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Original paper

Testing of a Piled (Permeable) Breakwater Made of Composite Materials for Coastal Protection. Part 2. Evaluation of Impact on the Shore State

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Abstract
The paper analyzes the effectiveness of a pile breakwater structure *Grebenka* for coastal protection purposes. From 03.10.2020 to 30.04.2023, full-scale testing of the structure was conducted on the northern shore of the Kaliningrad Oblast near the city of Zelenogradsk between the eroded and accumulative shore segments. Four breakwater modules were installed in a single line in the groin pocket at a depth of about 2 m offshore of the groin end but did not completely overlap the pocket. One module was installed in the immediate vicinity of the shoreline. The experiment covered several seasons of severe storms, which allowed us to compare the shoreline dynamics at the breakwater installation site and in the neighbouring areas. We carried out regular measurements of the beach width, aerial survey, repeated depth measurement at the installation site and assessed the underwater slope dynamics. We also determined the thickness of the sand cover layer at the structure installation site and placed tilting flow velocity sensors on the breakwater. It was found that the beach width at the breakwater installation site and in adjacent areas was changing synchronously. The absence of an obvious accumulative effect behind the installed breakwater was, first, due to the displacement of the breakwater modules and their partial immersion in the sand and, second, due to the limited line length of the offshore modules in proportion to their dis-tance from the shoreline. A temporary positive effect was achieved only for a solitary module as periodic beach progradation to the root of an old groin adjacent thereto from the east. The results of the full-scale test will be used to further improve the breakwater design.

Keywords: breakwater, shore protection, Baltic Sea, field experiment, beach dynamics, underwater slope dynamics, coastal erosion

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Испытание свайного (проницаемого) волнолома из композитных материалов для берегоукрепления. Часть 2. Оценка влияния на состояние берега

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Аннотация
Проанализирована эффективность применения свайного сооружения вида волнолом «Гребенка» для целей берегозащиты. С 03.10.2020 по 30.04.2023 были проведены натурные испытания данной конструкции на границе абразионного и аккумулятивного сегментов северного побережья Калининградской области вблизи г. Зеленоградска. Четыре модуля волнолома были установлены в одну линию в бунном кармане на глубине около 2 м мористее конца бун, но не перекрывали этот карман полностью. Один прибрежный модуль был установлен в непосредственной близости от линии уреза. Эксперимент охватил несколько сезонов сильной штормовой активности, что позволило сравнить динамику береговой линии в месте установки волнолома и на соседних участках. Проводились регулярные измерения ширины пляжа, аэрофотосъемка, повторное измерение глубин в месте установки, оценка динамики подводного вала, определение толщины слоя песчаного чехла в месте установки конструкции, размещение инклинометрических датчиков скорости течения на волноломе. Выявлено, что

ширина пляжа в месте установки волнолома и на смежных участках изменялась синхронно. Отсутствие очевидного аккумулятивного эффекта позади волнолома связано, во-первых, со смещением модулей и их частичным погружением в песок, а во-вторых, с недостаточной длиной линии мористых модулей по отношению к их удалению от уреза. Временный положительный эффект был достигнут только позади отдельно стоящего модуля и выражался в периодическом выдвижении пляжа к корню примыкающей к нему с востока старой буны. Результаты проведенного натурного испытания будут применены для дальнейшего совершенствования конструкции волнолома.

Ключевые слова: волнолом, берегоукрепление, Балтийское море, натурный эксперимент, динамика пляжа, подводный склон, абразия берега

Благодарности: создание и установка волнолома, а также проведение части визуальных обследований и промерных работ 2022 г., подготовка средств измерения течений выполнены за счет разработчика волнолома «Гребенка» – ООО «Торговый дом «Базальтовые трубы», г. Москва. Работы были поддержаны двумя темами государственного задания Института океанологии им. П. П. Ширшова РАН: работы по определению долговременных изменений ширины пляжа, аэровизуальные обследования 2022–2023 гг., промерные работы 2023 г., подводная съемка и определение толщины рыхлого осадка 2022 г. и измерение течений проводились при поддержке темы № FMWE-2021-0012, а анализ результатов эксперимента и подготовка статьи – при поддержке темы № FMWE-2024-0025. Авторы благодарят инженерный состав института и персонально А. П. Подуфалова, М. И. Немцова, Ю. Н. Перова за высокопрофессиональный вклад в проведение экспедиционных работ.

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Introduction

The widespread retreat of the marginal seas coastline [1] is also characteristic of the Baltic Sea. There is a pronounced trend towards increased coastal erosion in the southern Baltic [2–4], which is related to geological characteristics [5]. Negative dynamics is observed primarily for sandy shores, which are affected by storms of north-western, western, south-western directions [6, 7]. The storm impact along with the increased sea level [8, 9] is one of the main external factors contributing to the coastal erosion and retreat. Sea level rise as one of the vivid manifestations of regional climate change [10] is a characteristic phenomenon for the open coast of the South-Eastern Baltic, where the rate of sea level rise in the 20th century was 1.3–1.5 cm / 10 years [11].

During 2007–2017 [7], the coastal retreat in the Kaliningrad Oblast was estimated to be 0.2 m/year for the Baltic Spit, 0.4 m/year for the Curonian Spit, 0.5 m/year for the western coast of the Sambia Peninsula and 0.2 m/year for the northern coast.

In the Kaliningrad Oblast, various measures have been taken to counteract coastal erosion [12], such as installation of breakwaters and groins, reinforcement of cliff slopes with gabions or geosynthetic covers [13]. There is experience of coastal protection by inwash of sand obtained as a result of slope terracing near the village of Filino [14, 15]. This inwash provided shoreline maintenance for several years. Experimental dumping of bottom material near Baltiysk obtained during maintenance dredging of navigation canal [16] did not lead to the expected result as the near-bottom currents in this area [17] do not allow the material to deposit at the water's edge [18].

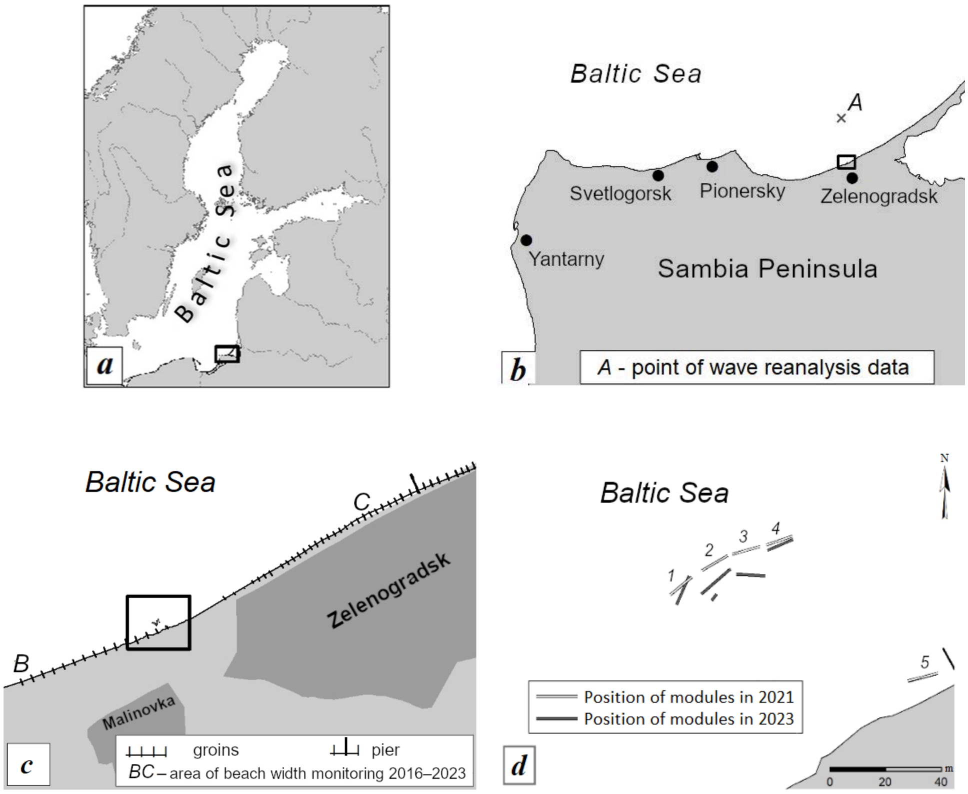
The most impressive is the example of a long-term discharge of material obtained by hydraulic washing of rock during amber extraction by the Kaliningrad Amber Combine. This discharge resulted in a complete change in the natural dynamics of the western coast of the Sambia Peninsula, namely, in the prevalence of accumulation over the naturally occurring erosion and the progradation of the water's edge by hundreds of metres [19]. The cessation of discharges allowed finding out that annual nourishment of at least 20% of the previously discharged volume is required to support the material washed up on the open coast [20].

Coastal breakwaters [1)] have never been used before on the Kaliningrad coast. There is experience in the application of such structures on the neighbouring coast of Poland [21], but it is not always positive [22], as the success depends largely on local conditions.

The aim of the work is to confirm or reject the hypothesis that it is possible to protect the coast from erosion using a relatively inexpensive permeable breakwater *Grebenka* (the comb) [23] and to identify its positive and negative aspects. Within the coastal protection concept for the coast of the Kaliningrad Oblast [24], it was recommended to apply underwater breakwaters, taking into account the existing conditions, so *in situ* testing of possible solutions was extremely useful. The creation of a permeable version of the structure was driven by the desire to obtain a lighter and cheaper construction compared to a monolith breakwater.

The experiment was conducted on the coast of the south-eastern Baltic Sea (Fig. 1, *a*, *b*), in the coastal zone of the Kaliningrad Oblast near the town of Zelenogradsk, on the border of a stable and erosion coast (site *BC* in Fig. 1, *c*). The tested breakwater of permeable construction *Grebenka* [23, 25] consisted of four 12-metre modules (seaward modules *1–4*, Fig. 1, *d*), installed at a depth of 2.5 m at a distance of 75–80 m from the water's edge, the distance between modules being 1.5–2 m. The modules were installed within the easternmost inter-groin pocket of a group of old semi-destroyed groins of the early 20th century, located to the west of Zelenogradsk. Module *5* was installed at a depth of 1.5 m at a distance of 35 m from the water's edge near the middle of the visible part of the easternmost part of the destroyed old groins.

[1)] A coastal breakwater is a structure located in the water area along the shore to protect the shoreline from destruction by wave action and to accumulate and retain sediment from movement (Russian state standard GOST P 54523-2011).



F i g . 1 . Testing site: *a* – the Baltic Sea; *b* – enlarged image of the area contoured in fragment *a*: the northern shore of the Sambia Peninsula, Kaliningrad Oblast; *c* – enlarged image of the area contoured in fragment *b*: a section of the shore adjacent to the Zelenogradsk city beach from the west; the rectangle highlights the breakwater installation site, *BC* – observation area for long-term dynamics of the beach width; *d* – location of the modules in 2021 (after installation) and in 2023 (during final inspection)

Details of the breakwater installation and changes in its design during the experiment are given in the paper [23]. This work uses the materials of the XXX All-Russian Conference 'The Coastal Zone of the Seas of Russia in the XXI Century' [2)].

[2)] Ogorodov, S.A., ed., 2024. [*Coastal Zone of Seas of Russia in the XXI Century: Proceedings of the XXX All-Russian Conference. Moscow, 3–7 June 2024*]. Moscow: Geografichesky Fakultet MGU, pp. 150–151 (in Russian).

Experimental area and meteorological conditions

In the study area, the deposit flow, on average directed from west to east, is quite saturated. At depths between 18 and 28 m, there is an extensive relic sand lens [3)] with an area of about 7 km^2.

Within the group of old groins of the early 20th century (2 km long), installed in 1925–1927, which traps and retains sand, the shore is quite stable with a beach of an average width of 30–40 m and foredune up to 6–8 m high (Fig. 2, *a*). The adjacent from the east shady section of the shore (Fig. 2, *b*) is more dynamic and characterised by a clearly pronounced erosion tendency.

F i g . 2 . State of the beach: *a* – stable beach at the western tip of the old groins site (the early 20th cent.) (27.04.2012); *b* – lee erosion at the eastern tip of the old groins site (27.04.2012); *c* – seasonal beach restoration identified by a strip of washed sand, including in the shady zone of the groins (27.04.2012) (photo by A. N. Babakov); *d* – the state before the period of autumn-winter storms in 2020, 19.10.2020. The arrows indicate the future position of the breakwater modules

[3)] Orlenok, V.V., 1992. [*Study of Stratigraphy and Lithology of Bottom Sediments of the Sambia Peninsula Based on Drilling and Seismic Profiling Data*]. Report of KGU. Kaliningrad, 64 p.(in Russian).

The rate of cliff retreat [4)] in the western part of Zelenogradsk in 1963–1974 reached 0.6 m/year, whereas in terms of volume it was 7.2 m^3/(running meter·year).

Only after the construction of a new group of groins in early 2017, the beach in the previously erosion-prone urban section recovered quickly. However, in the 700 m interval between the groups of old and modern groins, the beach is actively eroded by storm events (Fig. 2, *d*).

The dumping of dredged material from the construction of the International Marine Terminal in Pionersky, Kaliningrad Oblast (Fig. 1, *b*), was one of the sources of sediment in the area under consideration. The marine dump is located 5 km east of Pionersky within the same lithodynamic cell where the breakwaters were located. Prevailing westerly winds contribute to the alongshore transport of material [26]. A total of 834,000 m^3 of dredged material was delivered to the marine dump from 2018 to 2023: 291,000 m^3 in 2018–2019 and 347,000, 185,000 and 11,000 m^3 annually from 2021 to 2023, respectively.

The underwater slope of the study area typically has an underwater bar 50–150 m from the water's edge with a depth above the top of the bar being approximately 1.3–1.7 m. The bottom topography is uniform along the shore, but there are localised features in the form of depressions and shallow areas that actively migrate depending on the conditions of the last storm.

According to various estimates, the depth of closure for this area ranges from 7.5 m [27] to 8.4 m [28]. The wave breaker zone begins at a distance of more than 200 m from the water's edge [29].

Seasonal dynamics at this site are traditional. Autumn and winter storms wash sand away and transport it along and across the beach. Material arriving on the underwater slope from the west and east during the spring–summer period is rewashed onto the beach by more moderate waves, restoring the beach width (Fig. 2, *c*). Erosion and accumulation alternate continuously over a period of several years, and the installation of the breakwaters appears to have occurred during a phase of active erosion.

During the experiment (spring 2021 – spring 2023), several storms were recorded on the northern coast of the Sambia Peninsula. The longest and most destructive of them occurred during the autumn–winter period: 19–20 November 2021, 13–21 January 2022, 27–31 January 2022, 17–21 February 2022, 4–8 April 2022, 18–21 February 2023. The average wind speed on these dates exceeded 15 m/s and the direction was predominantly westerly. The consequences of their impact on the shores are shown in the work [30].

According to the reanalysis data, for a point with a depth of 17.5 m seaward of the breakwater location (point *A* in Fig. 1), the highest waves during the study period were recorded on 30 January 2022, their height being about 6 m and the direction of wave motion being from the northwest. The number of days during which a significant wave height reached 2 m was 105. The majority of these days were recorded in October–March (85%). The largest contributions were January 2022

[4)] Ryabkova, O.I., 1987. [*Coastal Dynamics of the Sambia Peninsula and Curonian Spit in Relation to Coastal Protection Problems. Extended Abstract of Doctoral Dissertation*]. Moscow, 17 p. (in Russian).

Parameters of main registered storm events during the experiment

Storm date	H_{max}, m	H_{max}_3h, m	H_{mean}_3h, m	Wave direction	Wave period, s
13–22 January 2022	5.52	5.31	2.80	Northern, north-western	5.42
26–31 January 2022	6.09	6.01	2.64	Northern, north-western	5.01
17–25 February 2022	3.73	3.60	1.80	Northern	3.60
30 January – 02 February 2023	3.06	3.02	1.93	South-western	4.22
17–21 February 2023	5.84	5.78	2.33	South-western	4.60

Note. H_{max} – maximum significant wave height: H_{max}_3h – maximum significant wave height for moving average 3 hours; H_{mean}_3h – average significant wave height for moving average 3 hours (re-analysis data).

with 17 days, February 2022 with 12 days, February 2023 with 11 days, and November and December 2021 with 10 days each. The total number of hours in which waves with a significant height exceeding 2 m were observed during the study period was 1139. Thus, the period of the experiment was rich in prolonged and rather severe storm events (Table).

Methods and scope of conducted studies

The position of the breakwater, beach and water's edge on the satellite images was referenced to the coordinates of fixed reference points; the location of the breakwater modules and tracing of the water's edge were carried out using GPS (error up to 2 m).

Aerial visual observation using a DJI Mini2 unmanned aerial vehicle (UAV) recorded the position of the shoreline and the boundaries of the underwater bar (in autumn–summer 2022 and winter–spring 2023). UAV were flying at an altitude of 120 m, with a longshore coverage of over 900 m, limited to the width of the beach (inland), and 100 m (seaward) in the transverse direction to the water's edge.

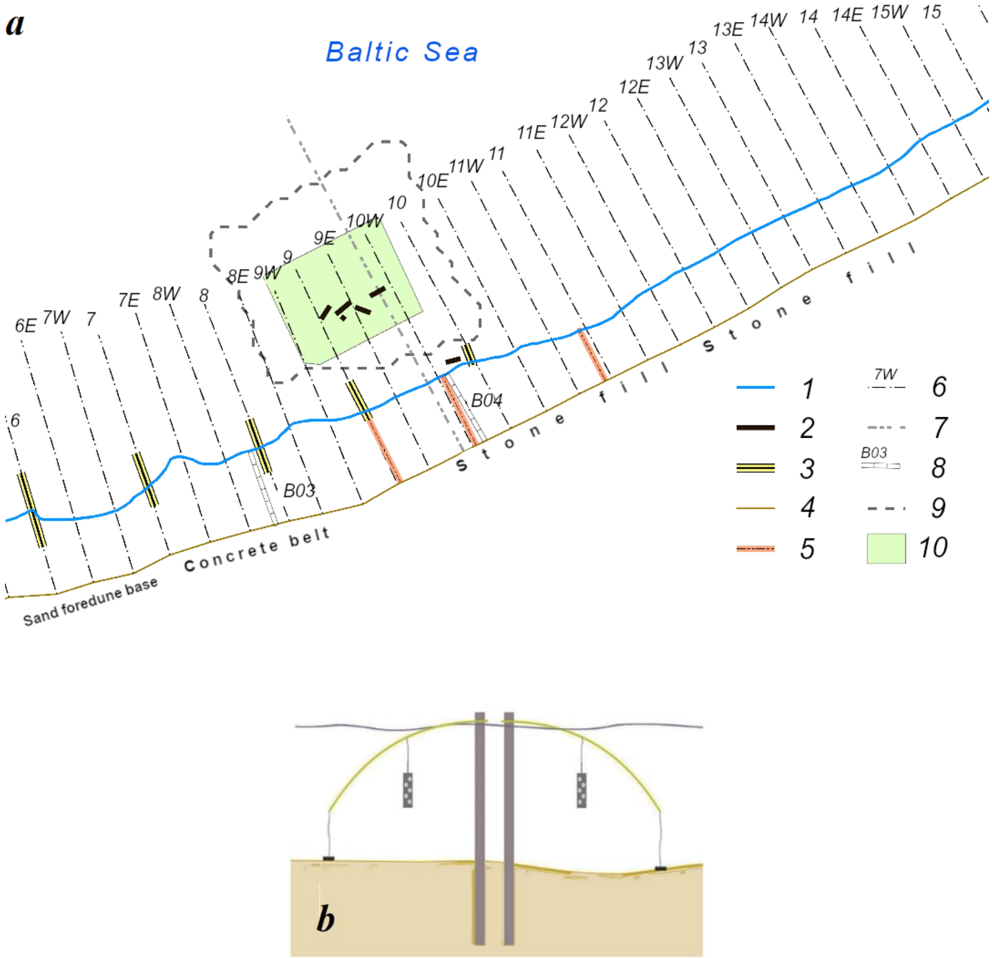
The underwater longshore bar was identified visually by its typical yellow colour without automated techniques. The top of the bar was defined as the area of the most intense yellow colour in the image.

Periodic beach width measurements (11 measurements between 15 March 2022 and 12 April 2023) near the breakwater were made on three profiles (line *5* in Fig. 3). The central profile was located between the breakwater modules, the left (west) profile was located on the traverse of the penultimate old groin, and the right (east) profile was in the central part of the lee erosion zone at a distance from the central profile approximately equal to the width of the inter-groin pocket. The data obtained by optical levelling were used to construct beach height profiles. Beach width measurements were taken after the winter 2022 measurement period: on 15 March – 21 April 2022 with a frequency of approximately one week, as well as on 1 July 2022, 22 November 2022, 1 December 2022, 12 April 2023. Changes in the beach width over a long-term period were assessed from the data of the beach width measurements in 2016–2023 using a set of profiles in the section from the western edge of the early 20th century groin group (previously mentioned old groins) to the western end of the promenade in Zelenogradsk (section *BC* in Fig. 1, *c*, lines *8* in Fig. 3).

The thickness of the loose sand layer at the cross-section passing through the breakwater modules (line *7* in Fig. 3) was determined by the hydraulic washing method: an electric water pump was used to create a constant water pressure, which was fed into a probing metal tube with a diameter of 20 mm. Under the water pressure, the soil was washed out and the probe was deepened. The measurements were carried out on 23 April 2023 and the results were normalised to the mean annual sea level according to the tide gauge in the port of Pionersky.

The bottom relief in the coastal zone changes from year to year due to various natural factors. At the breakwater location, depths were surveyed (with 40 m survey line spacing) on 7 September 2022 and 23 April 2023 (Fig. 3). A single-beam echosounder with navigation reference using a Garmin GPSMAP 421s chartplotter was used for the survey. The measurement results were referenced to mean annual sea level and interpolated to a grid with 10 × 10 m spacing. A differential digital relief model was then obtained by surface subtraction, from which bottom deformation zones were identified and the amount of sand loss and gain between the survey dates of 7 September 2022 and 23 April 2023 was calculated.

In order to quantify the effect of wave energy attenuation during its passage through the breakwater, two inclinometer-type current velocity meters were used [31]. One meter was attached to the seaward and the other to the rear part of module *3* (Fig. 3, *b*). As brackets for the inclinometers suspension, we used stapled together flexible glass-fiber reinforced bars with a diameter of 10 mm, the upper ends of which were fixed horizontally in the upper part of the module. Lead weights were tied to the free ends of the brackets. The weights dragged the brackets to the bottom and sank the inclinometers. The flexibility of the glass reinforcement prevented the weights from subsiding into the sand. The inclinometers were



F i g . 3 . Work layout: *a* – basic reference lines and layout of the *Grebenka* breakwater modules, cross sections and work areas: *1* – the water's edge on 24.09.2022; *2* – *Grebenka* breakwater modules; *3* – old wooden groins; *4* – basic reference line; *5* – profiles for determining the beach width (GBU KO *Baltberegozashchita*); *6* – profiles for estimating the width of the underwater bar and its distance from the water's edge; *7* – profile for determining the loose sediment thickness; *8* – profiles for measuring the seasonal dynamics of the beach width (data from previous years were used); *9* – the boundary of the measuring range; *10* – the polygon for calculating the deformation of the underwater slope; *b* – inclinometer installation diagram attached to 30 cm rope leashes so that they were positioned 1 m from the module and 1 m from the surface. The inclinometers recorded (at a frequency of 5 Hz) the absolute value of wave-induced current velocity and longshore transport from 12:00 on 23 April 2023 to 12:00 on 28 April 2023.

Results and discussion

Observations of beach condition and dynamics were carried out in 2016–2023 along with the eastern wing of the Zelenograd concavity, from the village of Priboy to the western edge of the Zelenogradsk promenade (section *BC* in Fig. 1, *c*, lines *8* in Fig. 3). The boundaries of the section are 2 km west and 2 km east of the breakwater installation site. Periodic surveys revealed marked variations in beach width depending on wind-wave and surge activity, as well as the amount of sediment input from the marine dump of the Pionersky port.

Photo survey of the water's edge position showed its periodic progradation after spring-summer moderate waves (Fig. 4, *a*, *e*), and beach erosion and narrowing after autumn-winter storms (Fig. 4, *b*–*d*, *f*). But the resulting stable beach attachment to the coastal module did not occur. The beach width varied here within the same range as before the breakwater installation.

A trend towards winter erosion of the beach (22 December 2016, 17 December 2021, 2 February 2022, 22 February 2023) and its re-expansion under weak wave action (5 May 2022, 25 August 2022, 19 December 2022, 12 May 2023) was observed along the entire section from the village of Priboy to Zelenogradsk (Fig. 5). Active beach erosion after the extreme storms of February 2022, during which wind speeds above 20 m/s were recorded on five occasions and the sea level exceeded the long-term average by 0.5–1 m, is indicative. The beach in the western section was half washed out to 20 m, while to the east of the old groins it was washed away completely to the base of the bouldery berm (see the graph for 02.02.2022 in Fig. 5).

The beach width within the early 20th century old groins (0–2 km) varies seasonally from 20–30 m in winter to 30–55 m in summer with a maximum of up to 45–55 m at the eastern end of the section (Fig. 5). Historical data [5)] (October 1976 – 43 m, July 1977 – 28 m, August 1978 – 43 m, September 1979 – 19 m, October 1981 – 25 m, August 1982 – 28 m) indicate the same.

The western two-kilometer section is fairly stable under any waves and features a wider beach than the typically eroded eastern section (2–3.7 km) even after the installation of new groins on the eastern section in 2017.

A noticeable beach protrusion at the eastern end of the early 20th century groin group, near the breakwaters, was observed throughout the measurement period (2016–2023), before and after their installation. The local beach dynamics was similar to that of adjacent sections, indicating that the breakwaters did not influence on the beach morphodynamics.

The orientation of the wind-wave vector also plays an important role in the dynamics of the studied beach. Westerly and northerly winds contribute to surge

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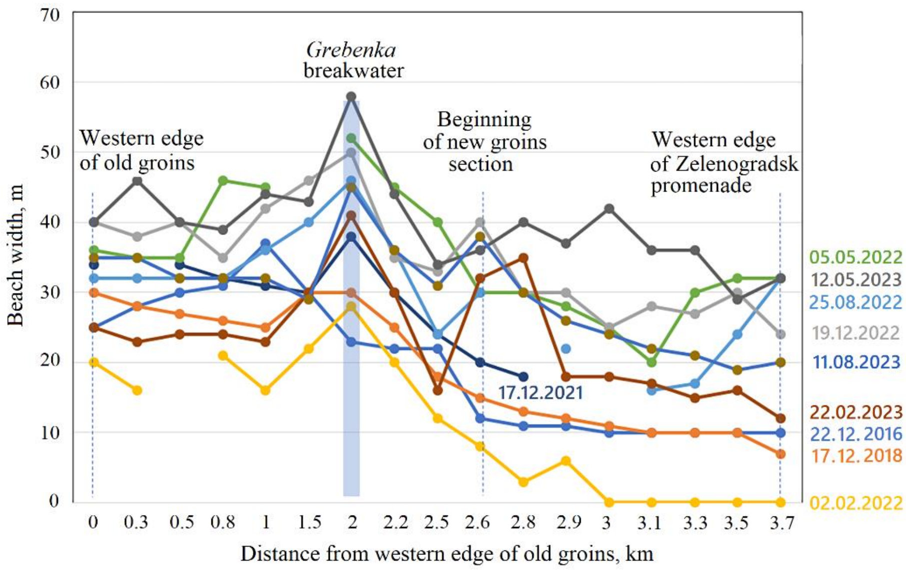
[5)] Personal archive of O. I. Ryabkova.

F i g . 4 . The beach dynamics after the installation of the breakwaters in 2021–2023: *a* – summer accumulation, 06.09.2021; *b* – beach narrowing after extreme storms, 02.02.2022; *c* – the state of the beach after the storm period, 05.05.2022; *d* – beach nourishment in the finishing phase of the winter storm, 19.12.2022; *e* – the beach restored by moderate spring waves, 12.05.2023; *f* – beach narrowing due to a noticeable increase in the sea level, 11.08.2023. Photo by A.N. Babakov

and beach erosion, while easterly and southerly winds restore the beach. Thus, in April–June 2023, moderate easterly winds dominated, which led to the sea level drop by 10–15 cm below the long-term average water level and the formation of a very wide beach (see the chart for 12 May 2023 in Fig. 5). However, a reversal of moderate wind to the southwestern quarter (July–August) resulted in a 45 cm rise in level and a marked narrowing of the beach (11 August 2023). It should be added that the beach was even narrower during a moderate south-westerly storm (8 August 2023), but three days after the end of the storm, an 8–12-meter wide sandy strip had already been washed up across the entire section.



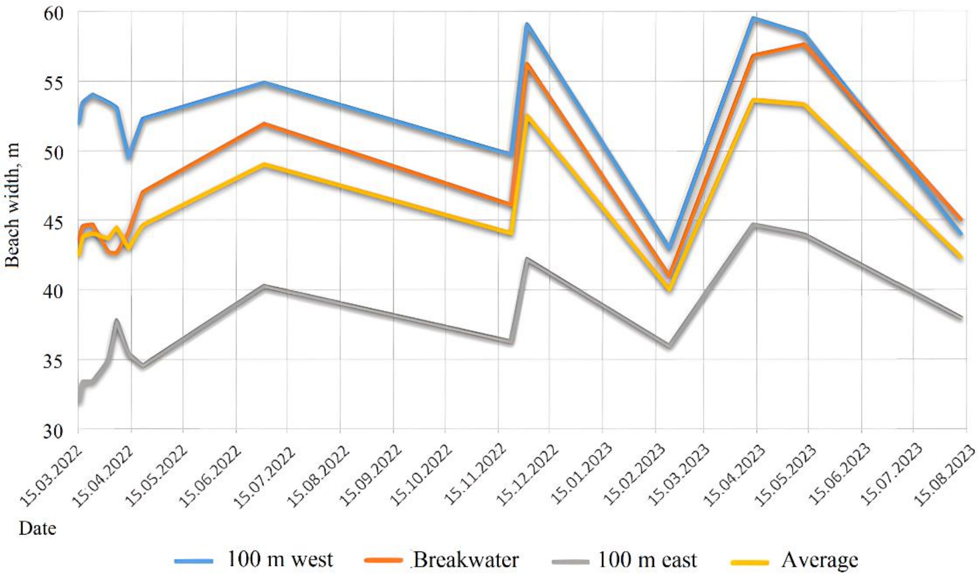
F i g . 5 . Seasonal dynamics of the beach width (for 2016–2023) in the area from the western edge of the wooden groins (early 20th cent.), including the area of new groins, up to the western edge of the promenade in Zelenogradsk. The location of the breakwaters is shown with a blue bar

Monitoring by the State Budgetary Institution Baltberegozashchita in 2020–2023 near the breakwater also recorded the presence of a stable wide beach both before and after the breakwater installation. The fact that after the installation of the breakwater modules by 23.06.2021, the beach became slightly narrower than before the installation, confirms the absence of accumulative effect in the shade of the breakwater (Fig. 6). Apparently, the beach narrowing is related to the above-mentioned sea level and wave activity fluctuations, whereas the longitudinal variations of the water's edge are related to the spatial heterogeneity of the wave field and morphology of the underwater slope.

Detailed measurements of the beach width at three cross-sections opposite the breakwater from March 2022 to August 2023 confirmed the close dependence of beach dynamics on wind and wave action. Weak, unstable winds (March to June 2022) following a series of February storms contributed to significant beach widening, but wind transition to the south-westerly quarter and its intensification to 12–15 m/s was accompanied by beach narrowing. Subsequent alternation of easterly winds (December 2022, March–May 2023) with southwesterly winds (January–February 2023, July–August 2023) caused corresponding beach widening and narrowing (Fig. 7).

An analysis of aerial photographs showed that during the experiment period the underwater bar was no more than 100 m away from the water's edge. The width of the bar (according to the data taken at the cross-sections: polygons *4*, *5*, *6* in Fig. 8) varied significantly from 10 to 70 m and the width of the beach varied

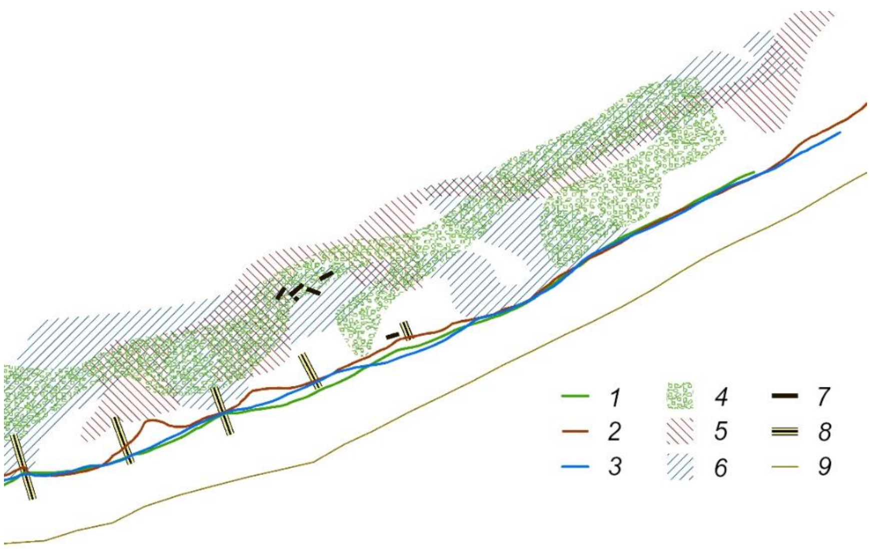
F i g . 6 . Interannual dynamics of the water's edge near the breakwater before and after its installation (2014 – GoogleEarth source, 2018 – satellite image ResursP, 2021 – GPS tracing)



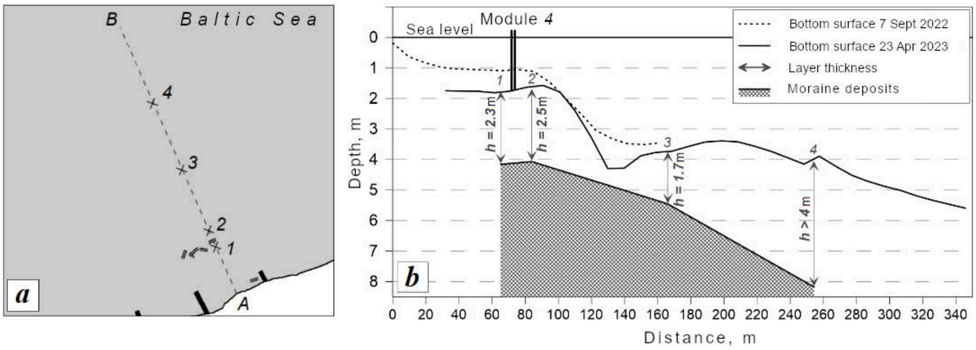
F i g . 7 . Intra-annual beach dynamics on a 200 m long section opposite the breakwater according to measurements of GBU KO *Baltbergozashchita* at three cross sections (lines *5* in Fig. 3), 15.03.2022–11.08.2023 from 10 to 15 m. No correlation between the longshore distributions of width values was observed (correlation coefficients from –0.15 to 0.34 on different dates). Alongshore variations in the distance from shore of the coastal and seaward boundaries of the underwater bar on some days correlated with a coefficient of 0.64–0.70.

An analysis of the underwater bar dynamics showed significant variability in its configuration, width and location of its seaward and coastal boundaries (Fig. 8). It is clearly seen that the structure of the underwater bar does not correlate with the presence of groins and the shoreline irregularity. The presence of the *Grebenka* breakwater does not affect the structure of the underwater bar and the water's edge position. Of note, in the area without groins, the shoreline is more flattened. A festooned shoreline structure was recorded several times in the section with groins, when the festoons edges overlapped the position of the groins.

In the study area, the underwater coastal slope between 0 and 5 m depth is characterised by an average inclination of about 0.016 (or 1:64). At the time of the 07.09.2022 survey, the top of the longshore underwater bar (Fig. 9) was adjacent to the breakwater line. However, this was a coincidental event in the dynamics of the underwater bar, as, e. g., during measurements on 23.04.2023, its top was 30 m seaward than the breakwater line and the depth in the area of the seaward breakwater modules increased by 0.5 m (Fig. 9).



F i g . 8 . The visible position of the water's edge on 10.08.2022 (*1*), 24.09.2022 (*2*), 01.11.2022 (*3*) and the underwater longshore bar on 10.08.2022 (*4*), 24.09.2022 (*5*), 01.11.2022 (*6*). The figure shows positions of the breakwater modules (*7*), old wooden groins (*8*) and the reference line of the artificial foredune edge (*9*)



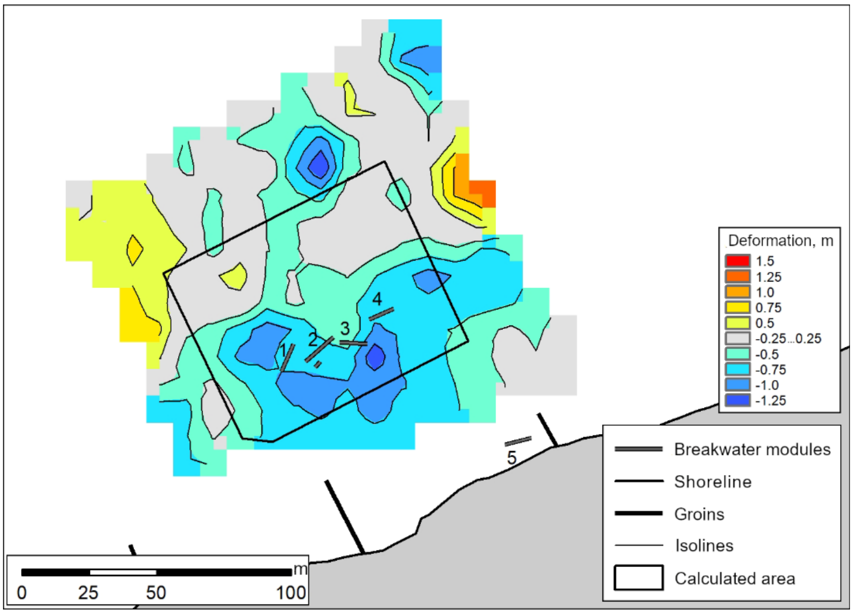
F i g . 9 . The profile of the coastal slope and the loose sediment thickness: *a* – the layout of the profile line and points of measurement of the loose sediment thickness; *b* – profiles of depths and the loose sediment thickness

The measurements on 7 September 2022 and 23 April 2023 illustrate the variability in the depth profile around the seaward modules associated with the migration of the underwater bar due to storm events in January 2023 (see Table).

At the maximum overlap area of the 7 September 2022 and 23 April 2023 measurement areas of 19,000 m^2 (Fig. 10), 5,000 m^3 of sand was lost between 7 September 2022 and 23 April 2023, with an average depth increase of 26 cm. In the area of the *Grebenka* breakwater modules (contoured by the black rectangular in Fig. 10, with an area of 6,700 m^2 covering the top of the underwater bar and its rear part behind the breakwaters), 2.7 thousand m^3 of sand was lost and the depth increased by 41 cm on average. The calculated deformation values ranged [–2.4...–0.9] m.

The measurements illustrate the changes in depth structure around the breakwater modules associated with the impact of the winter 2023 storm: a general deepening across the section and a lowering of depths behind the breakwaters. Given that depths around the breakwater modules were over 2 m in spring 2021 and approximately 1 m in September 2022 (measured on 7 September 2022), it is reasonable to conclude that storm characteristics vary significantly.

In order to assess the possible dynamics of the underwater shoreline slope around the breakwater over a longer period, we used the results of measurements for a similar area near the Zelenogradsk pier. The pier is located within the same lithodynamic shore segment 2 km east of the breakwater. Along the eastern edge of the pier (140 m long), which runs perpendicular seawards, depth was measured from early 2016 with a hand lead three to four times per year in 8.5 m increments, which corresponded to half the distance between the pier piles. The typical depth at the end of the pier was 3.5–4.5 m. On rare occasions of the underwater bar top's displacement towards the pier end at low sea level, the depth there was 2.0–2.2 m (20 April 2017 and 12 May 2023).



F i g . 1 0 . Diagram of the bottom relief deformation for 07.09.2022–23.04.2023 (positive values – accumulation, negative values – erosion), the calculated area for estimation of volumetric deformations of the coastal slope is delineated in black

The section near the pier of Zelenogradsk may serve as an analogue to the section with modules only in terms of deformations associated with underwater bar migration, but not in terms of absolute depths and inclination of the underwater shore slope. This is because the thickness of the sandy sediments layer (loose sediments) in the area of the old groins (where the breakwater modules are located) is generally significantly greater than in the area of the pier in Zelenogradsk. For this reason, in March 2022, when the Baltic Sea level was extremely low, exposures of the underwater bar closest to the edge were observed along the entire section of the early 20th century groins and elsewhere along the shore, but not near the Zelenogradsk pier.

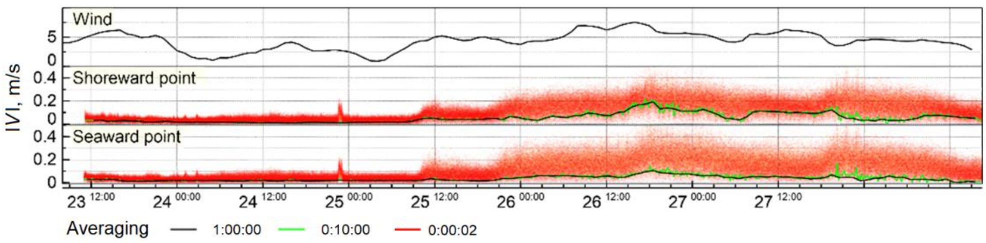
The data of measurements along the pier in 2016–2023 illustrate various situations: both when the top of the underwater bar was close to the water's edge (a quieter period of the year, at a depth of 2.2–3.7 m), and when it was significantly seaward (a storm period, at a depth of 4–5 m). By analogy to the breakwater section, it can be said that deformation of the underwater shore slope due to the migration of the coastal bar near the breakwater modules could be 2–2.7 m. This is comparable to the height of the structures themselves and may cause their subsidence to sand almost up to their full height.

We used the results of measurements (23 April 2023) carried out by the hydraulic washing method to construct a plot of thickness variations of the loose sediment (sand) layer along the profile perpendicular to the shore and passing through module 4 of the breakwater (Fig. 9). The loose sediment layer thickness was 2 m thick at a distance of 70 m from the water's edge at the rear of the breakwater (Fig. 9, *b*), from 3 m at the underwater bar top, from 0.5 m at the seaward base of the underwater bar, and 4 m at the seaward end of the profile. The inclination of the underlying surface was approximately 0.017 (or 1:59). Based on the geometric characteristics of the breakwater, its modules did not reach the level of the moraine bedrock when subsided in loose sediment (sand). Their subsidence was 0.5–1.5 m.

For technical reasons, the currents were measured from 12:00 on 23.04.2023 to 12:00 on 28.04.2023, and only a short-term episode of wind strengthening and wave increase was recorded. According to the surface wave reanalysis data in point *A* (Fig. 1), a westerly wind persisted during the inclinometric measurements and forming waves (the significant wave height averaged 0.6 m and the period averaged 2.3 s) propagating southeasterly (Fig. 11).

The most active waves were observed on 26–28 April 2023 under rather weak westerly wind with an average speed up to 5 m/s and gusts up to 13 m/s. The waves formed in the westerly wind, refracting on the relief, although turning towards the shore, ran over the breakwater module virtually with zero angle of attack, very close to the line of its strike. That is why the obtained record is not so indicative to judge the damping of waves on the breakwater module. The instantaneous (pulsation) values of wave velocities (Fig. 11) obtained from the two sides of the breakwater module did not differ significantly, and the current velocities from the seaward side of the breakwater slightly exceeded those from the shore side.

For the averaged characteristics, the opposite situation is observed: the average velocities from the frontal side of the breakwater are slightly less than the velocities behind the breakwater, which may be a consequence of the calculation of integral velocities using vector averaging laws. Wave motions from the seaward side



F i g . 1 1 . Results of registration of the absolute flow velocity with inclinometers from 12:00 on 23.04.2023 to 12:00 on 28.04.2023. Red colour is instantaneous values of current velocities, green colour is 10-minute averaging, black colour is one-hour averaging

a ***b***

F i g . 1 2 . Exposure of the top of the underwater alongshore bar in March 2022 shortly before its attachment to the water's edge at an extremely low sea level: *a* – the shore segment where the breakwater was installed (red arrows); *b* – the shore segment 400 m west of the breakwater installation site

of the breakwater are naturally asymmetric due to wave deformation on the relief, so their average value is not equal to zero. However, the waves from the shore side of the breakwater are significantly more asymmetric due to its influence, and as a result, the averaged (integral) current velocities may turn out to be larger than the velocities of the incoming wave.

The episode of extreme sea level lowering in March 2022 should be discussed separately (Fig. 12). Within a few weeks, the shoals near the water's edge along the entire coast became exposed in places where the underwater bar was in a state prior to its seasonal attachment to the beach in May 2022 (see the characteristic increase in beach width on 05.05.2022 in Fig. 5).

Notably, this exposure was most substantial in the inter-groin segment where the breakwater was installed (Fig. 12, *a*), although there were similar exposures nearby 200 m to the east and in other inter-groin segments to the west (Fig. 12, *b*). This probably indicates the influence of the breakwater when it retained its original configuration. It is not possible to state this reliably as in-depth monitoring was not undertaken at that time.

Conclusions

The studies showed that the beach width on the eastern flank of the Zelenograd concavity, including that at the location of the experimental breakwater installation, experiences natural seasonal and synoptic variations depending on sea level and wave action. We recorded a significant variability in the configuration of the underwater alongshore bar, the location of its seaward and coastal boundaries, and its width. The structure of the underwater bar correlated with neither the presence of groins, nor the shoreline irregularity, nor the presence of the breakwater. The migration of the alongshore bar provided significant depth variations (up to 1 m) at the breakwater location. Deformation during the 2022–2023 autumn–winter storms varied between [–2.4...0.9] m. Storm movements in the sandy base (the recorded values of loose cover thickness were from 0.5 to 2 m) contributed to subsidence of the structures by 0.5–1.5 m.

The beach width at the location of the *Grebenka* breakwater and at adjacent sections changed synchronously, which indicates a unified response to external impacts of the entire lithodynamic segment of the shore within which the breakwaters were installed.

It was expected that after the breakwater installation, the experiment would show progradation of the water's edge relative to the neighbouring areas and, under favourable conditions, formation of a tombolo behind the breakwater. However, no positive effect of the installed modules on beach dynamics was noted on either a seasonal or inter-annual time scale. The exception was the extreme low sea level event in March 2022, when the exposure of the tops of the underwater bar was more clearly observed (compared to similar neighbouring sections) in the intergroin segment where the breakwater was installed.

The absence of an obvious resulting accumulative effect from the seaward group of breakwater modules is due to their displacement and partial subsidence in sand under the action of the wave, which disrupted the linearity of the entire structure, as well as to the decreased area of their resistance to the wave front. After the 2021–2022 winter storm period, each module was already acting as a separate structure. It was not possible to register the response of the shore before this period, since careful observations were made after the structure had been breached. Another factor that did not allow achieving a positive effect from the structure installation was the limited length of the structure relative to its distance from the water's edge.

During certain moderate waves, the beach progradated and attached itself to the coastal module creating a temporary tombolo. However, a similar progradation of the water's edge was also noted at adjacent sections. The fact that the water's edge adjoined the base of the last, easternmost groin, and this position was kept in 2023, may indicate a possible temporal (no attachment in spring 2024) positive effect for the water's edge in the shade of the coastal module.

The question of whether the permeable breakwater *Grebenka* can protect the shore from erosion was only answered in part in the course of the work due to the flaws in the design of the breakwater, which determined a very weak effect of the structure on the shore dynamics. An important result of the work is the testing of the life-size structure directly in natural conditions. The experience gained has shown the usefulness of such tests and the need for their comprehensive planning with the involvement of a wide range of specialists to assist the design engineers in taking full account of all the peculiarities of hydro-lithodynamics, geomorphological and geological features.

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Oleg V. Bass – participation in structure installation, taking measurements in 2022, photographing the structure condition, participation in drawing conclusions on the structure

Vladimir I. Efremov – development of the breakwater design, supervision of and participation in installation, photographing the structure condition, partial funding of the works, drawing conclusions and recommendations regarding the structure

Olga I. Ryabkova – analysis of data on the source of sediment from dredging operations in the Pionersky port

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