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Protection of Transport Structures from Wave Action by Creating a Sandy Wave-Damping Beach

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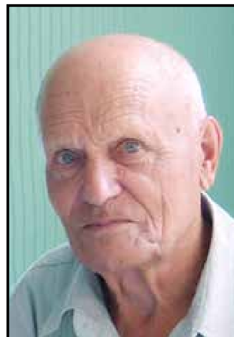

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ABSTRACT

The design and operation of transport structures (railways, roads, bridges) located on the seashores in the zone of possible erosion by waves requires particularly careful consideration of shoreline protection measures.

The article, using the example of a specific section of the Sambian Peninsula from Cape Taran to Cape Gvardeisky in Kaliningrad region, shows the problem of protecting a road running along the coast from wave action and suggests ways to solve it. The study describes results of laboratory studies on creation of a wave-damping sandy beach on the shores under conditions of material deficiency in the alongshore sediment flow. The research was carried out using the method of physical modelling in a wave basin.

The research has proved the fundamental possibility of creating a local stable sandy beach to protect transport structures from wave action under the conditions of material deficiency in the alongshore sediment flow.

The research results can be extended to other coastal sections of roads and railways.

Keywords: *road, shore protection, wave-damping structures, railway, lithodynamic processes, bridge support, sandy beach, erosion, physical modelling.*

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INTRODUCTION

Protecting transport structures (roads and railways, bridge supports, etc.) located on the shores of the seas from wave action has always been a difficult task [1]. Particularly difficult is the strengthening of shores with sandy sediments, when the intensity and direction of lithodynamic processes in the coastal zone of the sea cannot always be unambiguously and reliably assessed with the accuracy required for development of design measures for engineering protection [2].

One of the striking examples of a railway laid along coastlines with sand deposits is the Pacific section of the Far Eastern Railway Korsakov – Nogliki, where in some sections the roadbed and bridge abutments are already exposed to waves. Pic. 1 shows that the sandy beach is almost completely washed away and the abutments of the bridge over the Gar River (263rd km of Korsakov – Nogliki section of the Far Eastern Railway) are under the threat of being washed away by storm waves.

At another section (272nd – 273rd km) there is a narrow strip of beach in front of the railway roadbed (Pic. 2). Here the beach is considered as a coastal protection structure and its width must be sufficient to absorb wave energy at the design tidal sea level. On the section of coast under consideration, the width of the existing beach is insufficient to protect the roadbed from being washed away by waves. To protect the coast from wave erosion and ensure uninterrupted operation of railway transport, coast protection measures had been carried out for a long time. Currently, the coastal slope along almost the entire length of the considered section of the coast is covered with stones of various sizes.

When covering the coastal slope, mainly large stone was used. However, under the top layer of large stone, laid in one row, stone of a smaller fraction was placed. During the impact of waves on the slope, when the top layer of the stone fill was disturbed, small fractions were washed out, which led to deformation of the stone cover protecting the railway roadbed (Pic. 3). Covering the slope of the roadbed with stones of varying sizes in the absence of a wave-absorbing beach in front of it could not fully provide the necessary protection from wave erosion.

This work, using the example of the Sambian Peninsula (Kaliningrad region), shows the results of the studies on sandy beaches that ensure stability of the coast and safety of transport routes.

The problem of erosion of the shore in this area and the roads located along it has been relevant for several decades [3, 4]. Attempts to solve it have generally been not successful. Meanwhile, roads that are at risk of erosion are very important for the entire region. For example, the road along the Curonian Spit is the only one connecting the National Park with the city of

Pic. 1. Washing away of the bridge abutments at 263rd km of Korsakov – Nogliki section of the Far Eastern Railway. 2020 [photo made by the authors].

Pic. 2. A narrow strip of beach on 272nd –273rd km of Korsakov-Nogliki section of the Far Eastern Railway. 2020 [photo made by the authors].

Pic. 3. Washing away of the base of the roadbed slope at 273rd km of the section Korsakov – Nogliki. 2020 [photo made by the authors].

Zelenogradsk. Since for a qualitative solution to the problem of coastal erosion in this region, an accurate assessment of ongoing lithodynamic processes on the underwater slope is of primary importance, great importance is given to their study.

The northern coastal zone of the Sambian Peninsula from Cape Taran along its entire length has been subject to abrasion for a long time. The coastal protection and beach retention structures built at the beginning of the last century had already been destroyed or seriously deformed by 1971 [5], and the beach retention structures erected later were ineffective. Beach erosion continues, and the coast recedes [6].

The one-way movement of sandy material along the shores of the Sambian Peninsula (alongshore sediment flow) and its influence on the rate of coastal retreat was established back in the first part of the 20th century. It was shown that within the western coast of the peninsula the general movement of sediment is directed southward, towards the Vistula Spit, and within the northern coast – eastward, towards the Curonian Spit.

Studies of lithodynamic processes in the coastal zone of the southeastern Baltic in the sixties of the last century confirmed the existence of alongshore movement of sand sediments. The concept of a single alongshore flow of sand sediments, directed from Cape Taran to the entrance to the Gulf of Riga, was proposed [7]. At the same time, these studies showed a deficiency of sand sediments within the Sambian Peninsula to the root of the Curonian Spit, and, consequently, a deficiency of sand in the alongshore sediment flow.

The concept of a single alongshore flow of sandy material in practical terms resulted in construction of beach retention structures that retained part of the material from the sediment flow, causing a local expansion of the beach strip and a decrease in the rate of coastal erosion, but without stopping it completely. The removal of material from the alongshore sediment flow by the system of spur dikes increased the sediment deficit in the flow and the intensity of erosion of the lower section of the coast.

Currently, the idea of a single alongshore sediment flow in the south-eastern Baltic is considered outdated by several researchers, and a concept of relatively isolated morpholithodynamic cells of different scales has been proposed [8], according to which sections of diverging sediment flows alternate along the coast, counter flows are formed in cells of a smaller scale, converging at the tops of coastal arcs. The existence of morpholithodynamic cells is confirmed by the results of mathematical modelling of sand transport generated by wind waves in the coastal zone.

Within the coast under consideration, from Cape Taran to Cape Gvardeisky, there are two areas of convergence from Cape Taran to Svetlogorsk and an area of divergence of flows in Pionerskaya Bay [9]. Recommendations for the use of selected morpholithodynamic cells to solve practical problems of coastal protection have not been developed yet.

From the above it follows that several questions related to movement of sediment along the south-eastern Baltic remain open despite ongoing research [10–16], and the applied methods of coastal protection are ineffective [17].

Therefore, further research into lithodynamic processes in the coastal zone of Kaliningrad region is necessary, and the search for a rational way to protect eroded shores and transport structures located on them is one of the important practical tasks.

OBJECTIVE, MATERIALS AND METHODS

In this work, studies of stability of a sandy beach in combination with wave-damping and beach-retaining structures were carried out using the method of physical modelling in a wave basin.

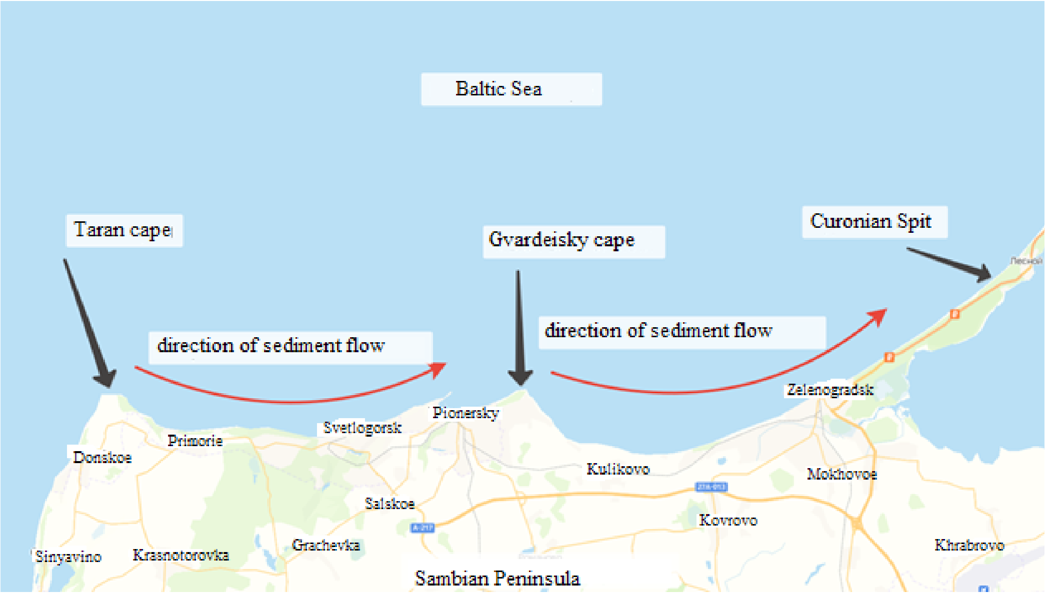
The coastal zone of the northern coast of Kaliningrad region from Cape Taran to the Curonian Spit inclusive is considered.

The objective of the study is to determine on a physical model a set of measures to ensure the stability of the created sandy beach on an abrasive section of the coast with a deficiency of sediment in the alongshore flow.

RESULTS

The History of the Issue

In 1976, the Black Sea branch of Central Research Institute of Transport Construction (TsNIIS) developed an engineering method for calculating the formation of artificial free beaches and prepared recommendations for their use on the Kaliningrad Baltic coast [18]. The possibility of creating a sandy beach without beach retention structures was indicated by the impressive difference in the dynamics between the western coast of the Sambian Peninsula in the discharge zone of the sandy pulp of the Yantarny [Amber]



Pic. 4. Northern coast of the Sambian Peninsula [developed by the authors].

plant and the northern coast of the peninsula, the sediment flow along which was replenished mainly with material from shore erosion. The northern coast of the peninsula during 1960–1970 retreated everywhere, in some places by up to 0,5 m per year, and the western one from the place of pulp discharge to the city of Baltiysk was accumulative for 33 km. The volume of sand deposited in this area by 1974 amounted to about 30000 m^3, and an extensive accumulative ledge was formed in the pulp drainage area. An attractive idea arose of creating a full-profile sandy beach without beach-holding and wave-damping structures, ensuring complete damping of storm waves and stability of the coastal slope. To do this, it was necessary to fill (refill) the required volume of sand material, from which a profile of dynamic equilibrium would be formed and this would cover the shore from the effects of waves.

On the northern coast of the Sambian Peninsula, abrasion predominates. The rate of retreat of the shore edge in 1976 in some areas was estimated from 0,1 to 0,5 m per year and remains approximately the same at present. It should be noted that before the start of the dumping of overburden from the Yantarny plant, the western coast of the Sambian Peninsula was retreating at approximately the same speed as the northern one [6].

Calculation of the dynamic equilibrium profile for the section Taran Cape – Kupalny Cape was carried out with wave parameters of 4 % probability in the mode and 50 % probability in the system along the line of the first collapse: wave height h = 4,4 m, period T = 9,5 s and average sand size d_{50} = 0,15 mm. The collapse of the calculated wave under such conditions occurs at the depth of H_{cr} = 7,6 m at a distance of 600 m from the shore.

A comparison of the actual profiles of the underwater slope within the six-hundred-meter strip of the coast under consideration with the calculated dynamic equilibrium profile showed that throughout the entire length the field profiles are located below the calculated one, indicating a shortage of sandy material in the coastal strip. The total sand deficit in the Taran cape – Kupalny cape section alone, with a length of about 25 km, amounted to 17,3 million m^3.

On a significant area of the bottom of the coastal strip, boulder-block material lies on the surface, forming an erosion pavement area bordering the Sambian Peninsula with a width of 250 m to 5 km. At capes Taran, Kupalny and Gvardeysky, the stone pavement area adjoins directly to the shore and the beach strip is completely washed away. Only at the tops of the bays beaches up to 30–50 m wide made of fine and medium-grained sand were preserved, and on the underwater slope there was a layer of sandy material above the stone pavement area. The wide distribution of stone pavements covering bottom sediments in the coastal strip served as the basis for the conclusion that the alongshore sediment flow in the area from Cape Taran to Cape Gvardeisky is formed mainly due to erosion of the coastal slope, and the proportion of material from bottom erosion is insignificant (Pic. 4). It was assumed that all the material from the erosion of the coast and bottom goes away with the alongshore flow and does not participate in the formation of the profile of the underwater slope of the abrasive sections of the coast.

The stone pavement of the bottom along the northern coast of the Sambian Peninsula causes the formation of an alongshore flow with a large sediment deficit. An alongshore flow without sediment deficiency can only form when there is a profile of dynamic equilibrium. Calculation of alongshore flow capacity, i. e. the transporting ability of waves and the alongshore currents of fine-grained sand excited by them with an average diameter of 0,15 mm off the northern coast of the Sambian Peninsula showed that it varies from 240 thousand to 520 thousand m^3 per year depending on the direction (azimuth) of the coastline. The actual alongshore sediment flow on the approach to Cape Kupalny was estimated at 200 thousand m^3 per year and, therefore, the sediment deficit in the alongshore flow ranged from 280 thousand m^3 to 320 thousand m^3 per year for certain sections of the coast.

The extent of the shortage of sandy material on the northern coast of the Sambian Peninsula and at the same time the shortage of sand in the alongshore flow showed the full scale of the solution to the problem of creating a wave-damping sandy beach without beach-retaining structures, but it seemed that technically this problem could be solved. It was only necessary to find the appropriate reserves of sand and pour (refill) it onto the shore into the zone of origin (formation) of the alongshore sediment flow. An option was also proposed to solve this problem by transferring the pulp of the Yantarny Plant to the northern coast of the Sambian Peninsula, but this proposal did not receive support, and the discharge of pulp to the western coast of the peninsula was stopped in 2000.

The idea of creating a wave-absorbing sandy beach without beach-retaining structures was implemented by the SNPO Baltberegozaschita. During 1987–1991, a beach with a maximum width of 140 m was reclaimed from the material cut from the high emergency shore in the Filino-Primorye section in the amount of 2,3 million m^3 of sand over an area of 1,1 km [6]. The man-made beach was created in a zone with a minimum capacity of the alongshore sediment flow of 240 thousand m^3 per year within the considered area of the northern coast of the Sambian Peninsula and, therefore, characterised by a minimum sediment deficit in the alongshore flow. However, the stability of the reclaimed beach turned out to be low, and the erosion rate was significantly higher than expected [18]. Eight years after the end of reclamation, the beach was almost completely washed away. At the same time, no noticeable increments of the beach were detected in the next areas along the sediment flow, and, consequently, the material left the reclaimed area not only along the coast, but also, and perhaps mainly, to the deep waters, forming a profile of dynamic equilibrium.

The continued erosion of the beaches and shores of the Sambian Peninsula necessitated the protection of local emergency areas with the help of beach-retaining structures, while the construction of spur dikes with a low root part continued [17], while a century of experience in using those spur dikes under the conditions of sand deficiency in the alongshore flow showed their low efficiency. The low root part of the spur dikes reduces their beach-holding capacity. The maximum efficiency of the spur dikes will be ensured when the profile of their crest follows the designed beach with a reasonable margin. That is why 40 previously erected wooden spur dikes in Zelenogradsk did not lead to stabilisation of the beach strip.

The deficiency of sediments in the coastal zone and in the alongshore flow of the Sambian Peninsula, as well as unsuccessful experience of creating a free wave-absorbing sandy beach, showed the futility of this direction. But the problem of protecting the eroded shores of Kaliningrad region remains, and the search for a way to solve this problem continues to this day.

Problem Statement

A promising direction for protecting the abrasive shores of Kaliningrad coast seems to be creation of sandy beaches in combination with wave-damping, beach-retaining and shoreline protection structures.

Wave-damping structure which is an intermittent breakwater made of tetrapods partially dampens wave energy and reduces the wave impact on the beach and reduces the width of the zone of intense alongshore transport of beach material. Beach retention structures which are spur dikes made of large stones with the root part attached to the blocking course provide relative stability of the beach and at the same time allow passage of the transit flow of sediment that forms on the approach to the protected area.

A beach of calculated dimensions is formed from material poured into the compartments between spur dikes. Coastal protection structures – a belt or a stone berm are erected along the base of the coastal slope to increase its stability and protection during storms of rare recurrence and high surge levels.

The transit flow of sandy material along the system of structures and the beach in a local area eliminates their negative impact on the adjacent section of the coast along the sediment flow associated with bottom erosion. At the same time, the transit of sandy material under conditions of material deficiency in the sediment flow determines the minimum width of a stable beach, which is determined by the beach-holding capacity of the complex of wave-damping and beach-retaining structures, and the actual sediment flow formed on the approach to the site. The size of a stable beach can be increased by placing sand material at the approach to the protected area, that is, by reducing the deficiency of material in the sediment flow.

The construction of a stable strip of sandy beach in combination with wave-damping and beach-retaining structures and backfilling (alluvium) of beach-forming material will make it possible to solve stage-by-stage the problem of protecting eroded shores and transport highways located in the coastal zone of Kaliningrad region. First, local (emergency) areas are protected, and subsequently, an artificial beach is created within the main zone of coastal erosion along the entire northern coast from Cape Taran to the Curonian Spit inclusive. The road laid along the Curonian Spit was repeatedly flooded due to the erosion of coastal dunes and the breakthrough of surge waters in Zelenogradsk region [17].

Experimental Study's Results

The study of stability of a sandy beach was carried out on a model of a fragment of the coast of the Sambian Peninsula in the area of Pionerskaya Bay with a deficiency of material in the alongshore sediment flow. The height of the coastal slope within the site varies from 3 to 10 m. The base of the slope is partially eroded. The width of the beach strip is 10–15 m.

The slope of the underwater slope in a hundred-meter coastal strip is 0,01, and in a five-hundred-meter coastal strip it is still settling down.

On the underwater slope there are two underwater sand embankments. The first embankment is located at a distance of 50 m from the shore, has a relative height of 0,6 m and a depth above the ridge of 0,9 m; the second embankment is located at a distance of 250 m from the shore, its height is 0,7 m, and the depth at the ridge is 3,4 m.

The average long-term sea level according to observations at the Pionersky HMS is 0,07 m in the Baltic height system. The maximum level with a 1 % probability is 1,36 m abs., and the minimum level is minus 1,10 m abs. (oscillation amplitude 2,46 m).

Experimental studies in a wave basin on stability of the dumped material were carried out during a western storm with a frequency of once every 25 years at sea level with a probability of 1 %. The parameters of the waves of the western storm on the approach to the breakwater were:

– average period = 13,5 s;
– height of waves h = 2,24 m;
– azimuth 331 degrees.

In experimental studies on hydraulic models of lithodynamic processes occurring on sandy coasts, sand was used as sediment, the size of which corresponds to the material of the beach in nature.

Using a model in a wave basin on a vertical scale of 1:37 and a horizontal scale of 1:131, the actual relief of the coastal zone of the Pionerskaya Bay section with a length of 700 m and a width of 342 m from the base of the coastal slope to the 5,0 m isobath was built. The relief surface was built according to the installed beacons.

At a distance of 170 m from the base of the coastal slope, three fragments of an intermittent breakwater were built from six layers of tetrapods weighing 3 tons.

The elevation of the top of the crests of the intermittent breakwater was +1,70 m BS (0,34 m above the calculated maximum level of 1 % probability), and the gaps between the fragments of the intermittent breakwater at the average level were 29 m.

Four 100 m long spur dikes made of large stone weighing from 100 to 300 kg were located in the central part of the selected area. The distance between the axes of the spur dikes was 100 m. The root part of the spur dikes, is made horizontal at an elevation of +2,0 m for 15 m. Further into the sea, the ridge is lowered to an elevation of +1,0 m at the head of the spur dike.

Pic. 5. View of the model during the experiment [photo made by the authors].

Sand with an average size of 0,50 mm was poured into the compartments between spur dikes. Within the coastal strip 59 m wide, the surface of the dumped material was made 20 cm below the crest of the rockfill spur dikes, and further into the sea the layer of dumped material decreased to zero 150 m from the shore. The surface marks of the dumped material were controlled by beacons distributed over the area. Outside the spur dike, on the upstream side relative to the sediment flow and on the downstream side, the bottom topography of the model remained natural.

According to observational materials, the duration of storms passing through the study area varies from 6 to 40 hours. The average duration of storms is 23 hours. When studying a beach model in a wave basin, the duration of the storm, which corresponds to the phase of its stabilisation, is taken equal to 24 hours in reality and, accordingly, 4 hours on the model.

During the experiment, under the influence of waves, a beach began to form from the material of the original fill (Pic. 5). The main part of the material moved to the upper part of the model. A small amount of sand material was thrown over the crests of the second, third and fourth spur dikes throughout the experiment.

During first two hours of the experiment, intense erosion of the natural bottom of the model was observed to the west of the first (western) spur dike. The eroded material partially accumulated in front of the first spur dike, and the remaining part compensated for the deficiency of material in the alongshore sediment flow and went beyond the site in transit. A decrease in the deficit of material in the transit flow of sediment and a restructuring of the profile of the filled beach under the action of waves, expressed in the massive movement of material from a depth of 2,5 m to 4,0 m to the upper and above-water part of the forming beach, caused the expansion of the beach and an increase in its elevations. At the beginning of the experiment, the width of the filled beach at a calculated level of 1,36 m within the entire area was 22 m. After two hours of the experiment (the first 12 hours of the storm in nature), the width of the beach increased in all three compartments and ranged from 38 m to 62 m.

During the last two hours of the experiment, erosion of the bottom of the model on the approach to the protected area decreased due to the depletion of sand reserves and the partial exposure of the stone-paved area. This led to an increasing shortage of material in the sediment flow. On the leeward side of the first spur dike, the beach was completely washed away, and on the windward side of the second spur dike from the west, the width of the beach was 26,6 m. Thus, in the first inter-spur dike compartment there was a sharp skew of the beach contour towards the movement of material.

In the second and third inter-spur dike compartments, a beach with a more even contour was formed, and its width was twice as wide as the width of the original fill.

Based on the results of measurements performed on the model, the volumes of relief deformations in the inter-spur dike sections and in adjacent sections of the coast were determined. In the area west of the first (western) spur dike, erosion prevailed throughout the experiment with a gradual decrease in intensity. The volume of erosion in a 15 m wide strip only adjacent to the first western spur dike amounted to 1892 m^3. It should be noted that mainly the outer low part of the bottom was eroded at levels from 0,0 m to minus 4,0 m, while the beach grew. As a result, a beach 26 m wide and 22 m long was formed in the re-entrant corner of the first spur dike, which remained until the end of the experiment.

In the first western compartment, the beach material and the bottom were partially washed away. The volume of erosion was 7452 m^3. In the second inter-spur dike compartment, accumulation of material of a volume of 10443 m^3 was recorded. In the third compartment, the beach accumulation amounted to 9963 m^3. Sandy material also accumulated on the eastern leeward side of the fourth spur dike. 1556 m^3 were deposited here.

The total volume of sandy material within the protected area with a length of 300 m along the axes of the outer spur dikes during the period of the estimated storm generally increased by 13151 m^3. Consequently, the proposed system of wave-damping and beach retention structures ensures the stability of the beach.

It should be noted that on the underwater slope in the area of the heads of the spur dikes of the second and third inter-spur dike compartments and further to the breakwaters, deformation of the bottom during the entire experiment was insignificant, as well as outside the breakwaters. The wave, passing through the gaps of the intermittent breakwater, bends around its fragment protruding from the water and two elements of the wave meet in the water area behind the breakwater, forming a new wave close in height to the original one. The meeting point of two wave elements deviates from the middle of the breakwater fragment depending on the angle of approach of the waves. As a result of this effect, the height of the beach along the abrasion coast changed from a minimum of 2,0 m in the zone of divergence of wave rays to a maximum of 3,60 m in the convergence zone.

CONCLUSIONS

Experimental studies using a physical model of a coast with a deficiency of material in the alongshore sediment flow showed that a complex of wave-damping and beach-retaining structures in combination with dumping of material makes it possible to create a local stable wave-damping sandy beach that provides protection to the coast and transport highways and other structures located in the coastal zone.

The experiments performed show the fundamental possibility of creating a local sustainable sandy beach on the northern coast of Kaliningrad region. The research results can be extended to other coastal sections of roads and railways. When protecting a specific area, it is necessary to search for the optimal size and layout of wave-damping and beach-retaining structures, which allows solving the problem at minimal cost.

Since there are still many unsolved problems in the field of protection of transport infrastructure situated on seashore with sand drift, the relevant research should be continued.

Thus, balanced assessment of transport of sand deposits in coastal zone is still among main problems. Most reliable description of morphodynamic processes and transport of sand deposits is made with mathematical models in [9; 19], which is confirmed by the data of field observations [15; 16; etc] and the research proposed in this work. Considering recent successful developments in the field of numerical models of the relief dynamics and application of models described in [9; 19], further research on those issues should be continued with the help of the methods of mathematical simulation.

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