Geomorphological engineering studies of anthropogenic variability of relief in the marine coastal zone

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Abstract. With the development of the coastal zone and the development of the urbanization process, coastal engineering poses a serious threat to local ecosystems. Poorly designed coastal engineering will have irreversible consequences for local ecosystems, such as loss of biodiversity, loss of connectivity and overall degradation of ecosystems. Therefore, it is imperative to improve the concept of ecosystem design of coastal infrastructure. One of the most important problems of marine engineering geomorphology is the drift of approach channels and changes in the coastal relief. These phenomena are a manifestation of a single process of sediment movement along the coast. The main deformations of the relief, as a rule, are determined by the features of the transverse structure of the alongshore sediment flow. This study discussed the methodology for calculating the movement of sediments, the transformation of the relief of the coastal zone. Regional examples show in general terms the assessment of the drift rate of different channels and different sections of individual channels. The problem of drift and artificial deepening of approach channels of ports is highlighted on the example of the coastal zones of the Baltic Sea. In general, these studies can contribute to improving the development of ecosystem coastal engineering.

1. Introduction

With the development of the coastal zone, natural resources concentrated in coastal wetlands and intertidal zones have been significantly influenced by human activities. First of all, this is the construction of ports, oil production, fishing, development of aquaculture, etc. [1]. Wetlands and intertidal zones play a significant role in the coastal ecosystem, which provides a range of services (for example, water purification to ensure the quality of the biological environment, maintenance of biodiversity, stabilization of coastal relief, and even regulation of local climate). The coastal zone can be viewed as a buffer zone that connects landscapes and their functions, forming a land-sea system [2]. The United Nations Environment Program (UNEP), in its forecast for the 21st century, includes coastal degradation as a key issue. Over the past 30 years, about 35% of mangrove formations have been destroyed, 20% of coral reefs have been destroyed and the same amount has been transformed. About 40% of the world's oceans are subject to one or another type of human impact.

Currently, ecosystems of the coastal buffer zone are facing increased pressure, especially in the context of climate change and human activities [3].

One of the typical problems is environmental degradation resulting from large-scale construction of onshore facilities. Therefore, it attracted great attention of many scientists [4]. Traditionally, the construction of onshore structures involves a “tough approach” to the implementation of artificial
structures such as coastal piles, breakwaters, ports, and artificial islands, which are mainly composed of artificial impermeable materials [5].

The patterns of manifestation of modern geomorphological processes and their impact on human economic activity, as well as on individual processes, form the basis of engineering geomorphology [6].

Back in the 1980s, Soviet scientists determined that the main objects of research in solving engineering issues on the banks are the movement of sediments and the transformation of the relief, and the goal is to calculate the movement of sediments and predict changes in the relief.

Coastal engineering activities can be classified into four classes:

- measures aimed at changing the natural regime of sediment movement or relief;
- measures to mitigate or eliminate the negative consequences of engineering intervention in the coastal zone;
- measures not intended to impact on the coastal zone, but leading to such;
- activities that do not significantly affect the processes or the relief of the coastal zone, but are themselves experiencing their impact.

The first class should include measures to combat coastal abrasion, the creation of artificial beaches, the provision of the necessary depths for navigation, and the construction of ports.

Examples of second class measures are artificial recharge of beaches in conditions of alongshore sediment movement interrupted by some structure. Measures to improve the technological scheme of mining in the coastal zone, contributing to the improvement of the balance of sediments in the coastal zone and compensating (at least in part) their withdrawal, can also be attributed to this class.

The third class is quite extensive in view of the fact that many seemingly very remote from the coastal zone, activities affect it in the most direct way. Transformations on watersheds and in river valleys, changing their solid runoff, entail a change in the relief and the regime of sediment movement in the estuarine areas. Various types of pollution of the coastal zone can be accompanied by the death of mollusks and corals, which often serve as producers of sediment in the coastal zone, and, naturally, lead to erosion of the coast. Thus, these measures are subject to assessment and can be considered as engineering ones.

The fourth class includes the laying of cables and pipelines within the coastal zone; in addition, the provision of amphibious operations is also an example of an event experiencing a specific impact of processes in the coastal zone, due primarily to its relief (conditions of wave refraction in shallow water) [7].

Failure to take into account the natural features of the coastal zone of the seas as a natural object often led to errors in the design of engineering structures. Meanwhile, the most successful engineering actions are almost always associated with a clear understanding of the specifics of natural processes on the banks.

Laboratory modeling is increasingly being used to reveal the details of natural processes that cause sediment movement in the coastal zone and change in the relief, as well as the features of processes caused by various engineering structures in the coastal zone. The general feature of the modeling problem is the need to divide any, even simple, phenomenon into its constituent individual processes.

Recently, the need for engineering and geomorphological studies of already existing enterprises and constructed buildings has increased, which can become an integral part of broader environmental studies. In this regard, it is necessary to solve important problems: analysis of relief-forming processes; assessment of the stability of the relief, identification of its response to various anthropogenic impacts; carrying out a geomorphological forecast; assessment of geomorphological risk for environmental insurance [8].

In this work, special attention is paid to the issues of artificial disturbance of sediment movement in the coastal zone due to engineering measures and transformations of the coastline, slope and bottom.
2. Technique of experimental modeling

In a rigorous consideration of the problem of modeling, not one process is reproduced, but the phenomenon as a whole, usually consisting of several processes. For each of these processes, if they do not belong to the same class (not caused by the same acting forces), an appropriate similarity criterion should be applied. The number of criteria should be equal to the number of processes - types of flow of flows and types of interaction of flows with particles. This implies the impossibility of a single universal criterion for all possible cases of process modeling [7].

When reproducing a phenomenon on a model, it is necessary to carry out modeling, both by the criterion of the flow and by the criterion of the movement of particles in it. These similarity criteria are dynamic.

The main regularities of the deformation of the relief, as a rule, are determined by the features of the transverse structure of the alongshore sediment flow. For the simplest cases, a relatively straight coast exposed to swell waves, the drift of a sufficiently deep approach channel can be calculated as the sum of the volumes of bilateral sediment migrations. These calculations are based on the dependence of the alongshore flow rate on the alongshore component of the wave energy. Thus, we obtain the maximum sediment flow rate, i.e. assuming their irrecoverable loss when crossing the channel traverse.

To assess in general the drift of different channels of different sections of individual channels L.A. Logachev introduces the drift coefficient \( p \), which represents the ratio of the thickness of the annual sediment layer to the depth of the cut [9]. For most objects, the value of these coefficients can be taken constant for each of the channels, and its value corresponding to the multiyear norm is given by the empirical formula:

\[
p = a \frac{h}{\sqrt{H_0}}
\]

where \( h \) - wave height, 1% coverage in the wave system and 4-5% in the wave mode, \( H_0 \) - channel depth; \( a \) is a coefficient equal to for canals laid in the coastal zone, where conditions exist for complete saturation of the flow with sediments: 0.5 - for silts; 0.4 - for silted sands; 0.3 - for sands. With a deficit of sediment and for canals located at an acute angle to the coast, it is recommended that \( a = 0.15 \). The above formula is applicable for calculating the drift of channels with depths up to 13 m.

The movement of alongshore sediments affects the relief of the coastal zone. In laboratory conditions, the analysis of the intensity of alongshore movement of the material looks like a dependence:

\[
Q = K(Y, d) \frac{h^3}{t} f(\alpha)
\]

where \( f(\alpha) \) is a function of the angle of approach of waves to the shore, \( K(Y, d) \) is a function of the wave steepness and the diameter of the sand \( d \). The dependence for determining the alongshore sediment flow rate assumes that it is proportional to the wave energy [10].

3. Regional examples of engineering and geomorphological studies in the coastal zone of the Baltic Sea

The port of Klaipeda is located on the section of the strait connecting the Baltic Sea with the Curonian Lagoon. From the sea side, the approach to the port is fenced off by two twin breakwaters. Due to the fact that rivers flow into the Curonian Lagoon, and its level is subject to fluctuations due to the complexity of water exchange with the sea, the conditions for the drift of the approach channel are extremely difficult.

There are five types of relief deformation in the section of the approach channel, depending on the direction and volume of sediment movement on the underwater slope:

1. deformation when moving sediment from south to north;
2. deformations associated with runoff from the strait during periods of high spring floods;
3. deformations when moving sediment from north to south;
4 and 5 - deformations associated with transverse movements of sediments in the coastal zone during wind-driven and surge storms, respectively [11].

During the study of deformations, it was found that changes in the relief cover the zone to depths of more than 20 m and can be traced along the coastline several kilometers long. According to the plan of deformation of the approach channel, solid lines are isolines of equal deformation (m), dashed lines are isobaths; areas of greatest deformation are shaded (figure 1, 2).

![Figure 1](image1.png)  ![Figure 2](image2.png)

**Figure 1.** The plan of deformation of the approach channel to the port of Klaipeda during alongshore sediment movement from south to north.

**Figure 2.** Plan of deformation of the approach channel to the port of Klaipeda at the outflow from the Curonian Lagoon.

The increased entrainment of the canal occurs only during alongshore movements of sediments (types 1-3 of deformation). At all depths, the channel is crossed by an alongshore sandy flow. Despite the sediment movement in the thin bottom layer, only a small fraction (5-10%) of the total sediment flow rate is deposited in the channel cut. The largest sediment layer is deposited in the deepest part of the cut, although deposition occurs over the entire width of the cut.

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Studies have shown the feasibility of expanding the canal by creating nanoscale "pockets", since the expansion increases the volume of sediments deposited in the cut, without reducing the accumulation layer, which occurs simultaneously over a large area, including outside the cut. The general role of the general location of the port in the distal part of the arc formed by the Sambia Peninsula and the Curonian Spit is revealed. In northeastern, northerly and northwestern winds, this situation leads to the formation of a surge in the concavity of the arc and stable gradient currents directed to the north.

Along the coastal movement of sediments during prolonged action of storms in this direction leads to the formation of erosion and sediment areas alternating along the coast.

The issues of cyclicity of the approach channel drift were studied at the example of the port of Ventspils. The port is located on the eastern coast of the Baltic Sea at the mouth of the river Venta.

The underwater slope and beach on this part of the coast has slopes of 0.007-0.008 and is composed of fine-grained sand. From the south, alongshore movement of sediments occurs, the flow rate of which is about 1 million m³/year. After the construction of the enclosing breakwaters in the late IXX - early XX centuries, the filling of the windward and leeward corners created by the breakwaters (depth of introduction 7.3 m) was in progress. At present, the flow of sediments bypasses the breakwaters, and
the depths on the approach channel are maintained by means of repair digging. 20-year observation and study of wind energy at 8 points for the port of Ventspils revealed a sharp variability from year to year. There is a cyclical nature of storm activity on the Baltic Sea coast with a period of about 24-26 years [12].

Assessment and prediction of the drift of approach channels requires taking into account not only storm phenomena, but also the arrival of solid river runoff (for pre-estuary approach channels).

4. Conclusion
The development of shipping in the world is accompanied in a number of cases by an increase in the drift of approach channels. The construction of the port inevitably leads to disruption of the alongshore movement of sediments, as a result of which the reentrant corner is filled on the leeward side, and erosion usually takes place on the opposite side. The propellers of large-tonnage vessels plying along the channel serve as a serious factor in disrupting the stability of the mesorelief.

However, the construction of a large port is causing very intense changes in the surrounding coastal environment as a whole, disrupting the coastal ecosystem. On the shores of the seas, pile structures are widely used for mooring ships, which have a negative impact on the development of the bottom relief.

As can be seen from the examples considered, geomorphological studies form the basis for the use of engineering structures in the coastal zone. This allows foreseeing the consequences of direct or indirect interference in the coastal zone.

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