Modeling methods to assess technical condition of low-pressure earthen dams

M A Bandurin, V V Vanzha, A S Shishkin, F S Litovko and A A Sidakov
Kuban State Agrarian University named after I. T. Trubilin, 13, Kalinina str., Krasnodar, 350044, Russia
E-mail: chepura@mail.ru

Abstract. The paper discusses the main parameters of the modern modeling methods and its application, which are used to assess the technical condition of long-running, low-pressure earthen dams. In Russia, the matter on justification to extend the operation life for hydraulic constructions of irrigation systems requires to be overhauled and discussed more. During the long-term operation of the low-pressure earthen dams, many construction elements can fail. Based on the surveys performed, the technical condition of the Kuban and Protoka rivers regulation system for a significant length is assessed as emergency. Over a long period of operation, some significant damages and changes in the main constructions of the river regulation system occurred. As a result of numerical experiments, the boundaries of the low-pressure earthen dams containing typical damage of the same type were systematized, which allows streaming the process of laying down the radargrams of georadar sounding subsurface and determining the points at which concrete strength should be measured during a field examination. As a result of numerical experiments conducted by the finite element method, the reliability of the low-pressure earthen dams of irrigation systems has been simulated to identify various combinations of possible destructive impacts. The degree of danger and the boundaries showing some characteristic zones of destruction which can occur in the low-pressure earthen dams’ parts have been defined. Empirical dependencies have been obtained to evaluate the performance of the low-pressure earthen dams with a changing location and nature of the lesions, allowing determining the maximum allowable damage scope for further safe operation of a hydraulic construction.

1. Introduction
The floodplains of the Lower Kuban occupy an area of 871 thousand hectares; by them are meant the wetlands of the Kuban River valley below the city of Krasnodar, which are flooded annually by meltwater and floods. Until 1930, the floodplains of the Lower Kuban were very poorly used by the population and were considered to be uncomfortable lands. The spring flood waters of the Kuban went late and cultivated plants that were sown after that did not have time to ripen. Summer floods of the Kuban and its left-bank rivers flooded crops, as a result of which the crop died. The floodplains of the Lower Kuban were used by the population mainly for grazing, whereas the reeds were used as fuel and building resources. Considering that the used land area in the Krasnodar Region now amounts to 5.04 million hectares, the area of the Lower Kuban floodplains occupies 17.3% of them [1].

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 2.4 t/ha yield was obtained. In 1913, the survey party, initiated by
an engineer Sokolov, was probably the first land reclamation project in the Lower Kuban floodplain, which provided a detailed topographic survey [2]. Professor of Don Agriculture and Land Reclamation Institute B.A. Shumakov in the south-east of Russia conducted a thorough agricultural and land reclamation survey of the floodplains of the Lower Kuban in 1923 - 1924 [3]. Floods in the Lower Kuban were recorded annually. Summer floods occurred mainly in June - July, winter ones (mashing) – in February - April, rising ones – in October - December.

A river regulation system is federal property and is on the balance of the Federal State Institution that regulates all operations of the water-engineering constructions located on the rivers - Kuban and Protoka. The total length of the low-pressure earthen dams from the Krasnodar reservoir to the river mouths is 650 km [4]. From 1998 to the present, repeated flood surveys have been carried out on the flood control regulation system, the main task of which was to identify sections of the low-pressure earthen dams which are in unsatisfactory technical condition. This fact can cause an emergency break in the debris. Additionally, topographic hydrographic surveys were carried out in separate debris sections research [5].

Based on the surveys performed, the technical condition of the Kuban and Protoka rivers regulation system at a significant length is considered as emergency. Over a long period of operation, some significant damages and changes in the main constructions of the river regulation system occurred.

- in many areas the low-pressure earthen dams are washed up and structurally weakened, the slopes are deformed [6];
- in some areas, sediment ridge crest of the low-pressure earthen dams of 30-50 cm and its deformation were revealed;
- in some places a body of the low-pressure earthen dam is destroyed;
- accumulation of sediment in the riverbed in certain areas led to a sharp reduction in the living section of the water flow with a simultaneous increase in erosion processes;
- found some areas with banks' erosion, where the soil collapses, dragging along areas of the low-pressure earthen dams.

Channel processes occurring in the Kuban river below the Krasnodar reservoir, together with a number of anthropogenic factors, in general, increase its throughput. So, at present, the following water flows should pass unhindered along the Kuban and Protoka rivers: 650 m³/s along the branches of the Kuban and Protoka below the Tikhov hydroelectric power system. However, the technical condition of the low-pressure earthen dams reduces these values to 1200 m³/s across the Kuban and 550 m³/s along the branches. At the same time, in some areas, the low-pressure earthen dams are so close to the edge of the banks, or have turned into the edge themselves, that only temporary measures for a bank fastening protect them from being destroyed [7].

2. Materials and methods

The Kuban relates to the rivers with the stressed aquacultural situation, the summary water drawoff in 2017 was 11.8 km³. Water-removal into the surface aqueous objects is equal to 11.8 to km³. Water drawoff for intra-basin and inter-basin diversion averages 4.3 km³, including water drawoff to the Great Stavropol Canal – 2.3 km³, to the Nevinomyssky Canal – 0.7 km³. The technical condition of 650 km of the low-pressure earthen dams of the Kuban and Protoka rivers was assessed as pre-emergency. The first turn reconstruction is thought to take 1.5 billion rubles.

The purpose of the numerical experiment performed as part of these studies is to determine, on the basis of mathematical modeling, the degree of reliability of the low-pressure earthen dam for a long term of operation (more than 50 years) [8].

Various types of malfunctions of the low-pressure earthen dam, the most common in practice of the irrigation systems operation, have been identified and this fact lied in the basis of this research. The stress-strain state of the low-pressure earthen dam was calculated on the basis of the model which describes their characteristic element - reinforced concrete buttress, considered as a thin-walled shell, taking into account the conditions of its abutment on a soil base.

The entire theoretical justification of the mathematical model is characterized on the basis of some
experimental studies to assess the reliability of the construction under various combinations of destructive impacts. All these impacts are performed on the basis of mathematical modeling to establish the degree of danger and permissible size of sections, existing and possible destructions, for example, reinforced concrete buttress is considered as a thin-walled shell, where the conditions of its support on a soil base are taken into account. The finite element model of the reinforced concrete buttress of the low-pressure earthen dam is shown in Figure 1. The number of elements and nodes was 438907 and 542901 respectively. The low-pressure earthen dam was represented as an object of simple geometric shape, the coding of the initial information was carried out in terms of the increment method, with presentation in the fragments.

![Figure 1. The finite element model of the reinforced concrete buttress of the low-pressure earthen dam](image1.png)

3. Results
When designing a solid-state model in the form of a reinforced concrete buttress of the low-pressure earthen dam without malfunctions, the aim was to determine the nature of a real low-pressure earthen dam. The location and characteristic parameters of malfunctions of the stress-strain state of the reinforced concrete buttress of the low-pressure earthen dam were taken in accordance with the data obtained during the field surveys in the Lower Kuban. Obviously, the most dangerous are the subsidence and loss of stability in the reinforced concrete buttress due to softening of the soil and the formation of voids from water filtration, resulting in the destruction and sliding of the buttress from the slope of the low-pressure earthen dam [9]. Numerical solutions in the form of diagrams of stresses and displacements going in construction parts with the defects in the underlying soil are presented in Figure 2.

![Figure 2. Decompression formation in underlying soil of the buttress in a low-pressure earthen dam: a - diagram of absolute displacements; b - stress intensity diagram.](image2.png)

This result is proceeded by the numerical experiments aimed at assessing the stress-strain state of the buttress from decompression of the soil base differentially for subsidence and movement along a low-pressure earthen dam.
Figure 3 shows stress intensity diagrams and total displacements. As can be seen from the figure, the most loaded area is the area under the soil base of the reinforced concrete buttress of the low-pressure earthen dam, as a result of which the lower part of the buttress experiences supercritical stresses, and the process of shifting in buttress begins.

**Figure 3.** Buttress of a low-pressure earthen dam when it is sliding: a - stress intensity diagram; b - total displacements diagram.

In conclusion, a situation was simulated with the presence of two or more malfunctions, in the form of subsidence and loss of stability of the buttress, at the base of the low-pressure earthen dam, and on slopes due to decompaction of the soil of the base [10].

The results of numerical simulations of subsidence and loss of stability of the buttress on the slopes of the low-pressure earthen dam in the form of stress diagrams along the horizontal and vertical axes and the displacements are presented in Fig. 4. When simulating subsidence and loss of stability of the buttress, it was found that the loss of stability in elements support occurs directly in the places of failure, subsequently leads to displacement and loss of bearing capacity and, as a result, to displacement at the base of the low-pressure earthen dam [11]. This leads to loss of stability of the elements and their displacement relative to the soil base.

**Figure 4.** The subsidence and loss of stability of the buttress of the low-pressure earthen dam on the slopes due to the formation of voids from filtration: a - diagram of the total displacements; b - stress intensity diagram.

It was revealed that the loss of stability in the elements [12] occurs at the places of malfunction, with its growth in the area along the longitudinal axis of the low-pressure earthen dam (Fig. 5). Vertical stresses in the elements of the buttress bottom increase stresses in the axis zone, and horizontal stresses appear in elements positioned perpendicular to the axis of the low-pressure earthen dam. Subsequently, with an increase in the intensity of negative impacts and a corresponding increase in stresses, the elements of the buttress bottom lose stability and they move relative to the soil base both horizontally and vertically [13].
Figure 5. The subsidence and loss of stability of the buttress of the low-pressure dam due to formation of voids from filtration: a – diagram of the total displacements; b - stress intensity diagram.

Thus, as a result of the numerical calculations, the zones of malfunctions formation were established under the reinforced concrete buttress of the low-pressure earthen dam. The modeling of various combinations of malfunctions in the form of voids and decompression of the soil base with sizes from 500 mm to 2000 mm in diameter was carried out. A threshold has been established for the intense danger of voids and decompression of the soil base under reinforced concrete buttress, starting with a diameter of 1200 mm [14].

There were calculated the maximum allowable geometric dimensions of the defects that were observed in the constructions, and the situations with two or more malfunctions on the low-pressure earthen dam were considered. Based on the calculated results, the stress and displacement diagrams of the construction elements were introduced, on the basis of which the graphs were built and regression dependencies were determined with the aim to calculate the stresses of the low-pressure earthen dam. On models of the low-pressure earthen dam, the situations of different operability were simulated, both of a new construction and of long-term operation in the presence of various malfunctions and their combinations (cracking, destruction of the bearing area of the buttress, subsidence of the soil base, etc.). The maximum allowable geometrical dimensions of the malfunctions were determined that did not reduce the operability of the low-pressure earthen dam, the criterion of which was a voltage value not exceeding the value as projected.

4. Conclusion
As a result of numerical experiments, the boundaries of the low-pressure earthen dams containing typical damage of the same type were systematized, which allows streaming the process of laying down the radarograms of georadar sounding subsurface and determining the points at which concrete strength should be measured during a field examination.

As a result of numerical experiments conducted by the finite element method, the reliability of the low-pressure earthen dams of irrigation systems has been simulated to identify various combinations of destructive impacts.

The degree of danger and the boundaries showing some characteristic zones of destruction going in the elements of the low-pressure earthen dams of irrigation systems have been defined.

Empirical dependencies have been obtained to evaluate the performance of the low-pressure earthen dams with a changing location and nature of the lesions, allowing determining the maximum allowable damage scope for further safe operation of a hydraulic construction.

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