparation would be required. However, the influence of coastal currents in the vicinity of the underwater berm in the absence of bottom preparation resulted in the breakwater subsidence into the sand.

Some of the modules changed their position after the experiment, which means that despite the use of concrete to weight the structure, the effects of the waves and currents were sufficient to shear the structures. One solution to this problem is to weight the structure or, as discussed above, to prepare the bottom more thoroughly.

One of the modules failed to withstand the load and split at the base (possible cause: underfilling of the cofferdams in the base with concrete). In order to clarify the details of this fact, it is necessary to examine the elements of the damaged module.

All vertical wave-dampening piled rows remained intact, indicating that the proposed structure is sufficiently resistant to wave and ice loads. The vertical pipe-piles forming the wave-dampening piled rows with cantilevered sealing at the base and free upper ends did not break off or corrode.

The large number of algae and other organic objects observed on the surface of glass-basalt-plastic indicates the friendliness of this material to the biotic component of the environment.

The experiment proved to be very useful for further improvement of the structure taking into account both negative and positive results achieved. It should be emphasised that this work is a rare example of testing a life-size structure in the very conditions, in which it can be used further after modification.

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Boris V. Chubarenko – planning and drafting the first draft of the article, analysis of all the results and drawing general conclusions, final editing of the article text

Dmitry A. Domnin – conduction of aerial visual surveys, underwater video surveys, analysis of the results

Ruslan B. Zakirov – georeferencing of satellite images, analysing changes in module locations, preparation of relevant illustrations

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