Mathematical modeling of the flood control system components presented by low-head earth dams for the Lower Kuban agricultural lands

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Abstract. The article discusses the main parameters of the application of modern methods of mathematical modeling by the finite element method, necessary to assess the technical condition of low-head earth dams and identify their defects that impact the flood control system for protecting the agricultural lands of the Lower Kuban. The problem is in substantiating the necessity to extend the life of the low-head earth dams of the flood control system in the Lower Kuban that are in unsatisfactory state and require modernization and reconstruction. The long-term operation of the low-head earth dams of the flood control system demands identification of defects and damage that violate the normal operation of the flood control system of the Lower Kuban; many structural elements fail, the soil base subsides, as well as the reinforced concrete lining can be completely destroyed. The most widespread, when assessing the residual life of the flood control system of low-head earth dams, is an integrated accident risk assessment. Based on the surveys, the technical condition of the low-pressure earthen dams of the flood control system of the Kuban River, over a considerable length, is assessed as emergency. Over a long period of operation, significant damage and changes to the main structures of the low-head earth dams of the flood control system have occurred. In many areas, the structural elements of the dams are washed up and weakened, in some areas, the ridge of the dams was found to subside by 30-50 cm, sediment accumulation in the channel in some areas led to a sharp reduction of the open cross section area with a simultaneous increase in erosion processes, etc. As a result of numerical experiments of mathematical modeling by the finite element method, the reliability of the low-head earth dams of the flood control system for various combinations of destructive influences is estimated.

1. Introduction

The floodplains of the Lower Kuban occupy an area of 871 thousand hectares. They are understood to mean the wetlands of the Kuban River valley flooded below the city of Krasnodar, flooded annually by meltwater and floods. Until 1930 the dams were very poorly used by the population and were classified as useless lands. The spring flood waters of the Kuban went late and the cultivated plants sown after that did not have time to ripen, the summer floods of the Kuban River and its left-bank tributaries flooded the crops, as a result of which they died [1]. The floodplains of Lower Kuban were used by the population mainly for grazing, and reeds were used as fuel and building material. Considering that the used land in the Krasnodar Territory now amounts to 5.04 million hectares, the area of the lower Kuban floodplains occupies 17.3% of them [2].
Suggestions for the reclamation of the floodplains of the Lower Kuban were made at the beginning of the 19th century; in 1909, the first attempt was made to grow rice in the floodplains of the Lower Kuban near the city of Temryuk and a yield of 24 c/ha (2.4 t/ha) was obtained. In 1913, the survey party of engineer Sokolov was probably the first land reclamation project in the Lower Kuban floodplain, including a detailed topographic survey [3]. Professor of the Don Institute of Agriculture and Land Reclamation B.A. Shumakov in 1923–1924 in the south-east of Russia conducted a thorough survey of the Lower Kuban floodplains. The floods were observed almost annually; summer ones occurred mainly in June–July, winter (ice-jam) ones were in February–April, and surge ones in October–December [4].

The total length of the flood control system of low-head earth dams from the Krasnodar reservoir to river mouths is 650 km [5]. From 1998 to the present, repeated surveys have been observed on this flood control system, the main task of which was to identify areas in unsatisfactory technical condition, threatening an emergency breakthrough of the ridging. In addition, topographic and hydrographic surveys were carried out in some areas [6].

Based on the surveys, the technical condition of the flood control system of low-head earth dams of the Kuban River for a significant extent is assessed as emergency. Over a long period of operation, significant damage and changes to the main structures of the ridging system occurred:
- in many areas, low-head earth dams were washed up and structurally weakened, the slopes were deformed [7];
- in some areas, the ridge of the dam subsided by 30–50 cm and its deformation was revealed;
- in some places the body of a low-head earth dam was destroyed;
- accumulation of sediment in the channel in certain areas led to a sharp reduction in the open cross section area with a simultaneous increase in erosion processes [8];
- areas were detected with erosion of the banks where the soil collapses dragging along sections of the low-head earth dams.

Channel processes occurring in the Kuban river below the Krasnodar reservoir, together with a number of anthropogenic factors, in general, increase its throughput. For example, at present, the following water flows of 650 m$^3$/s should pass unhindered along the branches of the Kuban and Protoka rivers below the Tikhovsky hydroelectric complex. However, the technical condition of the low-head earth dams reduces these values to 1200 m$^3$/s along the Kuban river and 550 m$^3$/s along its branches. At the same time, in some areas, low-head earth dams are so close to the edge of the bank or have become the edges themselves, that only temporary measures for bank strengthening protect them from destruction [9].

2. Materials and methods
The Kuban River refers to rivers with a tense water management situation, the total water withdrawal in 2017 was 11.8 km$^3$. Water discharge to surface water bodies is 11.8 km$^3$. Water withdrawal for intra-basin and inter-basin transfer is on average 4.3 km$^3$, including water withdrawal to the Great Stavropol Canal of 2.3 km$^3$ and that to the Nevinomyssky Canal of 0.7 km$^3$. The technical condition of 650 km of low-head earth dams of the Kuban River embankment is estimated as pre-emergency [10]. For the reconstruction of only their first stage, it is necessary to allocate 1.5 billion rubles (Figure 1).
Figure 1. Modeling the longitudinal profile of the Kuban River

The purpose of the numerical experiment performed as part of these studies was to determine, on the basis of mathematical modeling, the degree of long-life reliability of the structural elements of the flood control system of low-head earth dams. The excess of the water level over the ridge of the dam along the Kuban and Protoka rivers under the conditions of the idle Shapsugskiy reservoir is shown in Figure 2 [11].

![Diagram](image)

**Figure 2.** Modeling of the excess of the water level over the ridge of the dam in the conditions of the idle Shapsugskiy reservoir: a) along the Kuban river; b) along the Protoka river.

Various types of detected defects and damage to flood control elements of low-head earth dams were examined and studied. The results of simulation modeling when the discharge \( Q = 1000 \text{ m}^3/\text{s} \) from the Krasnodar reservoir under conditions of an inactive Shapsugskiy reservoir [12] are shown in graphical form in Figure 3.
Figure 3. Modeling of the excess of the water level above the ridge of the dam in the conditions of an idle Shapsugskiy reservoir in the conditions of discharge $Q = 1000 \text{ m}^3/\text{s}$ from the Krasnodar reservoir: a) along the Kuban river; b) along the Protoka river.

The results of simulation modeling when discharge from the Krasnodar reservoir discharges $Q = 1250 \text{ m}^3/\text{s}$ in the conditions of an idle Shapsugskiy reservoir [13] are shown in graphical form in Figure 4.

Figure 4. Simulation of the excess of the water level over the ridge of the dam in the conditions of an idle Shapsugskiy reservoir under conditions of discharge $Q = 1250 \text{ m}^3/\text{s}$ from the Krasnodar reservoir: a) along the Kuban river; b) along the Protoka river.

The entire theoretical justification of the mathematical model is characterized on the basis of experimental studies to assess the reliability of the flood control systems of the low-head earth dams [14] with various combinations of destructive effects, performed on the basis of mathematical modeling to establish the degree of danger [15].

Figure 5 shows the diagrams of stress intensity and total displacements. Evidently, the zone [16] under the soil base of the structural elements of the low-head earth dam is the most loaded, as a result of which the lower part of the structural elements experiences supercritical stresses, and displacement of the structural elements begins.
The situation was modeled with the presence of two or more faults, in the form of subsidence and loss of stability of structural elements of a low-head earth dam, at the base and on slopes due to softening of the soil [17].

The results of numerical simulations of subsidence and loss of stability of structural elements of a low-pressure earth dam on slopes in the form of stress diagrams along the horizontal and vertical axes and displacements are presented in Figure 6. When modeling the subsidence and loss of stability of structural elements of a low-pressure earth dam, it was found that the loss of stability of bearing elements occurs directly in the places of failure, subsequently leads to displacement and loss of bearing capacity [18].

The simulation of various combinations of faults [19] in the form of voids and decompressions of the soil base with sizes from 500 mm to 2000 mm in diameter was carried out. The threshold for the intense danger of voids and decompression of the soil base under the structural elements of the low-pressure earthen dam, starting with a diameter of 1200 mm [20], has been established.

The maximum allowable geometric dimensions of the identified defects observed at the structures were calculated, situations with the presence of two or more malfunctions on the structural elements of a low-head earth dam were considered.

3. Conclusion
The degree of danger and the boundaries of the characteristic zones of destruction of the structural elements of the flood control system of low-head earth dams from flooding are established.
Decommissioning of the Shapsugskiy reservoir significantly reduced the reliability of the flood protection system in the Lower Kuban basin. The modeling results showed that in the conditions of idle Shapsugskiy reservoir, discharges through the Krasnodar hydroelectric complex of 1500 m³/s even with a water intake of 230 m³/s in the site of the Fedorovskiy hydroelectric complex are unacceptable.

The estuary of the Kuban River is significantly affected by flood discharges from the left-bank rivers, which requires the redistribution of the flood discharges of the Kuban River in the Tikhovskiy hydroelectric section with an increase in flow to the Protoka River.

In the conditions of the idle Shapsugskiy reservoir, congestion is most dangerous for two settlement sites - from the Shapsugskiy reservoir to the Fedorovskiy hydroelectric complex and from the Fedorovskiy hydroelectric complex to the Tikhovskiy hydroelectric complex. The wind surge from the Sea of Azov significantly affects both water levels and flow rates in the Kuban and Protoka rivers.

The critical values of the diagnostic indicators of the lower Kuban embankment dams are quantitatively different before, during and after the flood. The stability of the upper and lower slopes of the embankment dams is significantly reduced taking into account the increase in seismicity. The results of the modeling of long-running dams indicate that in a large number of sections during the flood period their stability is not ensured.

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