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Geomorphological aspects of coast protection in high latitudes

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The problems related to the protection of settlements located on the coast, mainly on Holocene sand-pebble accumulative formations (barrier islands and spits) of the Okhotsk, Chukchi and Bering seas have been considered. Approaches of solving the problem on the shores of Alaska, Chukotka, Kamchatka, Western Priokhotye and Sakhalin have been compared as well. The evolution of coastal protection solutions on the Arctic and subarctic coasts has been shown. It is concluded that the justification of the design solutions does not always correspond to the level of modern knowledge about the dynamics of the shores. Herewith, the basis for determining long-term trends of erosion of problem areas of the coast is the interpolation of the long-term average data obtained at the analysis of remote sensing materials.

The main trends of erosion of coastal plains and dynamics of Holocene accumulative forms are considered in relevance to the problem of protecting of the coast. Specific features of geomorphological processes on the Arctic and subarctic coasts have been noted. It is concluded that biopositive and safe coastal protection solutions are possible on the basis of a complete set of data about the development and dynamics of the coastal zone of the seas.

Keywords: coastal erosion, coastal protection, freezing beach, permafrost, Arctic coast, Subarctic sea.

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Геоморфологические аспекты проблемы берегозащиты в высоких широтах

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Традиционный уклад жизни аборигенных народов побережья Арктики, наряду с максимальным приближением к объектам промысла, учитывал и особенности строения побережья, используя для поселения и хозяйственной деятельности песчано-галечные аккумулятивные бары и косы. В условиях вечной мерзлоты зачастую это были единственно возможные места для постоянного проживания. Мы не можем утверждать, что катастрофические подъемы уровня и размыв береговых аккумулятивных форм арктических и субарктических морей в результате серии штормов исключительной силы, аналогичные наблюдаемым в конце XIX и начале XX в. на южном побережье п-ова Сьюард, обходили эти поселения стороной. Тем не менее свидетельств тому, что они являлись катастрофическими в рамках традиционной системы жизнеобеспечения, у нас нет. Изменения интенсивности размыва берегов отмечены на всех рассматриваемых морях. Обострение ситуации в последние десятилетия, скорее всего, не является чем-то из ряда вон выходящим. Однако требуемый уровень комфорта и безопасности, а также ценность имущества сейчас куда выше, чем сто лет назад.

В работе рассматриваются проблемы, связанные с защитой населенных пунктов, расположенных на побережье, главным образом на голоценовых песчано-галечных аккумулятивных образованиях (барьерных островах и косах) Охотского, Чукотского и Берингова морей. Сравниваются подходы к решению проблемы на берегах Аляски, Чукотки, Камчатки, западного Приохотья и Сахалина. Показана эволюция берегозащитных решений на арктических и субарктических берегах. Сделан

Статья написана на основе доклада на международной конференции под эгидой Международного географического союза «Практическая география и вызовы XXI века», посвященной 100-летию Института географии РАН (4–6 июня 2018 г., Москва).

вывод, что обоснование проектных решений не всегда соответствует уровню современных знаний о динамике берегов. В основе определения долгосрочных тенденций размыва проблемных участков побережья лежит лишь интерполяция среднемноголетних данных, полученных при анализе материалов дистанционного зондирования. Специфика геоморфологических процессов на арктических и субарктических берегах также практически не учитывается.

Применительно к проблеме защиты берегов рассмотрены основные тенденции размыва прибрежных равнин и динамики голоценовых аккумулятивных форм. Наиболее страдающие от перестроения берегов населенные пункты – Shishmaref, Kivalina, Unalakleet – расположены непосредственно на дистальных окончаниях кос системы лагунного пролива. Соответственно берегозащитные решения должны иметь в своей основе анализ миграций пролива, возможностей изменений направления роста, формы и морфометрических параметров дистальных окончаний кос, модификации приливной призмы. Следует отметить, что на данных участках побережья достаточно наносов для любых инженерных решений в этом направлении. Сделан вывод о том, что на основе полного набора данных о развитии и динамике прибрежной зоны рассмотренных морей возможны биопозитивные и безопасные берегозащитные решения.

Ключевые слова: размыв берегов, берегозащита, промерзающий пляж, многолетняя мерзлота, арктическое побережье, субарктическое море.

Introduction

The traditional way of life of aboriginal peoples of the Arctic coast along with the maximum approach to the objects of the fishery took into account the features of the coast structure using sand and pebbly accumulative bars and spits for settlement and economic activities. In permafrost conditions, these were often the only possible places for permanent residence. A high level of specialization in life support and an abundance of marine fishery resources resulted in the XIX – early XX century on the northeastern coast of Russia and the northwestern coast of North America, one of the highest density of coastal hunters in the subpolar range is up to 3 people per square kilometer [Krupnik, 1989]. Obviously, permanent settlements arose primarily in places of settlements of extinct or emigrated communities, temporary fishing grounds and seasonal hunting camps, which during the life of several generations did not experience the destructive effects of the sea. In the period of industrial development of these territories, the experience of the local population played a very significant role among the criteria for choosing the location for an industrial site or a settlement.

At the present time, we cannot assert that catastrophic rise in level and erosion of coastal accumulative forms of the Arctic and subarctic seas as a result of a series of storms of exceptional strength, similar to those observed at the end of the XIXth and beginning of the XXth century

on the southern coast of the Seward Peninsula bypassed these settlements side [Mason et al., 1996]. However, there is no evidence that they were catastrophic in the framework of the traditional life support system.

Over the past few decades in the Arctic an increase in air temperature and a decrease in the area of the ice cover were seen, which has important consequences for the climate, the ocean, the coastal zone and the traditional way of life of the population [Kinnard et al., 2011; Polyak et al., 2010; Streletskiy et al., 2012]. The reduction in the area of drifting and pack ice leads to an increase in the length of gathering speed and, accordingly, of the parameters of the wind waves, in addition, the growing ice-free period increases the duration of the wave action on the shores. As noted in the climate assessment report in Alaska, climate change is much faster than previously forecast, which increases the level of danger to coastal settlements and energy-related infrastructure [Markon et al., 2012].

Problems with erosion and protection of shores of the Chukchi, Bering and Okhotsk seas

On the shores of the Chuckchee Sea, the coastal forms created by swelling predominate [Ionin et al., 1971]. However, at the present time, under conditions of increased wave activity, the susceptibility of the coast of the Chuckchee Sea to abrasion processes is the lowest of the northern seas of Russia [Molchanov et al., 2011].

In addition, there are only a few settlements on hundreds of kilometers of the sea coast. In the area of the western entrance to the Longa Strait that connects the East Siberian Sea with the Chuckchee Sea, on the bar of the lagoon Valkarkynmangkak there is the native village of Billings with a population of about 200 people. Features of the morpholithodynamics of the coastal zone, due to the small width and depth of the coastal summer polynia on which the wind waving develops, as well as the nature of the atmospheric circulation during the warm period are such that the buildings are located practically on the beach and no one is going to transfer them.

Unlike the settlement Billings located on a typical lagoon bar, the village of Vankarem is located on a tombolo formed in the wave shadow of the eponymous rocky cape at the distal end of the western lagoon spit. The villages of Inchun, Uelen, Neshkan, Cape Schmidt are located on the barrier forms of the lagoon directly near the stone banks, which are actively destroyed by frost weathering and abrasion, which are a powerful source of sediments.

On the Bering Sea coast of Chukotka at present time all the settlements are located in closed bays and on high terraces. However, at the beginning of the last century all the coast was densely populated, there were several dozens of aboriginal villages and settlements whose inhabitants were subsequently collected in large settlements [Krupnik, 1989]. One of the main reasons for relocation along with the change in the life support system is the degradation of the Holocene coastal accumulative formations on which these settlements were located [Kaplin, Porotov, 2002]. The last in this row was the village of Beringovskiy, located on the Lakhtin lagoon. Fighting with erosion here began just after the construction in 1945 of a mooring pier with a length of 80 m [Afanasyev et al., 1998]. In 1952–1954 to protect the shore from erosion in the area of the village 11 wooden bunks were built with an interval of 100 m. They were quickly destroyed with ice and stormy waving. The epic with coast protection lasted almost 50 years, until the inhabitants were moved to the settlement Nagorny, renamed after the people left by the village of Beringovskiy.

The problem of coastal protection is not indicated in the normative legal field of the Kamchatka region. Nevertheless, it exists. In connection with the change of technologies for processing fish, some of the settlements created at the fish bases were closed in the 60–70 years. Then followed a wave of “enlargements” of settlements, which mainly touched native villages. After the earthquake in 2007, village Korf, located on the eponymous spit, was resettled. The problem of coastal protection, thus, has lost its sharpness. However, the inhabitants of settlements Ilpyrskoye, Ivashka, Apuka and Pakhachi in the north-east of Kamchatka, a total of 1.260 people, are currently protecting their homes with improvised tools, mainly of old barges and fishing vessels.

Such settlements as Osora, Karaga, Vyvenka, Kostroma, village Tilichiki, located on low accumulative terraces and spits closed from waving with stable feeding of deposits, have no problems with shore erosion at present.

The problem with erosion and protection of shores is more well known on the West Kamchatka coast [Vladimirov, 1958; Zenkovich et al., 1971; Gorin et al., 2012]. And if small settlements and fish bases here have not existed, the Oktyabrskiy settlement with a population of 1600 people, located on the October Spit, still struggles with the sea disaster.

A similar situation develops on the western, mainland coast of the Sea of Okhotsk. The erosion of low Holocene terraces, bars and spits on which dozens of abandoned settlements and fishery bases are located is of no interest to anyone except scientists and local lore. However, the first in the Far East city, and now the village of Okhotsk with a population of 3,500 people, located on the Tunguska Spit and onshore bars of the river Okhota practically from the beginning of its foundation and up to the present time “fights” with the sea [Gershanovich, Zabelina, 1957; Zabelina, 1961]. And if the territory of the port on the distal end of the spit has been protected for several decades by repeatedly repaired wooden wave walls, the houses periodically flood with storms during the high tides that reach here 4 meters. The funding requested for bank protection is about 70 million rubles.

On the southern shores of the Sea of Okhotsk attributed by us to the subarctic type and on the Sakhalin coast of the Tatar Strait, the morpholithodynamic justification and design of more than 30 km of bank protection structures were fulfilled, of which about 15 km have already been built [Afanasyev, 2015] (Fig. 1). Nevertheless, here coastal cities and settlements are degraded and absorbed by sea, port facilities are destroyed and even existing protection projects in city Krasnogorsk, Ulegorsk, Vzmorie are not realized for decades.

A slightly different situation and a different view to the problem on the eastern shores of the Bering and Chuckchee seas. The environmental changes associated with accelerated erosion and floods threatening communities in coastal areas in Alaska are under the scrutiny of scientists and the government [Alaska native Villages... , 2003; Alaska native Villages... , 2009; Gibbs, Richmond, 2015]. Human rights organizations are also very active, emphasizing that the indigenous population of Alaska is concentrated in the permanent settlements that were selected by the federal government, mainly because of the requirement of the US Department of Education's Bureau of Education to create permanent school facilities [Bronen, 2013]. Nevertheless, now,

budget constraints of existing laws do not allow the relocation of even the most needy Alaska communities affected by problems associated with shore erosion. Moreover, after 2009, federal funding for shore protection facilities can be accessed only in the case of 35 % co-financing by the community [Smith, Sattineni, 2016].

In 2006, of the 7 settlements that required priority attention, 4 were located directly in the coastal zone. The national settlements of Shishmaref and Kivalina (with a total population of 997 people) were recommended for resettlement, estimated at 250–305 million dollars, and for the towns of Kaktovik and Unalakleet (with a total population of 949 people in 2016), bank protection was supposed to cost about 70 million [Alaska village... , 2006]. In 2009, the priority solution required the problems of 10 coastal settlements [Alaska baseline... , 2009]. Over the past few years about 40 million dollars have already been spent on coastal protection. According to the plans of U.S. Army Corps of Engineers, not less than 150 million dollars are necessary for the protection of such settlements as Shaktoolik, Unalakleet, Shishmaref, Kaktovik, Kotzebue. The largest settlements on the coast of Kotzebue and Nome have a length of a protected shoreline



Fig. 1. Coastal shore erosion protection (Sakhalin Island). The lower part of rock revetment is covered by artificial pebble sediments, the gabion wall at the top is a splash protection to prevent the formation of ice on the road during the cold period. *Photo by V. Afanasiev*

of more than 4.5 km and until recently solved these problems themselves. The total length of the coast protection on the eastern shores of the Chuckchee Sea is currently about 2.8 km of rock revetments and sandbags and about 2.0 km of riprap revetment. On the eastern shores of the Bering Sea, a little over 3 km of coast protection was built. There is incomparably more extent of riprap revetment in the northern part of the Gulf of Alaska. Protected, mainly, the territory of large settlements and transport highways (Fig. 2).

Coastal structures on the eastern shores of the Chuckchee and Bering seas have evolved from offshore dredging to beach nourishment (Barrow), timber seawall, barrels of filled sand to gabion walls, sandbags, geotextile tube, cement block mat revetment and rock revetment (Fig. 3). At present, rock revetment is built on the most problematic areas, located on barrier forms and spits in native village Unalakleet (400 m), native village Kivalina (730 m), native village Shishmaref (800 m).



Fig. 2. Protection of the shore by concrete debris, Seward (Alaska). *Photo by V. Afanasiev*



Fig. 3. Protective sand shaft, Barrow (Alaska). *Photo by V. Afanasiev*

Geomorphological aspects of solving the problem

As the review of the problem shows, shore protection is primarily needed for settlements located on Holocene sand and gravel-pebble accumulative formations (barrier islands and spits). Only two protected settlements Barrow and Wainwright, are located on 5–15 m terraces of the coast with a high content of the underground ice in the sediments of bluffs. Without doubt, due to the presence of permafrost and underground ice, the erosion of coastlines in the moderate, subarctic and arctic regions has significant differences [Are et al., 2002; Overduin et al., 2014]. However, despite a certain difference in operating mechanisms, the quantitative difference in the intensity and activity of abrasion and thermoabrasive arctic coasts may be less significant than expected [Leont'yev, 2004].

Nevertheless, the focus in recent years has been on the study of rapid coastal erosion that occurs along these permafrost-dominated shorelines [Brown et al., 2003; Overeem et al., 2011; Barnhart et al., 2014]. On the basis of the analysis of remote sensing data of various types, practically all authors note that since the middle of the last century and up to the present time, the speed of erosion of the banks has increased. It should be noted that literally only in recent works have been differentiated morphogenetic types in the analysis of the dynamics of Arctic shores.

Minimal movements are noted for spits and offshore bars, and maximum erosion rates are observed for the bluffs of the youngest land surface, recently drained lakes [Jones et al., 2009; Gibbs, Richmond, 2017]. Sand and gravel-pebble barrier islands on the delta coasts are stable, or are growing [Grigoriev et al., 2001; Jorgenson, Brown, 2005]. The increase in sediment accumulation in the areas of inherited accumulation with increased erosion of the coasts observed from the forties of the last century was established by us in analyzing of the changes in the morphometric parameters of the accumulative formations of the Okhotsk Sea coast [Afanasyev, Uba, 2017]. Bars and spits that do not lose connection with modern

areas of alimentionation, thus, do not degrade both under the conditions of the subarctic and in the conditions of the Arctic coast.

The accumulative forms, the shape of which formed during the last rhythm of coastal-marine accumulation associated with the rise in the ocean level, are rebuilt, but in conditions of minor tides (microtidal (<1 m) and short period of wave action are enough stable. In particular, Elson Lagoon bars and the bars in the area of Billings, where the rates of destruction of the lagoon's coasts are much higher than the speed of the displacement of the bars, in addition, the lagoon area is also increasing due to the addition of permafrost lakes [Brown et al., 2003].

Comparison of the position of coastlines (aerial photography, maps and geological descriptions) became also the basis for determining the long-term trends of erosion (coastal erosion) of barrier forms and spits ([Mason et al., 2012; Gorokhovich, Leiserowiz, 2011]. As main results, it can be noted that the observed spatial structure of erosion in basic features exists at least since the 30s of this century. For some regions, the features of the change in erosion activity are established. So, for example, the correspondence of actual trends in the development of the coastal zone, established as a result of observations and analysis of AFS base of different years, long-term changes in the intensity of wind-wave impact on the coast (calculated wind energy characteristics) allowed to construct the statistical models for forecasting the erosion of the northern shores of the island Sakhalin [Afanasyev, 1998]. However, when we speak about barrier forms and spits, the main planned changes (reducing, increasing in area) are considerably connected with the mechanisms of development of these forms, due to the parameters of the long-distance migration of sediments, the trends in the displacement of lagoon straits, the seasonal features of the structure of the coastal profile [Afanasyev, Uba, 2015; Leont'ev, Afanasyev, 2016; Afanasyev, Uba, 2017].

Storms and erosion undoubtedly represent a danger on the shores of this type. However, the danger multiplies with the ignoring of natural mechanisms and development trends.

For example, bank protection in the well-known village of Shishmaref between 1983 and 2003 led to low erosion and a rate of erosion twice that of unprotected shores. A newly built rock revetment protected the village from erosion even in the abnormally strong southern winds of the “Great Storm of 2011” [Mason et al., 2012]. Coastal erosion limiting permafrost is noted under the sediments of the active layer. We also consider the worsening of the wave-breaking properties of the shore profile during the freezing of beach sediments and the resulting increase in erosion of the shores. The concept of the dynamics of the coastal profile in the sequence; freezing of the beach, formation of marginal ice, formation of fast ice is developed [Afanasyev, 2016; Afanasyev et al., 2017; Afanasiev, 2017].

Conclusion

Unfortunately, the level of paleogeographic and archaeological investigate does not allow us to rely on on the paleodemographic model of settlement in dynamic coastal landscapes at the analysis of the stability of settlements on coastal accumulative formations created in the final period of the last transgression. However, settlements with a long history are located in the areas of inherited accumulation sediment, at the base of barrier islands, as well as accumulative formations such as tombolo in the wave shadow of rock formations. These areas were stable during all three rhythms of accumulation and erosion caused by sea level changes of 2–4 m amplitude in the last 6.5 thousand years. The main problems associated with erosion are observed in the case of the location of settlements on the coast areas, which are dynamically developing. The choice of location in the 20th century usually occurred in one of the phases of damping of the intensity of morpholithodynamics processes. Changes in the intensity of coastal erosion have been observed in all the seas being under consideration. For example, on the shores of the sea of Okhotsk, a cycle of changes in storm activity with a period of 60 years was revealed. The aggravation of the situation in last decades, most likely, is not something out of the ordinary. However, the level of comfort and safety requirements is now much higher than a hundred years ago.

During the period of intensive industrial development of the coast of Chuckchee, Bering and Okhotsk seas the settlements, that are the most suffering from the restructuring of the shores – Shishmaref, Kivalina, Unalakleet, have been created. These settlements are located directly at the ends of the barrier islands of the system of the lagoon strait. Accordingly, coastal protection solutions should be based on the analysis of migration of the strait, the possibility of changes in the direction of growth, form and morphometric parameters of the distal ends of the barrier islands, modification of the tidal prism. It should be noted that these areas of the coast have enough sediment for any engineering solutions in this direction. It is also necessary to pay attention to considerable deterioration of wave-damping properties of beach deposits at their freezing.

The first author was born and spent his childhood on the coastal spit of the Bering Sea and knows firsthand about possible dangers. Now we are absolutely sure that solving the problem of protection and planning activities on the coast of cold seas is a very real challenge for modern geomorphological science. However, scientific methods should offer the perspectives on the basis of a complete set of data on the development and dynamics of the coastal zone.

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