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An Experience of Studying Artificial Ground Terraces as a Means of Coastal Protection

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ABSTRACT

The planning of a rational use of coastal natural resources is meant to create favourable conditions for economic activities. It must provide for a stable functioning of the natural coastal system and of various man-made objects there. At present the majority of the world coasts are being destroyed, and, consequently, the shorelines retreat. Therefore, coastal protection is a problem of great priority. A new protective method was proposed near Port Yuzhniy on the Black Sea. It used artificial ground terraces. This paper reports the results of their study and estimates their efficiency.

INTRODUCTION

At the present-day stage of the world shores' development, most shorelines retreat at different rates, depending on the coastal zone's geological features, energy potential, relief, and other causes. This is why a goal of great priority in coastal zone planning is to create a complex of measures that would preserve the natural coastal zone with its components and provide for harmless functioning of various economic objects.

In the early 1970s, Port Yuzhniy was built in the Small Ajalyk Liman, on the Black Sea northern coast. It was found during the construction of the port that the shores are affected by landslide there, with intensive deformation, an average rate of cliff retreat being

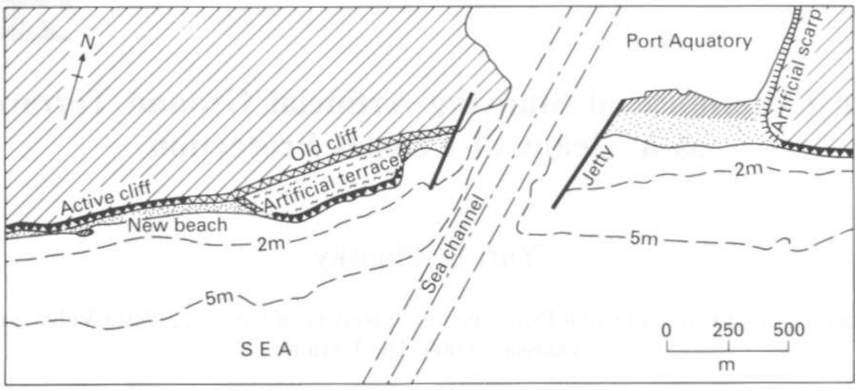

Fig. 1

11 m/year. In 1974, the liman was joined with the sea through a navigable channel over 10 m deep. Two jetties were constructed on each side of the channel to protect it from drifting, their seaward end reaching a depth of 3-5 m (Fig. 1). The liman's shallow bottom was deepened to facilitate navigation. Its steep slopes were smoothed, while the construction of buildings, installations and communications required the construction of fosses, hollows and ditches.

The longshore drift was found to be directed from the east westward. This is why it was expected that the channel and the jetties would cause the formation of a downdrift erosion zone along the coast to the west. Indeed, the anthropogenic activation of destructive phenomena was superimposed on the natural erosion.

Thus, the artificial changes of the sea coast near the Small Ajalyk Liman required to seek a solution for two problems: (a) how to protect the shore from erosion; (b) how to dispose of the great amount of soil obtained after the construction.

THE ARTIFICIAL TERRACE CONSTRUCTION

All in all, there was an 'excess' of 3 million m^3 of heterogeneous ground mass: nearly 70% of clay and sand with 30% of limestone, in accordance with the geological structure of the coast and the liman. Such an amount of ground mass could not be piled near the construction site, because all the land around is in agricultural and

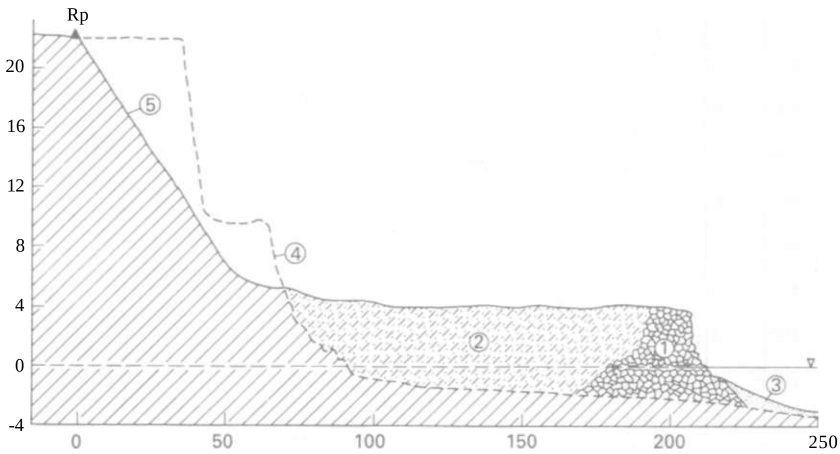

Fig. 2

residential use. Providing space for this purpose would have meant spoiling valuable chernozem soil. Removing the ground mass to a longer distance was too expensive. That is why it was decided to utilize it by making an artificial protective relief form composed of limestone and clay.

Clay, of course, is not the best material for shore protection. Therefore, an artificial wall was first made by dumping limestone debris at a depth of 2 m. The basin was further filled with limestone mixed with crushed stone and construction rubbish (Fig. 2). This allowed utilization of about 2-5 million m^3, or 83% of the material obtained from bottom-deepening and construction. Thus, valuable chernozem around the site was saved, as well as the fuel and other resources needed for removing the ground to distant landfills. The material dumped for the terrace was natural and non-polluted, so it caused no harm to the coastal environment.

At an early stage of construction, the seaward edge of the terrace was subject to strong abrasion, and the artificial shoreline quickly retreated. The active cliff formed a steep slope of limestone debris (Fig. 2). The rate of abrasion along the outer edge of the terrace was 9-8 m in 1972-1973, and only 5-7 m in 1973-1974. This abrasion supplied up to $40 m^3/m$ of debris to the shore zone, with approximately 22 m^3 of that amount in beach-forming fractions (this amounted to 25 000 mVyear over 1972-1974). Such supply exceeded by 11 times the previous natural supply from abrasion on this shore section. Further, the erosion of the terrace was providing up to 90% of beach-forming fractions.

Wave action along the outer edge also led to a tighter packing of the

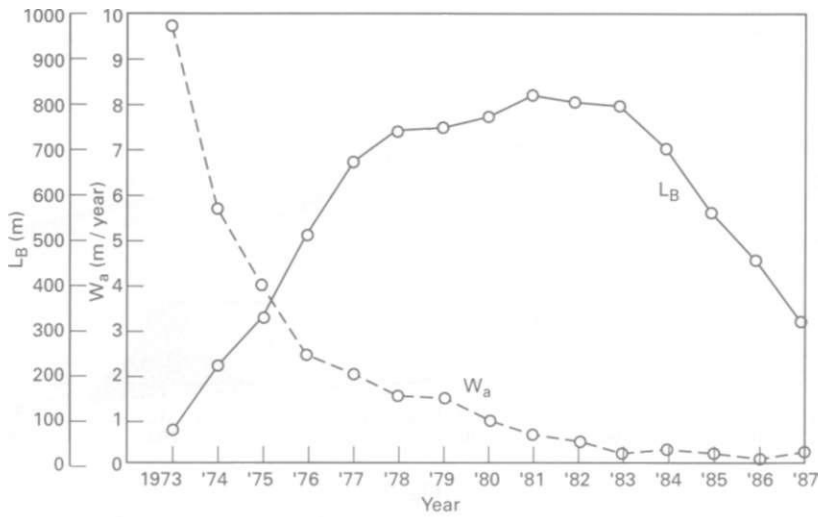

Fig. 3

debris. Thus the rocky frame obtained a higher resistance to waves, and the abrasion rate decreased as a profile of dynamic equilibrium was being formed (Fig. 3). It was significant to note that the linear and volume measurements of the ground terrace changed in accordance with the existing wave regime. The wave regime was the factor that formed a stable and elastic profile of the artificial terrace, while this property is absent in cases of traditional, rigid installations made of concrete or metal.

Relief changes in a shore zone are known to accompany a re-distribution of the sedimentary material. For abrasional forms, this changeability is irreversible. This means that a retreat of the seaward edge of a cliff or terrace results in the formation of drifts in the amounts described above. This is an important property of an artificial ground terrace, as no other traditional defence structures produce sediment.

The development of abrasion on the outer edge of the terrace indicates a usual regularity: a process caused by an abrupt disturbance of a historically formed equilibrium in a natural system developes in the most intensive way at the beginning, and with time wave remaking becomes less intensive. This exponential law was illustrated earlier with an example of a free non-protected beach on the sandy barrier of the Dniestrovsky liman (Fig. 4). This is a basic fact which should always be taken into account in coast-protective construction, including that of artificial terraces.

Thus an artificial ground terrace was built to the west of the jetties

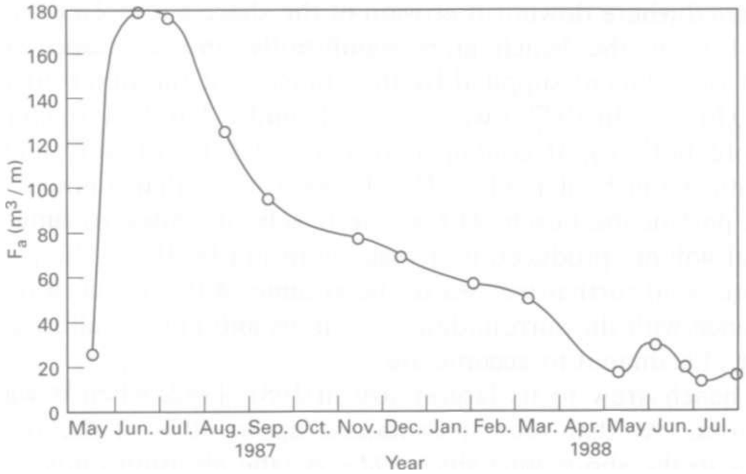

Fig. 4

(Fig. 1). It extended for nearly 800 m along the shore, had about 1000 m of shoreline length, with an average width of 165 m, and was about 4 m high at sea level and 7 m high in the back.

NATURAL DEVELOPMENT OF THE GROUND TERRACE

In the course of the construction and afterwards, the terrace started impacting the environment. The stabilization of its relief lasted till 1983, that is for more than 10 years. Nearly 127 000 m^3 of drifts were formed during this time, while the natural volume of the alongshore drifts would have been less than 7000m^3/year). The total amount of beach-forming drifts produced by the terrace over the whole period of 1972-1987 was at least 130000 m^3. Out of this amount, 96 300 m^3, were supplied in 1972-1977, corresponding to 74%. For this reason, in 1975, 1976 and 1977 a continuous stretch of beach was observed all the way to the west up to the Odessa Bay. However, this was a short-lasting phenomenon caused by a strong artificial supply of beach-forming fractions. In 1978, the stretch of beach was cut into separate pocket beaches, as it had been before the terrace construction.

The beach next to the terrace, however, proved to be more stable (Fig. 1). Its formation west of the terrace was important proof that the alongshore drift flows westward. The important thing is that the beach was formed where downdrift erosion of the shore had been expected. In the first years the beach grew significantly, in accordance with the amount of sediment supplied by the abrasion of the outer edge of the terrace (Fig. 3). In 1977 it was 20 m wide and T2m thick (including the nearshore bottom). It contained nearly 15 000 m^3 of sand and gravel drift with a touch of pebble. Nearly 6000 m^3 of that amount was the surface part of the beach. The whole beach amounted to only 16% of the total volume produced by terrace abrasion by 1977. The rest, 84%, therefore went further westward: the volume of this beach was in strict accordance with the surrounding conditions and did not allow a greater amount of sediment to accumulate.

This beach grew to its largest size in 1981-1982, when it was up to 800 m long. At that time it contained up to 40% of the new drifts supplied to the shore zone since 1973. As the abrasion rates decreased in 1983-1984, the supply of drifts also decreased: 43 000 m^3, of sediment were formed in 1973, but only 900 m^3 in 1983. Thus the new beach began to shrink. In 1987 it was only 300 m long, i.e. 2-6 times less than in 1981. If new portions of debris were dumped during the equilibrium profile formation, which would have prevented the sea edge from stabilizing, the drift-forming function of the ground terrace would have lasted longer.

Significantly, the terrace proved to be useful in another way. It protected the landslide-abrasive cliff. The terrace provided an average load of 1750 m^3 per year. This was more than enough to neutralize landslide on nearly 1000 m of shore length. An artificial smoothening of the slope (Fig. 2) intensified the loading effect of the terrace.

The natural development of the artificial terrace led to another important phenomenon. The surface of limestone fragments in natural conditions provides an ideal basement for biocenosis of the littoral area. Particularly important are filter-feeding organisms which provide a biological cleaning of the nearshore water. Before the terrace, in 1969-1970, the algae biomass amounted to 25-5-37-07 g/m^2 of Chlorophycea, and 1 g/m^2 of Rhodophycea. In the early 1980s, these figures changed, respectively, to 332-1366 and 688 g/m^2. The quantity of animal species observed grew from 7 before the construction to 27, and their biomass from 0-2 to 9-7kg/m^2. Nearly 7kg/m^2 of this amount is made up by Mytilus. Such a greater occurrence of biomass of benthos on the outer edge of the terrace provides for filtering and water-dust removal in 1501 of sea water.

Smooth sea walls and chinky blocks, in contrast to a terrace, cannot provide such a biological effect. As for the constructions with fragmentary riprap, they do possess similar biological properties, but are several times less efficient, as one can see on the Dniestrovsky and Tiligulsky Liman or the Tendra Spit barriers.

THE GROUND TERRACE EFFICIENCY AND NEW PROPOSALS

The artificial ground terrace, as we said before, was built of natural materials. There was no need to use concrete, ferroconcrete, bricks, metal, or timber in this case. Nor did this project involve artificial dumpings of sand or other beach-forming drifts, which is particularly important. The point is that there are no large sources of sediment drifts around this shore site that could provide for reliable, long-lasting artificial beaches as for example, in Georgia. Deposits of sand of suitable composition are too far away, and their transportation too costly. Further, the mining of sand has a harmful impact on the environment. This is why the ability of the terrace to produce sediment drifts was of great value.

The terrace and the new beach also blocked the landslide cliff which had been supplying sedimentary material before the terrace construction. Which of the two sources of sediment is more efficient: the ground terrace or the natural cliff? The cliff was 22 m high, with an average rate of abrasion of 1 m/year on a shore stretch of 1000 m. The terrace also blocked the nearshore bottom up to 2 m depth. These measurements and the content of beach-forming fragments in the deposits and rocks allow one to calculate that the shore zone has stopped receiving about 4500m^3/year of the beach-forming fractions. This is 3500m^3/year less than the amount produced by the front of the terrace until 1983.

The steep clayey cliffs suffering from landslides on the Black Sea coast are very inconvenient for recreational use. The beaches are very narrow, and there is not enough space for summer houses and for people to rest. Thus, it was important that this ground terrace provided additional space right near the shore. The total area of the terrace with the new beach near Port Yuzhniy is about 150000 m^2. This allows one to make better use of the coastal zone's recreational resources.

Through monitoring of the ground terrace over a number of years, we were able to propose a method of profiled protection of landslide shores in 1977. This method aimed to meet the following requirements: protect landslide shores from wave abrasion and preserve nearshore land; help to feed the shore zone with drifted sediments; utilize the ground mass; create additional space for recreational use; produce a positive biological effect and facilitate the cleaning of the nearshore water.

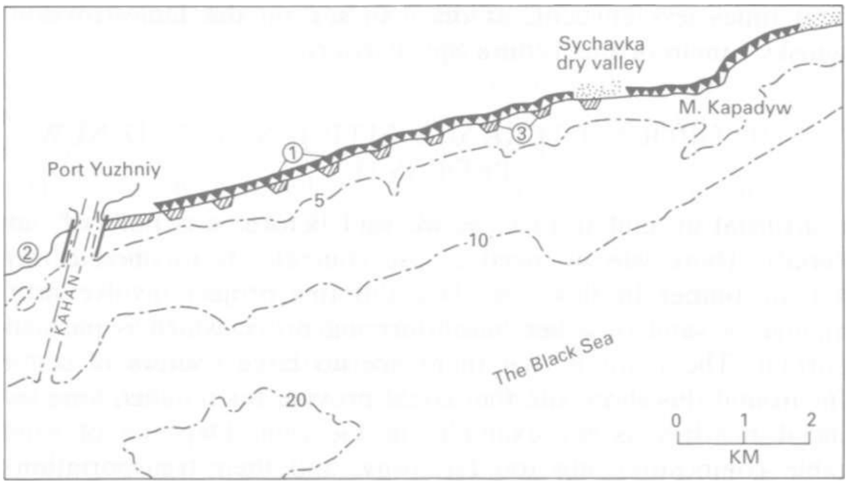

Fig. 5

This method can be implemented in different ways while solving technical problems, depending on the specific conditions of a site. The conditions to be taken into account are the hydrometeorological regime of the shore zone, the impact of tides, the lithology of the cliffs and the nearshore bottom, the morphometric parameters of the shore, the physical and chemical properties of the nearshore water, etc. In 1984 a scheme of profiled protection of the landslide coast between Yuzhniy Port and Sychavskaya dry valley (Fig. 5) was developed, and all the specific conditions of the site were taken into account.

This coastal section with a length of 7200 m is to have nine ground terraces. Each terrace fills into the natural shoreline contour and is built on the prominences of the shore. A terrace is to be 300 m wide at the base and 200 m wide on the seaward margin, extending into the sea for 150 m. Thus, the area of each terrace will be 37 500 m^3. Their seaward margins will be reaching a depth within 2-5 m, depending on the bottom relief of each site. The average elevation above sea level should be about 4 m so that the top of the terraces could not be reached by gales.

In accordance with the size, there ought to be 275 m^3 of the ground mass per 1 m of shoreline length in the underwater part of the terrace and 600 m^3 per 1 m in the upwater part, with a total of 875 m^3 of ground per 1 m of the length of the terrace. All in all, each terrace will have about 220 000 m^3 of the ground mass not accounting for the effect of compaction. No less than 25% of that amount will be rocky debris (limestone and sandstone), mostly on the seaward margin. The rest of the ground mass may consist of clay, loam, sand, and include building

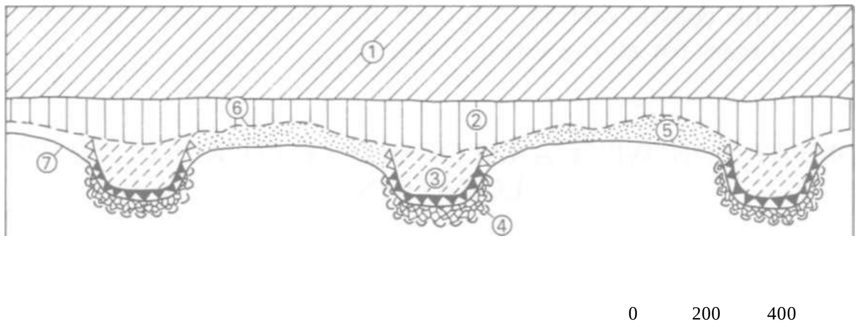

Fig. 6

waste, too. In any case, limestone or sandstone debris is dumped along the outer margin of the terrace (Fig. 2).

The relief structure of the abrasive coast between Port Yuzhniy and the Sychavskaya dry valley on the Black Sea has determined an average distance of about 800 m between its natural prominences. The artificial terraces, therefore, are to be located with the same interval (Fig. 5). Since a terrace occupies a 300 m length of shoreline, the distance between two terraces will be 500 m. The shoreline profile is thus made more winding: its winding coefficient becomes 1·25 versus 1·05 before the construction (Figs 5 and 6). As the front of the terrace is reworked by waves, a submarine bench is formed, which supplies beach sediment to the shore zone together with the artificial cliff. The sediment fills the concavities of the artificial shore, in which a new larger beach is formed (Fig. 6). After the equilibrium profile is reached, in accordance with the cliff dynamics (Fig. 3), it is expedient to replenish the debris on the marine side of the terrace by another dumping. This alters the equilibrium and keeps up the beach-forming process.

All in all, this section of landslide shore with profiled protection obtains 33·8 ha of additional ground on the terraces and 8 ha on the beaches. This largely increases the recreational capacity of the area and provides broad opportunities for its use. This method of coast protection meets all the above-mentioned requirements and largely contributes to the experience of coastal zone planning.

The construction of the nine terraces will require about 2 x 10^6 m^3 of heterogeneous ground mass, in which 500 000 m^3 should be made up by debris of rocks. Since landslide cliffs are usually made stable by smoothing, it is a smoothed slope that serves as the main source of the ground mass. If we take into account the sizes of the cliffs and the length of this coastal section, it is clear that there is a sufficient amount of ground mass for all the terraces (Fig. 5).

COMPARISON WITH ANALOGOUS FEATURES AT OTHER LOCATIONS

Ground terraces have been adopted on sea coasts for centuries. However, their only purpose was to create additional territory where settlements, ports, factories, roads, etc., were located. Suitable examples are the new territories built in the ports of Rotterdam and Yokohama, and in the cities of Mahama (Bahrein), Abu-Dabi and Dubai (the United Arab Emirates). Artificial ground terraces became a part of the ports in Damietta (Egypt), Mohammedia (Morocco), Bizerta (Tunisia), LaRochelle (France), or Marbella (Spain). At the same time, in all those cases, the ground terraces were protected by various hydrotechnical installations on the seaward side.

Those protective constructions include riprap, acropodes, tetrapodes, concrete blocks, different kinds of walls, and even groins. Therefore, those terraces are passive, devoid of elasticity, and also have lithodynamical and coast-protecting functions. Besides, such terraces cause serious damage to a landscape where the ground mass is excavated. These are mostly mountainous regions, river valleys, or eolian forms. Thus, many advantages of such artificial features are not used at all. Yet, the creation of artificial land could be combined with the coast-protecting functions of terraces.

When the experience of artificial ground terraces near the Yuzhniy and Illichevsk ports was analysed, this method began to be actively implemented in Georgia. A special research and construction centre was created there, which widely used natural materials to protect the Black Sea coasts from destruction. This work was based on making new beaches, terraces, and ridges. This allowed one to improve the shore zone conditions. This work also caused some damage to mountain landscapes and river valleys, but the scale of the damage is much less significant than the benefit for the coastal zone.

An interesting example of coast protection with ground terraces is the region around the city of Samsun, on the shore of the Samsun harbour, between the mouths of the Kizil-Irmak and the Yeshil-Irmak, on the southern coast of the Black Sea, in Turkey. The sea margin of a coastal plain there was eroded by waves at an average rate of 0-3-1-4 m/year. The erosion began to threaten the land occupied by a transport company, a mosque and the Ondokuz Mayis University. This

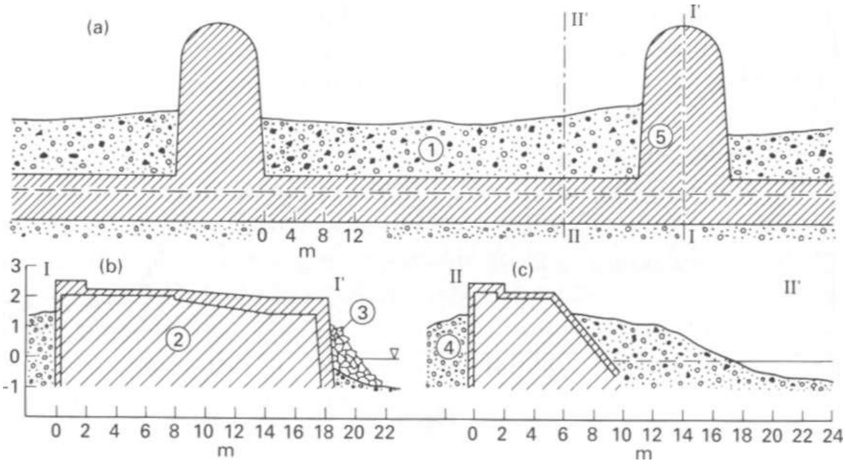

Fig. 7

is why a terrace was made first by dumping heterogeneous ground mass (alluvium), which was 50-70 m wide and 400 m long. This terrace, however, was only 1-5 m high and not intended as a shore protection. Therefore, its marine edge was framed with a concrete structure that had short groins (Fig. 7).

This structure consists of 6 groins, with a distance of 50 m between them. Each groin is 20 m long. The cells between the groins were filled with pebble drifts which also included some sand and boulders, and their main source was the debris from the Kiurtiun River. Unfortunately, after 10 years of use, the concrete structure was more partially destroyed (Fig. 7). There was no significant accumulation of sediment on the beaches between the groins. The maximum width of the beach did not exceed 11m and it was not sufficient to protect the concrete structures from breaking. Thus, at present the concrete groins and dykes are only a passive obstacle for waves. This comparison reveals the advantages of artificial ground terraces similar to those built near Yuzhniy.

Further east, closer to the sea port of Samsun, shore erosion was faced by means of groins built of volcanic and crystallized sedimentary rock debris. These reach 170-250 m in length and 2-5 m above average sea level, while the distance between the groins relates to their length as 1:2-5. The cells between the groins did not accumulate drifts, due to a general deficit in the shore zone. Sea waves kept destroying the cliff built of shale and sandstone. This became a threat to the Sinop-Samsun highway. This is why artificial ground terraces began to be constructed in the cells between the groins.

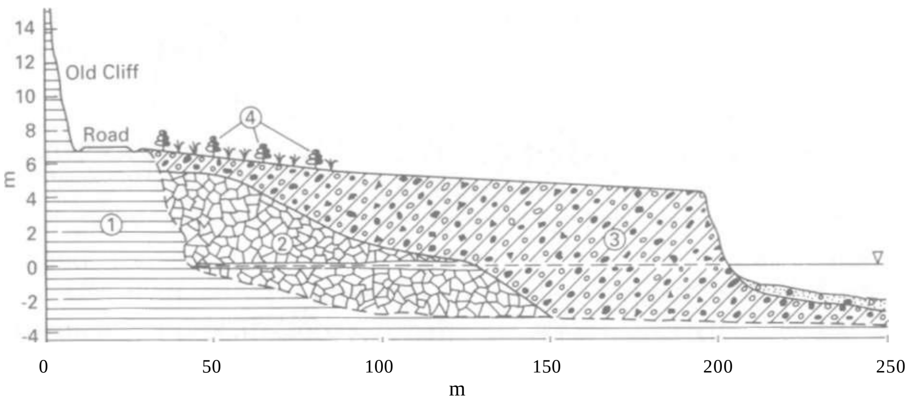

Fig. 8

The cliff base was first loaded with stone debris (volcanic and metamorphogenetic rocks). Heterogeneous ground mass was dumped from above; 50% of it was debris of rocks, while the rest was a clayey and sandy filler (Fig. 8). The terrace is about 180 m wide and 4-5 m high at the seaward margin with about 7 m at the back. The seaward margin is actively reworked during the construction, and the water dust concentration at 1-m-high waves is up to 3g/litre. As the terrace is eroded, beach-forming sediment is created, which mostly moves eastward in the longshore drift, towards the Kurupelit River. On account of this, the shoreline between the last eastward groin and the Atakum cape prograded by 32 m over 1982-1992 (or 2-9 m/year). This positive effect of the ground terrace was not planned, however. In contrast to the short concrete groins east of the Kiurtiun, which were described above, the artificial ground terraces did protect the shores from abrasion and made a positive impact on the adjoining sections of the coast, just like near Port Yushniy.

Thus, the threat to the Sinop-Samsun highway was removed, and the upper part of the ground terrace was improved: a layer of soil was dumped, and trees and bushes were planted (Fig. 8). It can be reasonably expected that the territory of the terrace will become a recreationally active part of the coast.

CONCLUSIONS

Artificial ground terraces can be useful not only to increase the nearshore area, but also to protect the coast. However, the coast-protecting capacity of terraces is seldom used.

The efficiency of artificial ground terraces as a means of coast protection has been analysed by the examples of two sites located near Port Yuzhniy (Ukraine) and Port Samsun (Turkey). It turns out that this feature allows one to solve a number of environmental and coastal planning problems. First of all, it was proved to be expedient to utilize extra ground mass that remained after the construction of large industrial units. In that case, agricultural land is safely preserved. The shore is protected from erosion, which is particularly important in the areas affected by landslides. The adjacent sections of the shore get a positive impact, too. The quality of sea water improves. Finally, this technique economizes a lot of valuable materials, such as concrete, metal, timber, cement and fuel.

Also, it creates better recreational conditions, it allows one to organize natural systems in the most feasible way, and preserves the nearshore biocenoses.

However, artificial ground terraces, as well as traditional hydrotechnical installations, require maintenance and management. It is important to maintain the safety and the drift-making effect of the outer edge of a terrace, and to ensure the natural purity of the ground mass. It should also be defined whether it is more expedient to build the terrace or to save the landscape intact where the ground must be excavated.

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