Morphodynamic conditions of particle size distribution of beach sediments of Coastal Area of Karadag Natural Reserve

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Abstract. The article presents the results of studying particle size distribution of sediments in the beach areas of the Karadag coastal area of the Crimean peninsula. In the framework of this study, this area is considered as a lithodynamic system. The paper describes the connection between the granulometric structure of sediments and external processes that affect this system, which is an important indicator of response of the condition of a coastline to dynamic environmental conditions. It is established that the wave processes, exogenous geological processes (mainly of a gravitational nature), abrasion of cliff and bench result in the transportation and accumulation of beach sediments along the coast, as well as determine the peculiarities of their distribution according to particle size distribution. Based on the particle size analysis, the differentiation of beach sediments along the coastline of Karadag is revealed. When calculating the static parameters of the particle size data, the morphodynamic conditions of distribution of sediments in the coastal area are characterized.

1. Introduction

The coastal area of the Karadag coast (the zone of contact between land, sea and atmosphere) with a total length of indentation of the coastline of 8 is an active lithodynamic system. Any activity that takes place here requires a complete study of the current state of the coast, its trends and dynamics in order to predict changes in the coastline.

A number of works with a very wide geography are devoted to the study of the modern lithodynamic state of sediments of seacoasts and rivers. For example, such studies are conducted in Ghana (the Volta River) [11], in New Zealand in the Canterbury Bay [10], as well as on the Pacific coast near the city of Timaru [5]. The distribution features of beach material, both sandy and pebbled, are studied in China (Beibu Bay beaches) [14] and in Canada (the Bay of Fundy) [16]. The relationship between distribution of sediment size, their volumes and the study of beach erosion is carried out in the USA (Plum Island and the Merrimak River) [9]. It should be noted that during these studies, particular attention is paid to the specific features of the redistribution of solid sediments of the coasts by particle size.

Domestically the study of the lithodynamic processes of seacoasts was carried out by such researchers as G.A. Safyanov [15], P.K. Bozhich [4], V.P. Zenkovich [17], N.A. Belov [2], whose works were devoted to the issues of geomorphology of seacoasts and particle size differentiation of...
sediments. The features of modern lithodynamics, particularly in the coastal area of the Black Sea, are reflected in the works of A.A. Klyukina [12], I.V. Agarkova-Lyakh [1], A.S. Boguslavsky et al. [3].

2. Methods and materials
As part of the study of differentiation processes of sediments on the beaches of the Karadag coastal area in the summer of 2018, sampling of solid sediment material was carried out, particle size analysis was made, as well as statistical processing with the main results represented in graphs.

![Figure 1. Points of beach sediment profiles in the bays of the coastline of the Karadag natural reserve](image)

The main object of the study is the deposits of the beach area, represented by coarse and sandy material.

The sediment material was collected in the beach areas of 15 bays: Karadag Bay, bay near the Kuzmichev Kamen cliff, Razboinichya Bay, Puttsolanovaya Bay, Pogranichnaya Bay (western part), Lvinaya Bay, Barakhta Bay, Yuzhnaya Serdolikovaya Bay, Srednyaya Serdolikovaya Bay, Severnaya Serdolovaya Bay, Livadia Bay, Graviinaya Bay, Lyagushachya Bay, Cape Malchin Bay, Koktebel Bay. In all the bays, the particle size analysis was carried out along the transverse profile in the widest part of the beach. However, due to the development of an extended beach area, the number of transverse profiles in the Karadag and Koktebel Bays amounts to 2 and 4, respectively. The sampling of solid material of beach sediments, represented by coarse and sandy material, was carried out along 19 profiles at certain points with the range from 2 to 3 meters, depending on the width of the beach. The morphological parts of it were also covered, i.e. the wave run-up area, coastal shafts, the shallow surface of the beach and the area at the foot of the adjacent slope.

At the selected points, the soil samples were collected from the surface of the beach sediments to a depth of 30 cm. A at the interval of 2 or 3 meters cm. A coarse material was measured using a caliper. The size of the sand fractions was determined by the sieve method in accordance with the current GOST 25100-2011 standard – “Soils. Classification ”[8]

In order to process and interpret the results of the obtained data, the following statistical particle-size parameters were calculated for each profile: roof-mean-square or standard deviation \( S_0 \) (used as sorting factor); average or median diameter (median) \( M_d \); kurtosis (\( E_k \)) and graphic average diameter (GAD) [7].

1) Sorting factor \( S_0 \) is calculated using the following formula:

\[
S_0 = \sqrt{\frac{Q3}{Q1}}
\]

where \( Q1 \) and \( Q3 \) are the first (smaller) and the third (large) quartiles in the graph of the cumulative curve of material distribution of beach sediment by size.
The first quartile is such a grain size (i.e., such an abscissa) with respect to which 25% of the grains are smaller and 75% are larger; the third quartile, on the contrary, is a size relative to which 25% of the particles are larger and 75% are smaller. The quartiles on the distribution graph are determined by drawing from the ordinates corresponding to the content of 25 and 75% of the data, the normal lines on the abscissa axis, which corresponds to the particle size and describes the quartiles sought [6].

The smaller the difference in grain sizes, the closer the quartiles are to each other and to the average diameter $M_d$, the closer $S_0$ to the unit, i.e. the better the sorting. In a well-sorted material $S_0 < 2$; in a medium-sorted material $S_0 = 2–3$; in a poorly sorted material $S_0 > 3$ [6].

The degree of sorting indicates the duration of the dynamic processing of material, during which the beach sediments of the clastic material tend to become homogeneous (or monofractional). If you look at the Gaussian distribution curve of such a material, then it would be more compressed and higher. Conversely, a bi- or polymodal distribution curve will indicate a mixture of material from different sources or a lack of dynamic environmental forces necessary for processing and sorting.

2) The average, or median, diameter $M_d$ (mm) is the size relative to which half of the particles are smaller and the other half is larger (this is the second quartile $Q_2$). This is an important indicator of the particle size structure of the rock and a genetic trait indicating the strength or speed of the current that has deposited this material. It is most informative for relatively well-sorted rocks. By the size of the debris (in particular, by $M_d$ value), one can navigate in the strength or velocity of the current that processes the beach material [6].

3) The graphic average diameter – GAD (mm) – is determined not by one point (50% of $Q_2$ ordinate), but by the biggest part of the particle size spectrum. This indicator is used for classification purposes when evaluating particle size distribution in a sample:

$$GAD = \frac{Q_4 + M_d + Q_5}{3},$$

where $Q_4$ and $Q_5$ are the particle sizes, with respect to which 16 and 84% of the particles in the sample are smaller.

4) Kurtosis ($E_k$) is a measure of peaks or “steepness” of the distribution curve:

$$E_k = \frac{Q_3 - Q_1}{2(P_{90} - P_{10})},$$

where $P_{90}$ and $P_{10}$ are percentiles (or deciles), i.e. the diameters of the grains by which the tails of the total curve are determined with $P_{90} > P_{10}$. Moreover, there is the following gradation: $< 0.67$ – strongly flat peak distribution curves; 0.67–0.90 – flat topped; 0.90–1.11 – normal (correspond to the normal distribution); 1.11–1.50 – weakly compressed (weakly pointed); 1.50–3.0 – medium (or highly) compressed (mid-peak) and $> 3.0$ – extremely compressed (highly peaked) [6]. High variability of values indicates that the modal and related classes are characterized by a high percentage of the material.

In accordance with the excess in statistics [13], the normal distribution has a value of the indicator equal to 0 (or tending to it), positive values characterize the peaks of the distribution curve, and negative values indicate the flatness of the curve. Linking this information with the kurtosis interpretation indices during particle size analysis, one may conclude that the calculated kurtosis values $> 1.0$ indicate stable active hydrodynamics, the stability of processing and re-sorting of clastic material, or the effect of active forces on the system for a long time. A significant positive excess indicates that strong hydrodynamic processes acted in a short period of time, or weak processes acted for a long period, and also the speed of dynamic processing (sorting) of the brought clastic material exceeded the intensity of its receipt. The kurtosis value that is $< 1.0$ indicates the instability of external environmental forces (wave-breaking process within the lithodynamic system) or the lack of activity, as well as massive, often avalanche, flow of debris material that is not able to process dynamically the
forces of the medium. For example, the bringing of clastic material and its deposition in dynamically stagnant conditions [6].

The final diagrams of the calculated particle size distribution were compiled in ArcGis 10.5. The numbers on the diagrams correspond to the following transverse profiles of bays:

1) Karadag Bay (profile1);
2) Karadag Bay (profile 2);
3) Bay near the Kuzmichev Kamen cliff;
4) Razboinicheya Bay;
5) Putstsolanovaya Bay;
6) Pogranichnaya Bay;
7) Lvinaya Bay;
8) Barakhta Bay;
9) Yuzhnaya Serdolikovaya Bay;
10) Srednyaya Serdolikovaya Bay;
11) Severnaya Serdolovaya Bay;
12) Livadia Bay;
13) Graviinaya Bay;
14) Lyagushachya Bay;
15) Cape Malchin Bay;
16) Koktebel Bay (профиль 1);
17) Koktebel Bay (profile1 2);
18) Koktebel Bay (profile1 3);
19) Koktebel Bay (profile1 4).

3. Results
The analysis of the particle size composition of beach sediments makes it possible to establish a number of patterns of their distribution along the entire coastline of the Karadag reserve. The material in the beach sediments under the influence of the wave-breaking process is distinguished differently. The decrease in particle size in the northeastern part of the coast is explained by more yielding rocks and an actively eroded cliff. On the contrary, sediment enlargement is the source of terrigenous material and is observed on coastal areas composed of more solid rocks, as well as in places where the impact of disturbance is limited.

To analyze the coastal variability of statistical parameters of the grain size distribution of sediments, distribution diagrams of sorting values ($S_0$), median (Md), and graphic average diameter (GAD) were compiled.

When analyzing the distribution of sorting values ($S_0$), it was found that well-sorted beach sediments prevail within the considered area. The sorted sediments are found on the periphery of the coastal area, usually at the foot of a slope or in the center of the beach. Poorly sorted material is present in the Karadag Bay, in the upper part of the beach. This indicates the inflow of foreign material associated with active exogenous geological processes on the front of the coastal ledge, as well as with the heterogeneous composition of the flyschoid strata.

Having carried out the analysis of the median particle size along the coast it was revealed that larger sediment particles are located in the northeastern part of the coastline, starting from the central part of the beach to the sea edge (Bay at Cape Malchin, Koktebel Bay profile 1 and profile 2). In the eastern and western parts of the coastline, the median size decreases sharply. The consolidation of sediments was noted in the bay near the Kuzmichev Kamen cliff at the beginning and at the end of the transverse profile (at the point at the foot of the adjacent slope and in the zone of the wave run, respectively), as well as at the edge of the sea in Putstsolanovaya Bay. The consolidation of sediments can be explained by the local, avalanche-like inflow of coarse clastic material and the composition of the rocks.
When passing to the central part of the beaches of the coastline, the redistribution of sediment material occurs in such a way that their median size is relatively uniform, and is not represented by large particles (sizes to small pebbles).

When analyzing the distribution of the values of the graphic average diameter, we can conclude that the central part of the coastal section under consideration is characterized by a minimal coarseness of deposits. In the eastern part of the coastal area, sediment consolidation is observed in the bay near the Kuzmichev Kamen cliff in the upper and lower parts of the beach. In this transverse profile, landslide processes are observed at the adjacent slope. In the eastern part of the coast, the GAD indicator has the maximum value in the coastal section under consideration.

![Figure 2. Distribution of sorting values (S₀) of beach sediments of the Karadag coastal area. Notes: • – sediment sampling point; S₀<2 – well-sorted material; 2<S₀<3 – medium sorted material; S₀> 3 – poorly sorted material. Horizontal direction is a distance along the coastline, m; vertical direction is a distance perpendicular to the coastline (beach profile), m](image)

The enlargement of sediments is also explained by the local inflow of coarse clastic material and is observed in the areas where the influence of waves is limited. What is observed here is an active inflow of coarse clastic material into the lithodynamic system due to the active abrasion activity influencing the yielding rocks. In general, one may say that the beach sediments of the Karadag coastal area are composed of small and medium pebbles.

The kurtosis value along the entire coastline of the Karadag reserve (<1.0) indicates the instability of external environmental forces (wave-surf process within the lithodynamic system) or their weakness, as well as massive, often avalanche inflow of clastic material, which can not be processed by the external forces of lithodynamic system due to casting and deposition of clastic material into dynamically stagnant zones, where the activity of the beach’s lithodynamic system is minimal.
Figure 3. Distribution of the values of median particle size (mm) of beach sediments of the Karadag coastal area. Notes: • – sediment sampling point. Horizontal direction is a distance along the coastline, m; vertical direction is a distance perpendicular to the coastline (beach profile), m

Figure 4. Distribution of values of graphic average particle diameter (mm) of beach sediments of the Karadag coastal area. Notes: • – sediment sampling point. Horizontal direction is a distance along the coastline, m; vertical direction is a distance perpendicular to the coastline (beach profile), m
4. Conclusion

There is a connection between the particle size differentiation of beach sediments and the dynamic processes effecting the system (beach). Testing the material of beach sediments and revealing spatial variability of the particle size structure gives general characteristic of various processes that manifest themselves within the lithodynamic system. When conducting particle size analysis and identifying sediment differentiation along the coast, some conclusions can be drawn about the lithodynamic processes of coastal zone functioning.

In general, sediments in the bays of the Karadag coast are mainly well-sorted. Sorted sediments are present on the periphery of the coastal area, and, as a rule, at the foot of the slope or in the center of the beach. Poorly sorted material is present in the Karadag Bay, in the upper part of the beach, which indicates the inflow of foreign material into this area. The heterogeneous material of small-plate structures entering the beach area as a result of exogenous processes on the frontal part of the coastal ledge is associated with geological structure represented by the flyschoid strata.

It was revealed that, according to the median particle size, larger sediment sizes are located in the northeastern part of the coastline, starting from the central part of the beach to the sea edge (Bay at Cape Malchin, Koktebel Bay profile 1 and profile 2). In the eastern and western parts of the coastline, the median size decreases sharply. The enlargement of sediments was noted in the bay near the Kuzmichev Kamen cliff at the beginning and at the end of the transverse profile (at the point at the foot of the adjacent slope and at the edge of the sea, respectively), as well as at the point near the sea of the Putstsolanovaya Bay. The enlargement of sediments is explained by the local inflow of coarse clastic material and is observed in the areas where the impact of waves is limited.

Thus, it was found that in the particle size composition of beach sediments at the foot of the slope along the entire coast of Karadag dominated by medium-size and small-size pebbles, except for the southwestern part of the coast where large pebbles prevail. In the last 2 profiles of the Koktebel Bay there is a sharp decrease in the size of sediments to fine gravel. In the northeastern part of the coast, the size of sediment particles also sharply decreases compared with the central bays – pebbles and fine sand.

Pebbles prevail in the center of the beach area of the coast, with the exception of some bays. In the bay at the Kuzmichev Kamen cliff in the center of the beach as a part of sediment coarse sand prevails. In the eastern part of the coast, there is a tendency for increased size of sediments material up to small and medium boulders (Bay at Cape Malchin, Koktebel Bay, profile 2). In the East, the prevailing sediment size is reduced to pebbles and fine sand.

Along the entire coast the deposits of the beach area are represented by pebbles of various sizes in the bays where the 1st coastal ramp stands out, with the exception of Yuzhnaya Serdolikovaya Bay, where the 1st coastal rampart consists mainly of fine gravel. In the zone of the wave run-up, the composition of beach sediments includes mainly medium and small pebbles, with the rare exception of some bays. In the Putstsolanovaya Bay fine gravel prevails and in the north-eastern part of the coast there are medium boulders in the bay.

The decrease in particle size distribution in the northeastern part of the coast can be explained by less durable types of sediment rocks and an actively eroded cliff.

Throughout the coastline of the Karadag reserve, instability or inadequate activity of external forces acting on the coastal area was observed in combination with the massive inflow of clastic material due to exogenous geological processes in the coastal area, as well as the inflow of clastic material into dynamically inactive areas.

Acknowledgment

The work is a result of the following state order: Study of spatial and temporal organization of water and land ecosystems with the aim of developing an on-line monitoring system based on remote sensing data and GIS technologies. The registration number is AAAA-A19-119061190081-9.
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