Coast Protection Against the Action of Waves and Currents

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According to the information available in the USSR, now in the world there are more than 13000 reservoirs with storage capacity over 1 million m^3 in service and under construction. The largest ones are illustrated in Table 1. In some countries these storage reservoirs constitute rather a great per cent relative to all the reservoirs of the given country. (Table 2).

Lately, such reservoirs have substantially grown in number in many countries of the world, especially in the USSR and USA, what is seen from the chart (Fig.1).

In this connection, one can conclude on the great area of some reservoirs (reaching sometimes thousands of square kilometers), on their importance in the balance of the controlled runoff, making up in some countries over 95 per cent and on the intensive increase of their storage capacity beginning from the fifties of the present century. The above said is one of the reasons of greater interest in the action of waves and currents of the shore line showing up most intensively on the largest storage reservoirs.

The length of the shore line of the USSR reservoirs is over 40000 km. The length of the erosion shores of storage reservoirs at the hydroelectric projects on the Volga and Dnieper River make up more than 30 per cent of the total shoreline of these reservoirs, while that of the reservoirs on the Kama River - 35 per cent. Most intensively the erosion is going on in the first decades of the operation of the reservoirs. The action of waves on the shore results in formation of the underwater slope with a gradient at which the wave energy is dissipated on the shoal, and the shore erosion slows gradually down until it ceases completely. However, it is rather difficult now to determine the period of the shore formation attenuation process in view of the fact that the problem of distribution of wave energy between all the phenomena taking place here is not properly studied yet and it is not also clear what width and gradient of the shoal can fully baffle the wave energy and how much time it will take for such a shoal to get formed. The observation carried out on the natural water bodies well prove it. On the Seligher Lake (2) the shores of some large

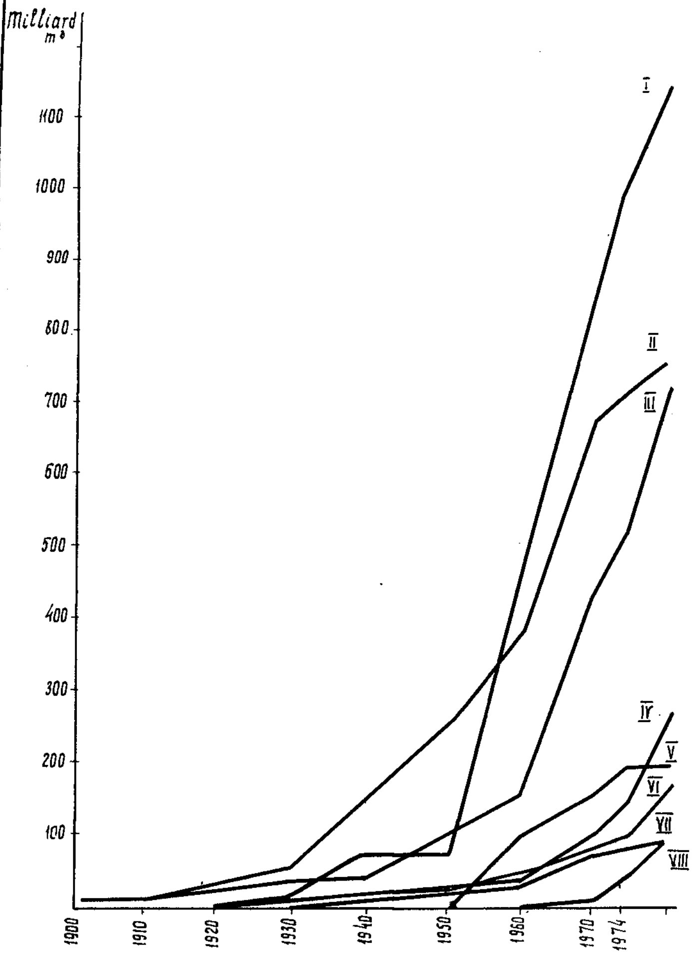


Fig.1. Trends in reservoirs with storage capacity over 100 million m^3 for the following countries: I-USSR II-Canada IV-Brasil V-China VI-India VII-Argentina VIII-Mexico

Main data of the world largest storage reservoirs

Table 1

Storage reservoir	River, lake	Country	Back-water curve, m	Area, km^2	Reservoir volume gross, km^3	Reservoir volume live, km^3
1. Owen Falls	Victoria--Nile, Victoria Lake	Uganda Tanzania Kenya	22	76000	204.8	204.8
2. Bratsk	Angara	USSR	106	5470	169.3	48.2
3. Kariba	Zambezi	Zambia	100	4450	160.3	46.0
4. Nassr	Nile	ARE Sudan	95	5120	157.0	74.0
5. Volta	Volta	Chana	70	8480	148.0	90.0
6. Daniel Johnson	Manicouagan	Canada	154	1950	141.9	85.9
7. Krasnoyarsk	Yenisei	USSR	100	2000	73.3	30.4
8. Gordon M. Shrum	Peace-River	Canada	105	1683	70.1	37.0
9. Zeisk	Zeya	USSR	90	2419	68.4	32.1
10. Ust-Ilim	Angara	USSR	88	1870	59.4	2.8
11. Kuibyshev	Volga	USSR	25	6448	58	34.6
12. Bukhtarma	Irtish and Lake Zaisan	USSR	67	5490	49.6	30.8
13. Irkutsk	Angara and Lake Baikal	USSR	31	32966	48.5	46.0

Ratio of reservoirs with storage capacity 100 million m^3 and over to the total number and gross volume of all reservoirs in the respective countries, %

Table 2

Country	In percent to the total number and gross volume of reservoirs: number	volume
USSR	16	99
Spain	16	86
India	14	93
Japan	2	47
China	28	96
The Union of South Africa	10	92
USA	17	84
Canada	26	98
Brasil	22	94
Average for the above countries	15	96

islands have retreated during the last thirty years by 50-80 m with the shoal width varying from 64 m to 210 m. The signs of recent erosion of the shores have been discovered on the Kish-Lake with the shoal width being 80 m. In view of the variability of wave regime and, especially, level fluctuation in the reservoirs, it is believed that the wave erosion of the shores can proceed for rather a long period of time.

Inproper studies the action of waves and currents on the shoreline of the reservoirs is explained by the availability of a number of circumstances, complicating the studies, as compared to the sea and lake conditions. First of all, it is the geological and geomorphological factors and, especially, comsiderable water level fluctuations which influence the waves and currents formation. These factors are most effectual in the first decades of the reservoirs operation. In this period the length of the longshore currents owing to a sinuous shoreline is not great. As the shoreline simplification proceeds, the currents become stronger and lengthy. One of the causes of a more complex relation of the wave growth vs. the duration and fetch length is the size of water bodies and their volume, which are less as compared with the sea ones. The height of waves on the reservoirs is less than on the sea and is usually not more than 3m. As a rule the waves here steeper than on the sea. Owing to a less volume of water in the reservoir, the wind waves here attenuate very quickly, contrary to the sea condition, where the swell remains long. The water circulation in the zone of waves disruption is caused by the setup of the longshore currents and of compensating currents (countercurrents or rip currents, being a particular case of the first ones). All this governs the complexity and variability of the hydraulic regime of the littoral zone in which the protection works are located. When working the problem of building the protection works the economic analysis is usually made which includes the study and comparison of the following alternatives:

- absence of protection works, and as a consequence necessity arises to relocate or remove the national economy projects; there are land losses caused by shore transformation and flooding;
- provision of protection works after five-ten and even more years of the reservoirs operation. In view of the transformation and flooding of the shores during this period it becomes necessary to take into account the protection measures to be undertaken and the conditions of construction of the coast engineering works with account for the developed underwater and above-water shore slopes;
- construction of the protection works during the period of creating the reservoirs.

The above analysis makes it possible either to discard the protection works or choose the constructive solutions, which from the viewpoint of their designation can be divided into two large categories:

- shore erosion protection works and
- shore flooding protection works

The first category of works include the shore protection walls made of stone, concrete, reinforced concrete; shore revetments made of rock, concrete, reinforced concrete, asphalt-concrete and cement-earth mixture; groins, breakwateres, sand inwash, planting and different combination of the above protection works. Depending upon the hydrogeological conditions and usage of the littoral area, the construction of drainage can be required. The length of the protected shoreline of the storage reservoirs at the hydro projects on the Dnieper River is over 400 km.

The socond category of works include the works which protect the shores against erosion and flooding. very often it is a complex of protection works, including levees, pump stations and drainage arrangements. Such protection works can afford a considerable saving, especially, in case of protecting the towns against floods.

So, vast areas of valuable arable lands near many storage reservoirs in the USSR have been protected against flooding.

Only near the reservoirs on the Dnieper River over 200000 hectares of lands have been protected what gave a 30 per cent saving in land easement. On the Lower Kama and Cheboksary storage reservoirs which are being constructed now, the work is under way also to protect about 50000 hectares of lands. Rock and concrete are widely used in protection works.

If rock is available, it is possible to use riprap. Its advantage is easy and simple placement procedure and repair and suitability for all types of underlying soils. The job is easily mechanized and can be carried on at any time of the year.

The merits of the protection of continuous and cellular precast and cast-in-situ concrete slabs are the following; strength watertightness, possibility of wide me - chanization (and for precast slabs-possibility of prefabrication) and carrying the job in winter.

Among the demerits are the necessity of importing such materials as cement, reinforcing steel and aggregates; rigidity and low roughness of structures and for precast slabs - thorough slope levelling; difficulties in concreting the joints and in repair. The analysis of malfunction of such types of protection has shown that the underestimation of one or another factor such as the upper limit of water level fluctuation, wave action, ground water seepage velocities and deformation properties of the underlying soil had a great effect.

The analysis of the state of the structures in service affords a valuable information that can be used in their designing.

The most interesting is the analysis of the behaviour of the works under the extereme conditions which allow for revealing the reliability and disadvantages of the construction.

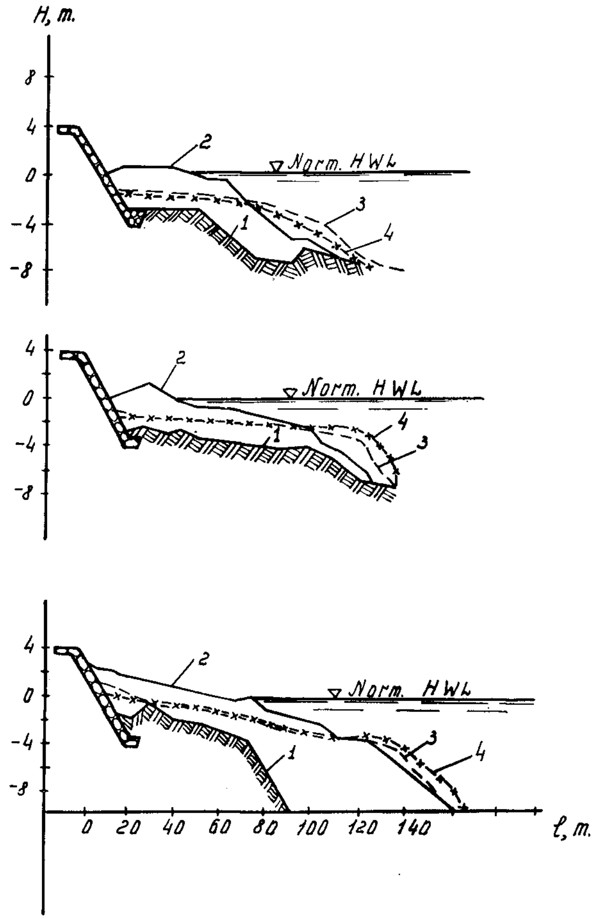


Fig.2. Sand inwash at the Kamensk protection dike transformed by the storm.

1.-Original shore profile; 2.-initial inwash profile; 3-inwash profile before the storm; 4-inwash profile after the storm.

Fig.3a) Upstream slope of the Kamensk dike during the rock toe repair

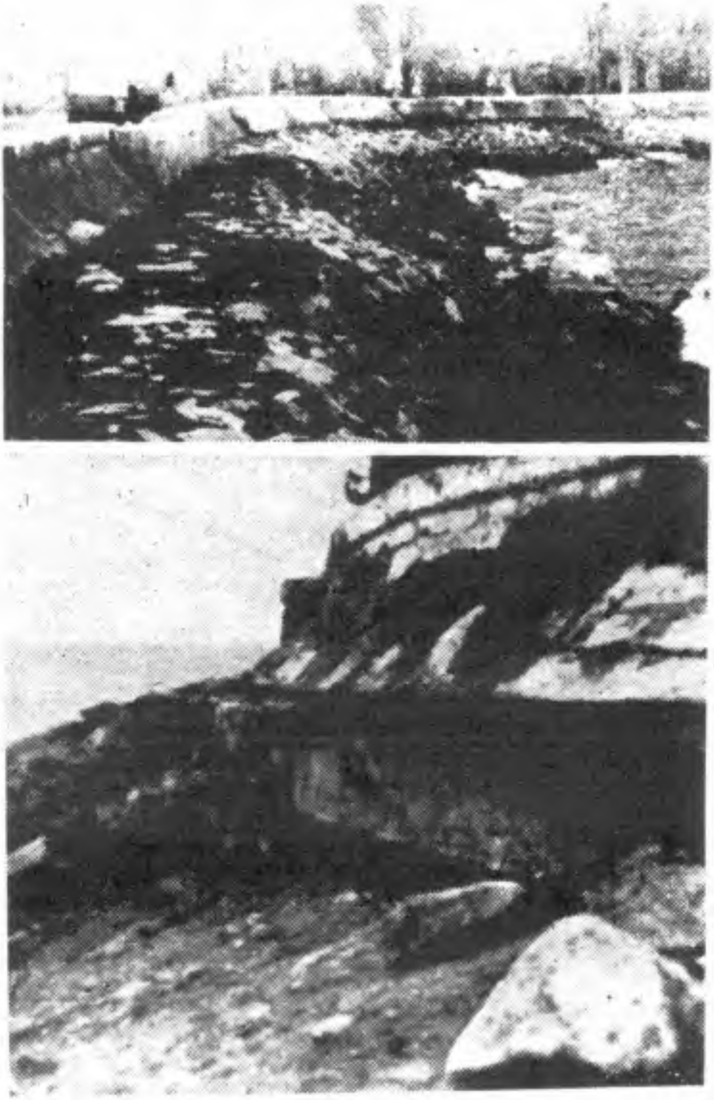


Fig.3b) Shore protection in the town of Kakhovka after the storm.

Such conditions appeared on a number of storage reservoirs on the Dnieper River where a storm of rare frequency was recorded in October, 1969. With the wind velocity of about 35-40 m/s in the area of the Kamensk dike on the Kakhovka reservoir the wave reached 2.5 m in height. The upstream slope of the dike is made m=3 and protected with a riprap layer 0.55-0.7 m thick, placed over an inverted filter 0.7 m thick.

To protect the downstream cut-off the sand inwash o.5-2.0 m was provided, that appeared to be a very reliable means of protection. The transformation of the inwashed fill during the storm followed the pattern: erosion - in the water edge zone and soil accretion at the outer side of the inwashed fill (Fig.2). The visual observations proved that the disruption of high waves had taken place on the outer side of the inwash at a distance of 90-120 m from the water edge. No evidence of the dike slopes damage was traced. The inwashed fill had undergone inconsiderable transformation (Fig.2) , while the Znamensk dike on the same reservoir had been damaged. The upstream dike slope is m=3.0, the downstream slope is m=2.5. The upstream slope is protected with stones weighing 40-180 kg and placed over a double-layer inverted filter 60 cm thick. To prevent the underwashing of the cut-off, silty sand was sluiced in one place, while the rock banquette was built in the other place. The crest of the sluiced sand fill was 3-3.5 m below the Norm. HWL, that is why its effect in the waves extinction was insignificant. The slope protection was damaged locally with scours which appeared two meters above and below the Norm. HWL and reached 84-480 m^2. Here, the filter material had been washed out and stone had subsided. So, about 864 m^2 of slope protection and 2400 m^3 of rock banquette had been destroyed (Fig.3)a)b). In so far as the sluiced sand fill its lowered top elevation (3-3.5m below Norm. HWL) did not promote the extinction of waves, the Znamensk dike slope protection was damaged. The comparison of behaviour of structural elements of practically the similar design illustrated how effective in wave energy dissipation the sluiced sand fill was. The cause of damage of the Znamensk dike slopes was the unjustified lowering of the sluiced fill crest by 3-3.5 m, below the Norm. HWL.

The cost analysis of the coastal engineering projects showed that the most expensive structures are the dike of economical section with concrete protected slopes; their cost makes up 70-80 per cent of the total cost of the coastal engineering, and the cost of slope protection is about 40 per cent of the dike construction cost (5). That is why, one of the most important trends in searching the rational design solutions is finding out of the ways to reduce the cost of the slope protection or to eliminate it. The latter, to some extent, be met by the dikes with gentle slopes.

On the reservoirs at the hydroprojects on the Dnieper River the length of such dikes is about 200 km; 120 km of the dikes are with a "beach" upstream slope (1:25-1:50) and downstream slope (1:4).

The dikes of this type have been built to protect the shallows and shores against the waves not more than 1.5 m in height. The height of dikes is 6-7 m and soil particles d_{50}= 0.18-0.25 mm (6).

When the dike is over 7-8 m in height and wave is over 1.5 m in height the smooth slopes are economically inefficient. Under such conditions the "beach" slopes are protected against the currents and waves with the help of rockfill groins and underwater intermittent breakwaters.

The advantages of the dikes with gentle slopes are the following:

- good stability of the dike body;
- elimination in many cases of drainages in the dike body and on the protected area;
- safety of the dikes founded on the easily compressible soils;
- elimination of imported materials (concrete and rock);

However, a demerit of the dikes in question is rather a great area they occupy.

The construction of the above dikes affords a saving of 8-10 per cent as compared with the other dike types; the running costs are only 10-15 per cent higher than these of the economical section dike and for some of them they are practically the same (6).

Quite promising are the shore protection works of economical design worked out by the Institute of Hydromechanics, AS Uk SSR, using the method of "natural analogues". The essence of the method consists in simulation of the natural process of transformation of the erosion shore into the stable accretion one under the dynamic action of waves and currents.

The designation of the protection structures using the principle of "natural analogues" is that they direct the energy of the wave flow to the transformation of unstable shore (intensively transformed by waves and alongshore currents) into the dynamically stable ones. Owing to this, on cessation of the undirectional shore transformation, the protection works which had been used to control the wave energy, become its permanent elements and maintain the shore in the dynamically stable condition. Thus, the protected shore become a hydraulic structure functioning as an "artificial analogue" of the self-protection element of the shore that had transformed to the dynamically stable one.

The protection structures employed lately in coastal engineering are the intermittent protection of the shore and double-groins (tombolo).

The intermittent protection of the shore makes it possible to stop the development of the shore and transform it into the bay-shaped shore, dynamically stable at any wave (Fig. 4) and it can be used in the cases, when the shore retreat deep into the territory is permissible. When it is not permissible (Fig.4, b), the double-groins shall be used.

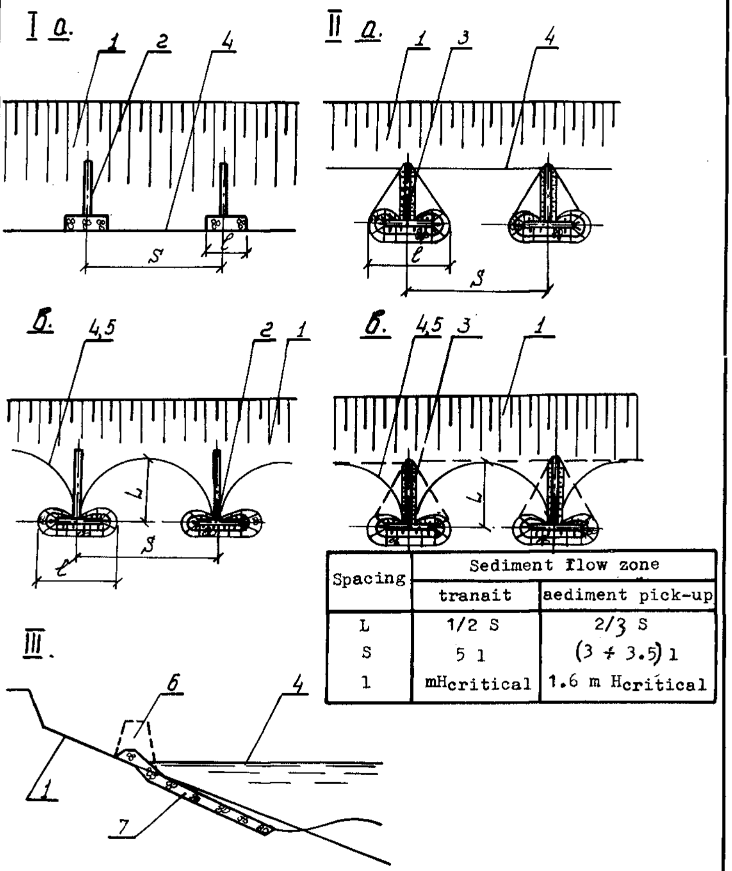
The relationship between the size of protection and the dynamically stable shore shape depending on the zone of the alongshore drift (transit and sediment pick-up zones) is illustrated in **Fig. 4**, where T-the coefficient of the dynamically stable slope for the design waves and normal wave approach to the shore (7). Under the action of waves every adjacent couple of double-groins and the length of the protected shore enclosed between them from "bays". In time, the shore profile in plan changes in accordance with the shape of the waves getting into the water area and curved due to diffraction and refraction. So, the frontal approach of waves to the water wedge is provided lengthwise the whole perimeter of the bay irrespective of the direction of initial wave what ensures the development of the bay shape with dynamically stable surface of the underwater shore slope. Being completely transformed the bays take the form of semicircumferences, with the radius $L = \frac{1}{2}S \div \frac{2}{3}S$ (Fig.4) (8). The construction of the above protection works makes it possible:

- to transform the eroding shore into the stable bay-shaped one by a directed harnessing of the energy of waves eroding it, thus eliminating the possibility of development of the unique alongshore wave flow, as one of the causes of the shore erosion;
- to cut down the requirements in building materials (concrete, rock) considering the intermittent protection, as compared with the conventional breakwaters;
- to facilitate the execution of work, since it can be done ashore and during the reservoir operation.

The economic analysis proves that the intermittent protection works in some cases are 1.5-3 times cheaper than the continuous riprap protection (3).

Provided the rock is available, the reservoir coasts are protected by riprap of graded and ungraded rock placed in two layers: the upper layer consists of large-size material, the lower layer-of rock with fraction size decreasing towards the protected surface. Based on the results of the study of the riprap behaviour and in order to facilitate the work execution the double-layer riprap protection has been substituted now by a single-layer riprap protection, i.e. by a mixture of all fractions which form two layers. However, it didn't eliminate the work on levelling the slope before placing the riprap to protect it and the construction of the rock toe (cut-off) atthe base of the slope revetment. When the reservoir was filled, the work was much more complicated and the cost grew up.

Provision on a number of storage reservoirs of the transforming banquette of rock muck designed on the principle of "natural analogues" allowed for eliminating the mentioned shortcomings of the employed revetments of rock muck.



Spacing	Sediment flow zone	
	tranait	aediment pick-up
L	1/2 S	2/3 S
S	5 l	(3 ÷ 3.5) l
l	$mH_{critical}$	1.6 m $H_{critical}$

Fig.4. Types of shore protection works
I. Intermittent protection (water edge receasion deep into the ehore ie permisaible)
II. Double - groin (water edge recession deep into the shore is not permissible)
a) shore profile after the construction of shore protection works
b) profile of the shore after its transformation to the dynamically stable bay-shaped shore.
III. Protective rock banquette
1.-Shore to be protected; 2-intermittent protection works; 3-double-groins; 4-water edge; 5-water erosion prediction line.

The natural analogue of the above construction was the shoals at the erosion shores with their body composed of highly desintegrated rocks.

Immediately after its completion, the banquette is a prism filled of rock muck lengthwise the shore to be protected at the level of water edge with natural (for this material) angles of repose for the upstream and downstream slopes (Fig.4).

Under the action of waves and alongshore currents a part of the shoal in front of the structures is washed out and the front end of the banquette gets deformed. The rock muck in this case rolls down onto the coast shoal at the banquette base and spreads to form a train of V-shaped cross section. At the same time the rock muck brought by waves to the train body is segregated as if in the inverted filter, thus making the protection stable to the wave hydrodynamic loads and preventing the beach shoal from being eroded.

The applied methods of calculations (8) enable one to choose the main dimentions and construction work quantities for the structures of different service life. Among the above tasks to be solved when designing the banquette are the substantiation of the design parameters of wind waves; calculation of movement of the load under the wave action within the length of the protection structure and on the adjacent shore sections; choosing of the grain size distribution of the rock muck to be used for the banquette according to the wave parameters and characteristics of soil composing the beach shoal.

This structure, depending upon its designation and proposed lifetime, can be comsidered as the temporary, permanent or, constructed in seversl stages.

The operation of the similar type structures on the Kakhovka reservoir and designing of the shore protection on the Volgograd reservoir attests that the use of a rock muck banquette to protect the shore against erosion is 18-38 per cent cheaper than the conventional type of protection - riprap protection; a combination of concrete revetment and riprap and others (9).

Besides, the design of the rock banquette makes it possible to mechanize practically all construction operations, to employ the unskilled labour and, what is most important, to carry all the work under conditions of the filled reservoir. The same advantages are characteristic of the structures isolating the shallows and simulating the natural accumulation forms, such as spurs, bay-bars and bars.

The approach to such structures differs from the traditional one, i.e. when the alignment of the structures is chosen on the principle of their longitudinal axis orientation along the most elevated points of the reservoir bed. However, this principle is inacceptable, if such structures are considered as the artificial analogues of the natural accumulation form. In this case their shape in plan shall follow the natural acumulation forms stable to the action of waves and currents which could develop under the natural conditions with a required amount of sediment available and under the action of prevailing winds. Such works, creating the natural "analogues" (spurs, doublegroins, bars) by the directed utilization of the energy of waves and alonshore currents, provide the isolation of shallows and comparatively cheap protection of shores against erosion.

The coastal engineering works make possible at the same time, the rational development of the natural resources and are of importance for nature conservation, namely:

- protection of arable lands, mineral deposits, historical and architectural monumental against underflooding, flooding and banks collapse;
- improvement of sanitary and hygienic conditions of the water bodies by slowing down the intensity of water "bloom" and by reducing the shallow areas;
- selection of the hydroelectric project site and Norm. HWL that guarantees the most rational utilization of natural resources by all the users.

In the USSR the coastal engineering works protecting the shores and agricultural lands against flooding and erosion find expanding application. The protection works are being erected on the reservoirs under construction as well as on the existing reservoirs. Carrying out of these works in an even increasing scale is dictated by the considerations of nature conservation stated in the USSR Constitution and in other legislative documents.

Conclusions

1. Intensive increase of the number of large storage reservoirs, a considerable share in control of the total runoff, great length of erosion shores and complex action of waves and currents on the reservoir shores prove the urgency of the problem of elaborating the economical designs of the protection works;

2. The most expensive elements of protection works are revetments. One of the progressive trends in studies aimed at working out the structural solutions which enable one either to reduce the quantities of work involved or to eliminate the protection is the "method of natural analogues";

3. The protection works allow the rational utilization of natural resources and at the same time they conserve the nature, namely, they conserve the land resources, prevent the shore erosion, improve the sanitary and hygienic conditions in the reservoirs etc.

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