Analysis of Stability Criteria of Retaining Structure Slope and Reservoir Banks with Deformed Reinforced Concrete Anchorage

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Abstract. The conditions of the impact of wind waves on the soil upland slopes of retaining structures and natural banks, which are fastened in the form of reinforced concrete slabs of the covering with deformations, are considered. The results of the analysis of field examinations of the state of reinforced concrete fastenings of slopes and banks of artificial water bodies under the influence of wind waves are presented. A criterion is proposed for assessing the stability of soil slopes and coastal slopes with reinforced concrete fasteners with a broken structure, and the conditions for its applicability are determined.

1. Introduction
The hydraulic structures of the Nyтva reservoir were built in 1756. In 1957-1960 the main reconstruction of the hydroelectric complex was carried out. Wooden structures were replaced with reinforced concrete with an increase in the capacity of the spillway. Design organization: USSR Ministry of Construction, Design Institute Glavstroyproekt, Leningrad. Reconstruction of the outlet channel was carried out in 1976 according to the project of Soyuzvodokanalproekt (Sverdlovsk branch).

The complex of hydraulic structures of the reservoir includes (Table 1): ground dam; a regulated spillway (includes a water-supplying part, a fast flow, a stilling well (damper)); outflow channel (trapezoidal cross-section). The regulation of the throughput of the structure is carried out using flat steel gates. The gates are maneuvered by a gantry crane with a lifting capacity of 2x10 tons.). The total length of shore protection structures and fixed slopes of dams by various types of fastenings on the Nyтva reservoir is about 650 m. The length of damaged and destroyed shore protection structures, according to field surveys conducted from 2018 to 2019 is estimated at 60% [1].
Table 1. Basic parameters of the Nytva reservoir.

| Indicator                          | Unit of measurement | Indicator values |
|------------------------------------|---------------------|------------------|
| 1. Normal retaining level (NRL)    | m                   | 101.50           |
| 2. Dead-storage capacity (DSC)     | m                   | 98.80            |
| 3. Volume at NRL                   | million m³          | 32.20            |
| 4. Effective volume                | million m³          | 19.40            |
| 5. Volume at DSC                   | million m³          | 12.8             |
| 6. Mirror area at NRL              | km²                 | 9.10             |
| 7. Reservoir length at NRL         | km                  | 11               |
| 8. Average width at NRL            | km                  | 1.50             |
| 9. Maximum depth at the dam        | km                  | 7.70             |
| 10. Average depth at NRL           | km                  | 3.60             |

Structural elements of the upstream slope on the left-bank area have characteristic defects associated with prolonged exposure to the environment, operational loads and mechanical influences, namely: all structural elements of the upstream slope are characterized by: chips and potholes of reinforced concrete, local layer separation of concrete, exposure and corrosion of reinforcement metal; roll of the monolithic wave-breaker wall and reinforced concrete blocks of the parapet fence (deviation of the fence from the vertical up to 15° towards the reservoir); continuous surface destruction of concrete of a monolithic wave-breaker wall with exposed reinforcement, reinforcement corrosion; destruction of the leveling concrete layer under the precast foundation slab along its entire length; a network of multidirectional cracks with a depth of up to 40.00 mm when opening up to 15.00 mm, partial destruction of the slope reinforcement, littering, subsidence zones of the slope reinforcement; overgrowing of the slope structural elements with grass; partial absence of gratings (n = 9 pieces - 8%) of the parapet fence. And also there are indirect signs of a slope sliding, namely a roll from the vertical to 15° towards the reservoir of a monolithic wave-breaker stack and parapet blocks fixed to it. The presence of such defects on the bank protection structure leads to the destruction of the pressure slope and, as a result, to the loss of the overall stability of the hydraulic support structure with the development of a hydrodynamic emergency.

2. Stability of a slope with a reinforced concrete fastening with a broken structure under wave action

One of the causes of emergency situations on water bodies is a violation of the local stability of the pressure front, which results in damage to the seams, mechanical destruction of the surface of the plates for fastening bank protection structures, etc. occurs, which, in turn, leads to an accident. Figure 1 below shows typical damage to Bank protection structures registered in the reservoir.

![Figure 1. Slope’s of the dam damages.](image)

Design schemes for the destruction of bank protection structures are characterized by the following indicators (Figure 2) [2]: 1) NRL is located below the destroyed filling of tile joints; 2) NRL is located in the lower part of slabs with destroyed filling of tile joints; 3) NRL is located in the upper part of the slabs with destroyed fillings of tile joints.
The most common schemes of coastal anchorage destruction are: destruction of inter-slab seams as a result of combined loads (waves, level fluctuations, etc.); washout of the preparation and soil forming the body of the slope from under the fixing plates and their partial collapse; complete destruction of the anchorage at elevations of the headwater close to the marks of the normal retaining level (NRL), and violation of the general stability of the retaining structure, determined by the length of the destruction section along the front. The last scheme is the most dangerous.

The destruction of the fastening of slopes and banks of reservoirs goes through a number of time stages, which were identified in accordance with the schemes given above.

A systematic analysis of the reasons influencing the state of bank protection showed that the main reasons causing their destruction include:

- insufficiently complete accounting of the operating conditions of the reservoir, associated with changes in the nature of regulation, which affects the level regime of the water body and the wave regime [2, 3];

- engineering calculations using integrated design schemes and dependencies developed for sea conditions and conditions of large reservoirs;

- inaccuracies in surveys combined with low quality of construction and installation works;

- lack of proper technical supervision over the quality of construction;

- a low level of operation and repair of structures (sealing of joints, backfilling of erosion, etc.);

- lack of a separate operational service and a system for monitoring the state of the structures of the hydroelectric complex.

Figure 2. Diagrams of the slope fastening buckling: a - slab subsidence above the water's edge; b - subsidence of the slab above the water's edge and sliding of the slab above it; c - the slab collapse above the water's edge and the slab above it.

The stability of the bank protection structures of reservoirs is determined by: hydrodynamic, hydrogeological, climatic, hydrometeorological, geomorphological, biological and other factors and conditions [2-6]. The main factors causing deformations of dam and dam slope fastenings, as well as natural shores of water bodies, include level, wind-wave and ice regimes, as well as current regime and alongshore sediment movement.

During the full-scale survey of the reservoir with bank protection structures, conditions were also identified that affect the scale and intensity of the slopes deformation: the shape and angle of the underwater and above-water parts of the slope and the coastal slope; elevation of the slope and the height of the bank over the NRL of the reservoir; the shape of the coastline in plan; composition, structure, physical and mechanical properties of soils; excessive moisture and suffusion processes, as well as the very design of bank protection structures [1, 3-7].

In accordance with [8, 9], stability refers to the ability of a structure or structure to maintain its functions, protective and bearing capabilities under the influence of external factors. Factors expressed
in the form of loads and impacts leading to the processing of the coastline and deformation of structures' anchorages, as well as their distribution and combination, should be taken into account for assessing the stability of the fastenings of slopes and bank protection structures.

In reservoir conditions with limited linear dimensions, the force of filtration pressure exerting a weighing effect on the attachment plates and the slope surface due to a significant gradient can be manifested exclusively under the conditions of natural banks when the filtration front is unloaded onto the slope, which causes the development of suffusion processes. When the filtration flow from the reservoir is infiltrated into the coastal slope, the effect of "pressing" the plate to the surface of the slope occurs [9].

A diagram of the impact and distribution of wave pressure along a slope with a coating of reinforced concrete slabs is shown in Figure 3. The greatest loads occur on the slope at point 2, which corresponds to the breaking zone of the wave. The nature of the distribution of velocities in the wave flow during fracture on the slope is displayed in the form of a diagram of the velocity distribution (Fig. 4). In the zone of destruction and overturning of the wave, the values of the erosion velocities for the preparation soil and body structure are higher than permissible for erosion (Figure 5, Figure 6), which, in the presence of open seams, causes the removal of soil from the sub-tile space located at elevations close to the NRL.

According to field data, the observed inter-tile deformations range from 3-5 to 10-30 cm with the height of possible wind waves up to 1.2 m [3, 4]. In a hydrodynamic emergency situation, the estimated speed of the wave flow at points 1, 2 and 3 (see Fig. 4) for soil erosion will be most effectively determined by [12]:

\[ v_1 = \frac{10 k_{rc} \sqrt{g}}{2\pi m} \sqrt{h^2 \lambda}, \]  
\[ v_2 = v_1 \cdot \left(1 - \frac{1}{h_{wr} \sqrt{1 + m^2}}\right), \]  
\[ h_{wr} = 2 \frac{k_{rc} m}{h \sqrt{\lambda}} \]  
\[ v_3 = \frac{\sqrt{\pi \lambda} h}{m} \frac{4\pi H}{\lambda}, \]  
\[ H_1 = \frac{1,22 m^{0.8} \sqrt{h \lambda}}{\lambda}. \]

where: \( k_{rc} \) - roughness coefficient equal to 0.9 for concrete slabs; \( g \) - free fall acceleration, m / sec\(^2\); \( h_{wr} \) - wave roll height, m; \( m \) - slope setting coefficient; \( h \) - calculated 1% wave height; \( \lambda \) - wavelength, m.

Figure 3. Diagram of the maximum wave pressure on the slope. Reinforced with slabs.  
Figure 4. Distribution of wave flow velocities along the slope.
3. Stability of the slope in conditions of wave action during wave rollback

Let us consider the stability conditions for a soil slope covered with a reinforced concrete pavement with a broken structure under the action of a wave flow in the case of a wave slope from the slope.

The following forces act on a soil element located on a slope at an angle \( \alpha \) to the horizon (Figure 7):

- the force of gravity of the soil element \( w \gamma_s \), where \( w \) - the volume of the soil element; \( \gamma_s \) - specific gravity of soil particles, N / m\(^3\);
- the force created by the surface flow during wave rollback, \( F_{aom} \gamma_w u^2 / 2g \), where \( F \) is the area of the soil element, m\(^2\); \( \gamma_w \) - specific gravity of water, N / m\(^3\); \( U \) - surface flow speed, m / s; \( a_{om} \) - coefficient of the effect of the velocity head on the soil element; \( g \) - acceleration of gravity m / sec\(^2\);
- wave weighing force \( F_{aw} h_w \), where \( h_w \) - design wave height, m; \( a \) is the coefficient of the weighing wave pressure; \( a = 0.27 \) (1 - \( n_s \)) for granular materials; \( a = 0.27 \) for solid fastening; \( n_s \) - soil porosity on the slope;
- the holding component of the gravity force \( w \gamma_s \cos \alpha \), N / m\(^3\);
- shear component of gravity \( w \gamma_s \sin \alpha \), N / m\(^3\).

Equating the shear and component forces, taking into account the soil friction coefficient \( f \), we obtain the equation of limiting equilibrium in the following form:

\[
\begin{align*}
\gamma_s \sin \alpha + \frac{a_{om} \gamma_w u^2}{2g} &= (\gamma_s \cos \alpha - F_{aw} h_w) f. \\
\end{align*}
\]  

Dividing the left and right sides of equation (6) by \( F_{aw} \), we get:

\[
\begin{align*}
d\gamma_s + \frac{a_{om} \gamma_w u^2 \sqrt{1+m^2}}{2g} + a \gamma h_w f \sqrt{1+m^2} &= d \gamma_s mf. \\
\end{align*}
\]  

**Figure 5.** Graph of the initial erosion wave velocity for non-cohesive soil

**Figure 6.** Graph of permissible values of non-washing bottom velocities

**Figure 7.** Diagram of forces acting on a soil element on a slope during wave rollback.
where \( d = w/F \) - soil particle diameter, m; \( m = \cot g \alpha \) is the slope setting factor.

Dividing equations (7) by \( d \rho_w \), we get:

\[
\frac{\rho_s + \rho_m \sqrt{1 + m^2}}{\rho_s} + \frac{a_h f \sqrt{1 + m^2}}{d} = \frac{\rho_m f}{\rho_s}.
\]

where \( \rho_s, \rho_m \) - the density of soil and water particles, respectively, kg / m\(^3\).

We denote \( \rho_s / \rho_m = \rho_s' \) (relative density of soil particles) and multiply equation (8) by \( d \), then after transformations the equation will take the form:

\[
(\frac{\rho_m f}{2g} + a_h f) \sqrt{1 + m^2} = \rho_s' (mf - 1) d.
\]

The ratio of the right side of equation (9) to the left is a criterion for the stability of the slope \( P_k \) (including the one fixed by plates), which, with mean values of the coefficients \( a = 0.27 \) (1-\( n_s \)) and \( a_m = 0.02 \), has the form:

\[
\Pi_k = \frac{\rho_s' (mf - 1) d}{\sqrt{\frac{0.02n_s^2}{2g} + 0.27(1 - n_s) a_h f} \sqrt{1 + m^2}}.
\]

The stability of the slope is ensured if the criterion \( P_k \geq 1 \) is met, at which the shape of the slope with fastening with plates with a broken structure acquires the contour of the dynamic equilibrium profile adopted for the design type of soil.

4. Conclusion
As a result of the analysis of deformations and destruction of slope fastenings in natural conditions and after the study of the distribution of the removed material of the return filter, it was found that for the reservoir, there are three schemes for the loss of stability of bank protection structures. The obtained schemes correspond to the stages of destruction of fasteners established as a result of field studies.

The generalization of the experimental material made it possible to propose a criterion for the stability of fixed slopes, taking into account the possibility of the occurrence of destruction of the fixing plates of the \( P_k \). It is assumed that at \( P_k \geq 1 \), the profile of the slope with fastening by plates deformed during operation acquires the contour of the dynamic equilibrium profile adopted for the design type of soil as a result of the destruction of the slope by waves. When assessing the stability of various types of bank protection of soil slopes of retaining structures and coastal slopes, it is recommended to take into account the proposed criterion for the stability of \( P_k \), taking into account possible deformations of the coatings.

To ensure the safe operation of the ground dam, it is recommended to perform a set of works within the framework of the overhaul of the reservoir's hydraulic structures complex: restoration of the dam crest to the required marks; consolidation of soils in waterlogged areas of the dam body by injection; dismantling of emergency structures of metal stands with wooden flooring; dismantling of defective areas (or complete dismantling) of a monolithic reinforced concrete break wall and parapet blocks, restoration of the dam body in these areas, construction of a new breakwater wall and parapet with the implementation of waterproofing and drainage measures; dismantling of defective sections (or complete dismantling) of monolithic slope reinforcement, restoration of the cross-section of the slope in these areas, installation of a new reinforced concrete reinforcement with a return filter under the reinforcement; repair of surfaces of other structures and elements of reinforced concrete breaker walls, parapets and strengthening of the upper slope; processing of concrete surfaces with protective compounds.
5. References

[1] Overhaul of the hydraulic structure of the reservoir on the river Nytva in the town of Nytva, Nytva district Technical report on survey results Unpaved dam 2019 61

[2] P 92-2001 Recommendations for the survey of hydraulic structures in order to assess their safety

[3] Levkevich V E 2015 Dynamic stability of the banks of water reservoirs in Belarus Law and Economics (Minsk) 306

[4] Zolotorev G S 1955 Engineering-geological study of the coastal slopes of reservoirs and assessment of their processing Academy of Sciences vol 12 188-235

[5] Mikhnevich E I 1988 Stability of the channels of open watercourses 240

[6] Levkevich E M 1977 From the experience of operating the fastenings of the upper slopes of earth dams and the banks of reservoirs of the BSSR 97-105

[7] Kondratyev I E 1951 Calculation of wind waves and reshaping of the banks of reservoirs 107

[8] Chebotarev A I 1970 Hydrological Dictionary 78

[9] Levkevich E M 1971 Laboratory studies of the reshaping of unreinforced slopes of earth dams under the influence of waves and filtration forces 8 (1971) 98-102

[10] Kanarsky V S 1982 Stability and Strength of Slopes of Earthworks 46

[11] Maksimchuk V L 1981 Rational use and protection of the banks of reservoirs 112

[12] Shaitan V S 1962 Investigation of wind waves at the reservoir

[13] Shimanovsky L A, Shimanovskaya I A 1973 Fresh underground waters of the Perm region

[14] Surface water resources of the USSR Hydrometeozdat vol 11 846 1973

[15] SP 39.13330.2012 Dams made of soil materials

[16] SP 58.13330.2012 Hydraulic structures. Basic Provisions

[17] SP 80.13330.2016 River hydraulic structures