NUMERICAL MODELING OF A BREACH WAVE THROUGH THE DAM AT THE KRASNODAR RESERVOIR

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Variational analyses of a breach wave through the pressure front of the Krasnodar hydroproject are conducted using modern approved procedures.

The Krasnodar Reservoir on the Kuban' River — a federal property — is operated by the FGU "Krasnodarskoe Vodokhranilishche," which is subordinate to the MPR of the Russian Federation. Based on a classification corresponding to the "Instructions concerning management of the Russian Register of Water-Development Works" issued on 12 July 1999, the level of safety of its water-development works are rated as *depressed*. During the period of the reservoir's service (since 1973), various kinds of emergencies have occurred in individual sections of the earthen dam [1]. Analysis of the risk of failures has indicated that the most negative effect with catastrophic consequences (even victims, and economic and ecological losses within the land surrounding the Lower Kuban') is associated with the possibility of a breach in the dam.

Some results of investigations based on mathematical modeling of a breach wave through the pressure front of the dam retaining the Krasnodar Reservoir, which were conducted by the JSC NIIÉS and the JSC "NPP Akvarius" in 2004, 2006, and 2008 [2 – 5], are cited in this paper. Scenarios of a hydrodynamic failure are developed. A digital model has been created for the relief of the locale around the Krasnodar Reservoir basin and tailrace to the Elizavetinskaya village) over an expanse of approximately 80 km. A breach wave was analyzed using two-dimensional St. Venant equations in two different models of breach development. Zones, levels, and depths of flooding were obtained and superposed on a cartographic base, and the flow velocities and running time of the breach wave calculated. The results are to be used in planning alternate schemes of future development in the city of Krasnodar, and in substantiating plans for reconstruction of the Krasnodar hydroproject (KHP).

Objective of and problems associated with investigations. The Krasnodar Reservoir is located in the middle Kuban' River 248 km from its mouth immediately above Krasnodar (Fig. 1). At the time of the analyses, the reservoir with its 394-km^2 surface area at the normal backwater level (NBL), and full capacity of 2.91 billion m^3 (at the forced operating level — FOL) had a useful capacity of approximately 2 billion m^3. The capacity of the anti-flood prism is 0.64 billion m^3, and the stagnant volume 0.19 billion m^3. The computed water levels in the reservoir are: normal backwater level of 33.65 m, FOL of 35.23 m, and MOL of 25.85 m. The average depth of the reservoir at the NBL is 5.8 m, the length 46 km, and the average width 8.7 km. The overall length of the thrust-front structures amounts to approximately 23 km including: an 11.4-km earthen dam, an 11.4-km right-bank enclosing dike, and concrete structures (spillway dam, sluice, and water intake) totaling 0.1 km.

The earthen dam (Fig. 2) is built of clayey loams and light clays over a length of 4.4 km, and fine- and medium-grain sands over a length of 6.7 km; in the breach-prone section, the body of the dam consists partly of cohesive, and partly of sandy soils. A railroad embankment, which partitions the broad left-bank bottomland and is depressed in its midsection, and a railroad bridge across the Kuban' River with a broad span of 290 m comprise a significant characteristic feature of the tailrace at the KHP. The river channel in the section in question is separated from the bottomland by a dike (embankment) that prevents flooding of the bottomland when water is discharged into the tailrace of the dam with flow rates of up to 1500 m^3/sec.

According to regulatory documents, breach-wave analysis is required in substantiating elevation-planning solutions for development of the bottomland. Placement of new residential neighborhoods in zones of possible catastrophic flooding is prohibited in existing cities in conformity with Construction Rule and Regulation 2.01.51–90 "Engineering and technical measures for civil defense." According to Construction Rule and Regulation 2.07.01–89* "Municipal planning. Development of urban and agricultural settlements," lands that are inundated to a depth of more than 1.5 m and may be subjected to the destruction of buildings and struc-

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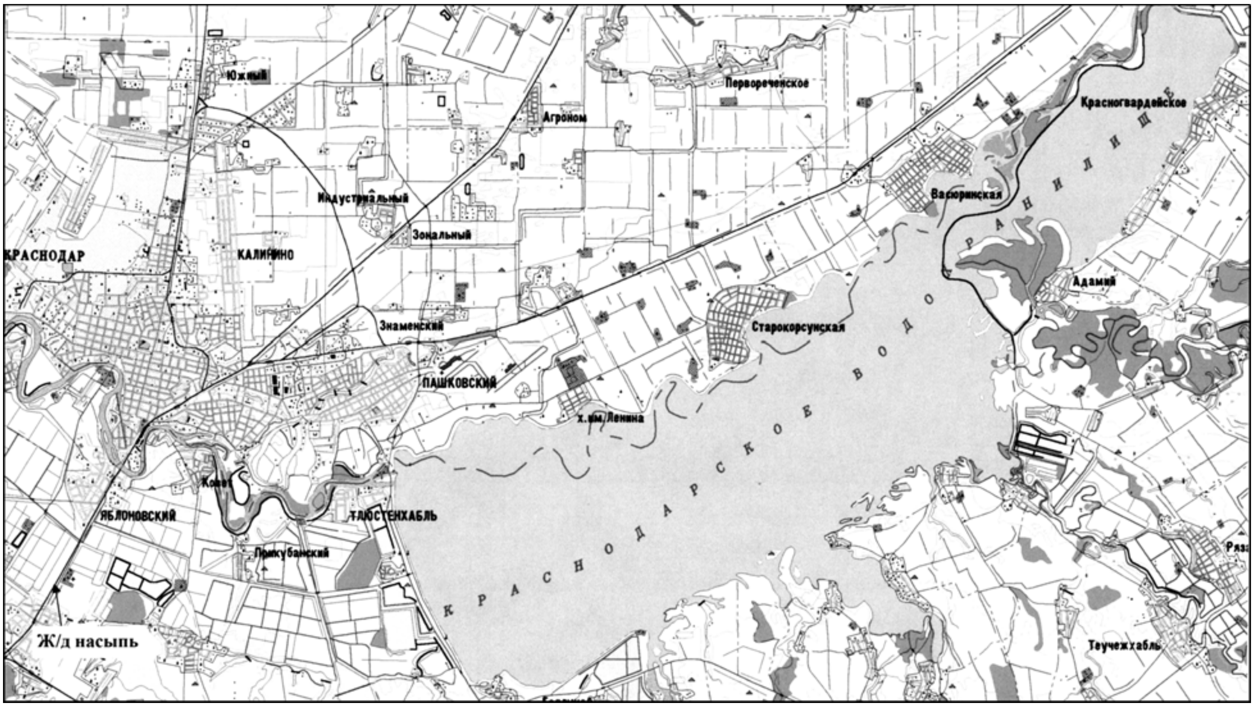


Fig. 1. Electronic topographic map of Krasnodar Reservoir and its surroundings.

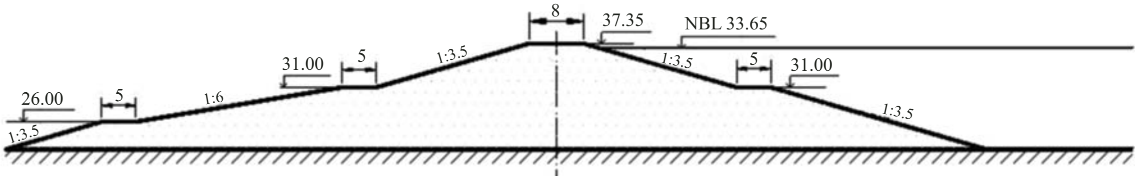


Fig. 2. Schematic section through transverse axis of dam at Krasnodar hydroproject.

tures, loss of life, and malfunctioning of factory equipment are considered zones of catastrophic flooding.

The basic purpose of the 2004 investigations [2, 3] was to determine the flooding parameters of lands within the limits of the city of Krasnodar during passage of a breach wave caused by partial failure of the dam retaining the Krasnodar reservoir. The importance of the problem was predetermined by the fact that some of the existing urban neighborhoods and sections scheduled for future development (in the Novaya Adygeya District) may fall within the flood zone and dictate the need for their engineering protection. Let us note that the problem of providing hydrologic safety in developing bottomland is extremely urgent, and we have also examined it for suburban Moscow, and the cities of Perm' and Rostov-on-Don [6, 7].

The parameters of a breach wave caused by partial failure of dam with the FOL raised to 36.5 m were determined in the 2006 investigation [4]. The goal of the 2008 investigation was to compare the results of analysis of the out-flowing wave in accordance with the approved procedure [8], and by a new method of direct numerical modeling of breach development in an earthen dam [5] with the Krasnodar hydroproject as an example.

Numerical-modeling procedure. The procedure employed for the analyses was developed and refined with consideration given to the stated goals and characteristic features of the subject under investigation. For many years, the NIIÉS has conducted computer modeling of breach waves for failures in the thrust fronts of hydroprojects. The "BOR" and "Losses due to Flooding" software packages [11, 12], which are based on numerical solutions of two-dimensional St. Venant equations (shallow-water equations) in adaptive triangular-tetragonal grids, have been developed and registered in the Russian Patent Office. Use of S. K. Godunov's loop-type algorithm provides for analysis of churning flows, hydraulic jumps, and currents along a dry bottom by a continuous model with no numerical oscillations and negative depths [13, 14]. The programs make it possible to analyze water entities of a large expanse with complex bathymetry and planform configurations with allowance for roads, bridge crossings, bank-protecting dikes, and other structures.

Procedures employed in geoinformation systems (GIS), electronic topographic maps, radar elevation matrices, and satellite photographs are widely utilized in preparing initial data and visualizing the results (depth of flooding, flow velocities) [7, 15, 16]. During the period since 2001, breach waves have been analyzed for more than 20 hydroprojects, including the Krasnoyarsk, Bratsk, Novosibirsk, Saratov, and others [3, 6, 7, 13 – 16]. Positive expert conclusions of the Federal Center for Sciences and High Technologies run of the Emercom of Russia have been drawn from analyses conducted for the Kama, Uglich, Rybinsk, Tsimlyanskoe, and Pirogovo hydroprojects, and the Skhodnya HPP.

To determine the rate of expansion of a breach in a dam constructed of noncohesive material, the NIIÉS [8] derived the following relationship, which confirms results of many experiments:

$$\frac{dB}{dt} = K_{\mathrm{s}} \frac{h^{2.5}}{\Omega}, \tag{1}$$

where $B(t)$ is the width of the breach at time t, Ω is the cross-sectional area of the dam, and $h(t)$ is the difference between the water level in the upper pool and the elevation of the base of the dam. The scouring-intensity factor K_{s} will depend on the properties of the material in the body of the dam. For sandy soils, it approximately 0.07 $\mathrm{m}^{0.5}/\mathrm{sec}$.

To describe the formation of the breach, Eq. (1) is supplemented by certain relationships that make it possible to close the mathematical model, and obtain the desired width of the breach as a function of time [8].

In practice, propagation of a breach wave for an earthen dam is calculated in the following manner with use of the "BOR" program [11]. According to the procedure outlined in [8], the dynamics of breach development is considered in the first step, i.e., the time dependence of the variation in breach dimensions is determined. In the second step, combined numerical modeling of the current in the reservoir and tailrace of the hydroproject is carried out for a given law governing breach development over time in accordance with the "BOR" program [14]. This approach permits a more accurate calculation of the conditions in the upper pool (particularly for narrow lengthy reservoirs), and the rise in the ground-water table on the side of the tailrace, which frequently occurs for the most part under bottomland conditions. As a result, maximum breach flows are usually somewhat lower than those calculated directly from [8].

The procedure in [8] has certain constraints in its range of application. For example, it does not take into account characteristic features of the initial period of breach formation. In a number of familiar packages for breach-wave analysis, including the "MIKE-11" package [9], rather primitive models of breach development, which do not correspond to the physical mechanism of breach formation, and yield large deviations from parameters of the actual phenomena, are employed [10]. The situations noted suggest the need for additional refinement of breach-development models that more in tune with actual processes.

The NIIÉS has recently developed a method for direct numerical modeling of breach development in an earthen dam, which is based on solution of a system of differential equations in partial derivatives describing transport of soil in the flow, and the change in elevation of the bottom of the breach with consideration of the effects of sliding of the underwater slopes, and caving of the slopes above the water [5]:

$$\frac{\partial hS}{\partial t} + \frac{\partial USh}{\partial x} + \frac{\partial VSh}{\partial y} = -K(S - S_{\mathrm{s}}) \tag{2}$$

$$(1-p)\frac{\partial Z}{\partial t} = K(S - S_{\mathrm{s}}) + \frac{\partial}{\partial x} D \frac{\partial Z}{\partial x} + \frac{\partial}{\partial y} D \frac{\partial Z}{\partial y}; \tag{3}$$

$$K = \begin{cases} \alpha U_* + (1-\alpha)W, & U_* > W \\ W, & U_* \le W \end{cases}, \quad 0 \le \alpha \le 1.$$

$$D = D_1 + D_2 + D_3, \; D_1 = \beta_0 ShW;$$

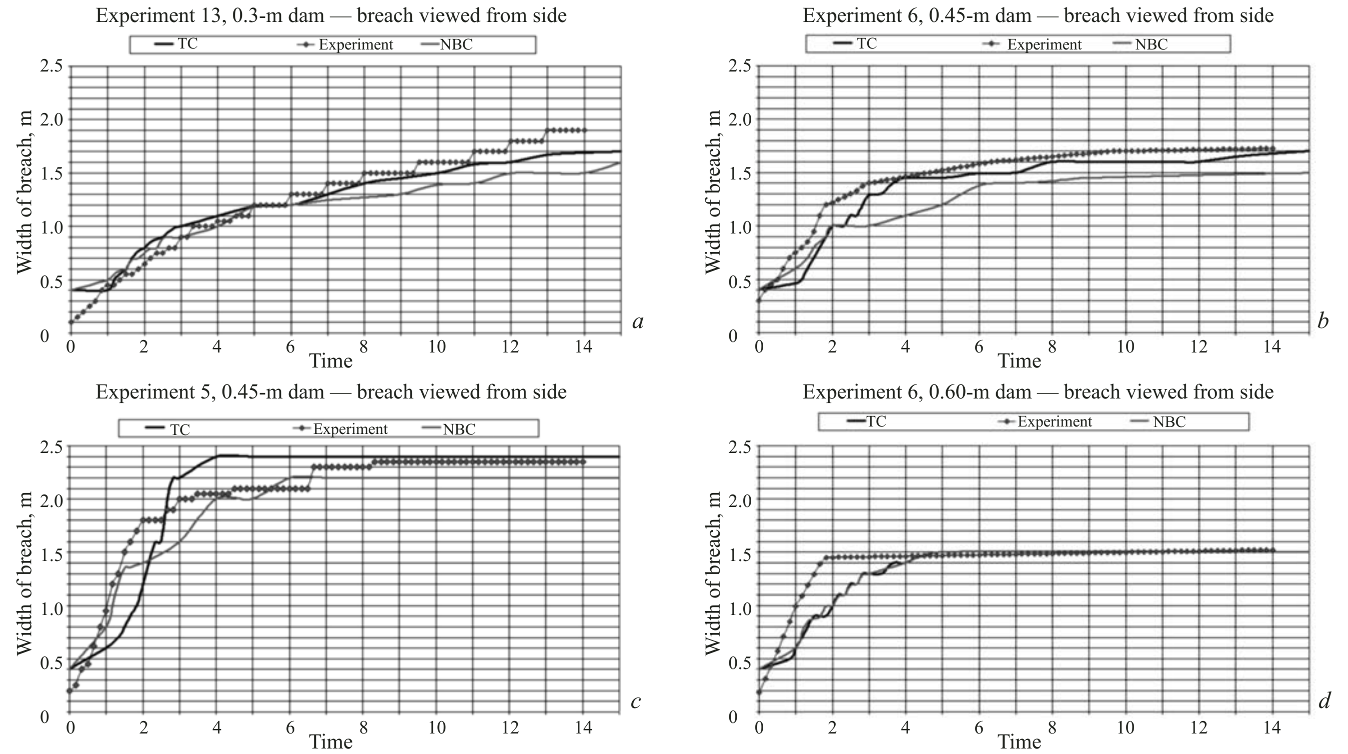
$$D_2 = \beta_1 \sqrt[4]{\left(\frac{\mathrm{tg}\,\gamma}{\mathrm{tg}\,\varphi}\right)^2 - 1}, \; \gamma > \varphi, \; h > 0;$$

$$D_3 = \beta_2 \sqrt[4]{\left(\frac{\mathrm{tg}\,\gamma}{\mathrm{tg}\,\varphi_{\mathrm{c}}}\right)^2 - 1}, \; \gamma > \varphi_{\mathrm{c}}, \; h = 0;$$

$$S_H = \alpha_1 \frac{(U_* - U_{*N})^2}{2gh} \left(\frac{0.13}{\mathrm{tg}\,\varphi} + 0.01 \frac{|U|}{W} \right), \tag{4}$$

where h is the depth of water, U and V are the velocity components along the X and Y axes, S is the bulk concentration of detritus particles in the flow, S_{s} the equilibrium concentration of particles (saturation concentration), which can be assigned on the basis of the modified Bagnold formula (4), K is the coefficient of vertical detritus exchange between the bottom and flow, p is the porosity of the soil, γ is the angle of repose of the soil, φ and φ_{c} are the angles natural repose of the soil under and above the water, respectively, in the body of the dam, W is the fall velocity of the soil, U_* and U_{*N} are the dynamic and nondisplacing velocities of the current, respectively, and α, α_1, β_0, β_1, and β_2 are empirical coefficients as determined from experimental and field data.

Equations (2) and (3) describe the convective transport of soil particles by the flow, the suspension and deposition of detritus in a nonuniform flow, and the change in elevation of the bottom over time with consideration of the smoothing effect (transverse diffusion) of the underwater slope in a direction orthogonal to the velocity vector [17]. By analogy with the underwater slope, a diffusion model is also selected for the slope above the water, the angle of which exceeds the


Experiment 13, 0.3-m dam — breach viewed from side

Experiment 6, 0.45-m dam — breach viewed from side

Experiment 5, 0.45-m dam — breach viewed from side

Experiment 6, 0.60-m dam — breach viewed from side

Fig. 3. Comparison of development of breach width as determined by new procedure with experimental data: TC, total concentration; NBC, near-bottom concentration.

angle of limiting stability of the soil. The purpose of a detailed description of the collapse of the slopes (which is quantum in nature [8, 18]) does not, in first approximation, fall within the limits of the problem being resolved, and the transport of soil from an above-water to below-water position while satisfying the law of mass conservation is simulated only approximately.

The initial surface $Z(x, y, 0)$ of the bottom, and the instantaneous-velocity $V(x, y, 0)$, -depth $h(x, y, 0)$, and -concentration $S(x, y, 0)$ fields that correspond to it, are taken as initial conditions for the modeling, and the flow rates of water and detritus, and/or levels of the water surface are assigned to the liquid boundaries. Numerical integration of system of Eqs. (2) and (3) with respect to detritus concentration and bottom elevations, which is carried out simultaneously with solution of the two-dimensional St. Venant equations, makes it possible to model breach development in earthen dams without use of additional hypotheses.

The proposed model was confirmed by experimental data on the scouring of a longitudinal underwater slope [17], propagation of the breach wave above the deformable bottom, and experiments conducted by the NIIÉS [18]. The latter were conducted in a rectangular trough 25.0 m long and 3.48 m high in which a homogeneous earthen dam formed from medium-grain sands was installed. In the numerical experiments, the computational domain was covered by a uniform rectangular grid with 10 × 10-cm cells. Seven alternate computational schemes were utilized for the dam with a height of 0.30, 0.45, and 0.60 m. The width of the breach opening along the crest of the dam for the various alternate computational schemes and experimental data was compared based on results of the calculations (Fig. 3). It can be judged from the plots that the results obtained from the new model compare satisfactorily on the whole with the experimental data. The character of the scouring for the numerical model of the 0.30-m high dam at certain times is shown in Fig. 4. When the breach opens, the slopes of the dam collapse, and soil from the body of the dam is carried away by the flow into the tailrace, and is partially deposited in the shape of an oval; this was observed in the experiments (Fig. 5).

Computer model of pools at Krasnodar hydroproject. Initial data for construction of the model were:

— an electronic 1:200,000 topographic map of the section under consideration;

— 1:25,000 raster topographic maps;

— 1:10,000 pilot maps of the Kuban' River;

— curves of volume versus level of water in Krasnodar Reservoir;

— geometric and technical parameters of the water-retaining structures; and

— the magnitudes of flood flows of various probability and the carrying capacity of the Krasnodar hydroproject at the NBL and FOL.

Digital relief was formed during creation of the computer model of a section of the trough. An electronic topographic map was combined with the vectorized pilot maps of the

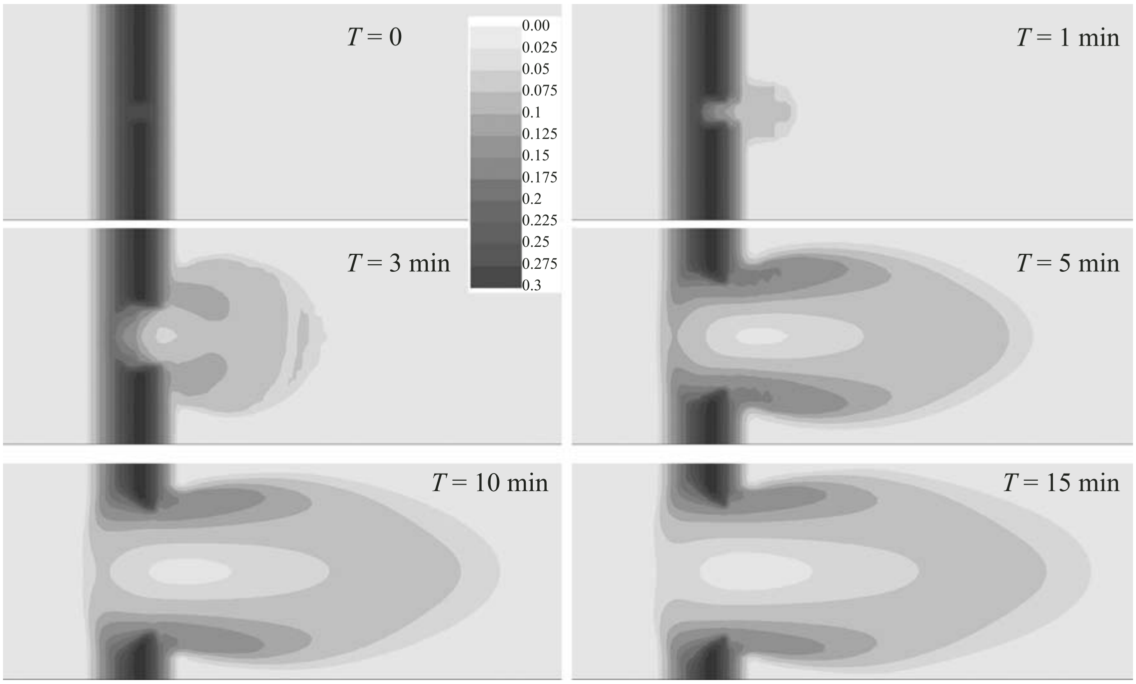


Fig. 4. Plan views of stages of scouring of numerical model of earthen dam 0.3 m high at certain times.

Kuban' River, and raster topographic maps. A single file of the relief in the form of a set of points in Cartesian coordinates *X*, *Y*, *Z* was then formulated. As a result, a digital model of the relief of the water body at the Krasnodar Reservoir, and tailrace of the Krasnodar hydroproject with an overall expanse of approximately 80 km was constructed with consideration given to bottomland sections subject to inundation during high water and breach waves.

A specially developed procedure was employed to construct hybrid computational grids. Ultimately, a grid consisting of approximately 48,000 cells with side lengths of from 50 to 1000 m in the reservoir, and from 40 to 500 m in the tail race was constructed for the 2004 analyses. A similar grid was also used in the 2006 analyses. In the 2008 analyses, the need to thicken the grid extensively (to 10 × 20-m cells) in the section of assumed breach development and in the section of possible overflow of the railroad embankment was manifested to ensure the possibility of detailed modeling of breach development (Fig. 6).

In view of a lack of data on levels and gradient of the water surface at flow rates exceeding 1500 m^3/sec, it was decided to adopt the following roughness coefficients in the Manning formula on the basis of experience with numerous analyses of other entities: $n = 0.06$ in the bottomland, and $n = 0.025$ in the Kuban' River channel and in the reservoir.

Results of analyses performed in 2004 and 2006. Belikov et al. [2] (also see [3]) evaluated the consequences of a breach in the dam within its channel section, and within the bottomland in the section where defects had been observed in the body of the dam. Examination of possible scenarios of hydrodynamic failure indicated that breach development in the channel section of the dam is restricted by the dimensions of the inlet to the outer harbor to which the channel is adjoined. The outer-harbor dikes are composed of large reinforced-concrete blocks, thus preventing significant broadening of the inlet to the outer harbor.

Fig. 5. Shape of breach after termination of experiment.

Outflow waves during breach formation in the channel and bottomland sections of the dam were analyzed at upper-pool levels equal to 33.65 m (NBL) and 35.23 m (FOL). It was ascertained that structures in the outer harbor limit the value of the maximum flow rate quite considerably; in continued analyses, scenarios of breach development in the bottomland section of the dam were examined as most probable (in connection with structural inadequacies of the dam), and as most serious with respect to consequences.

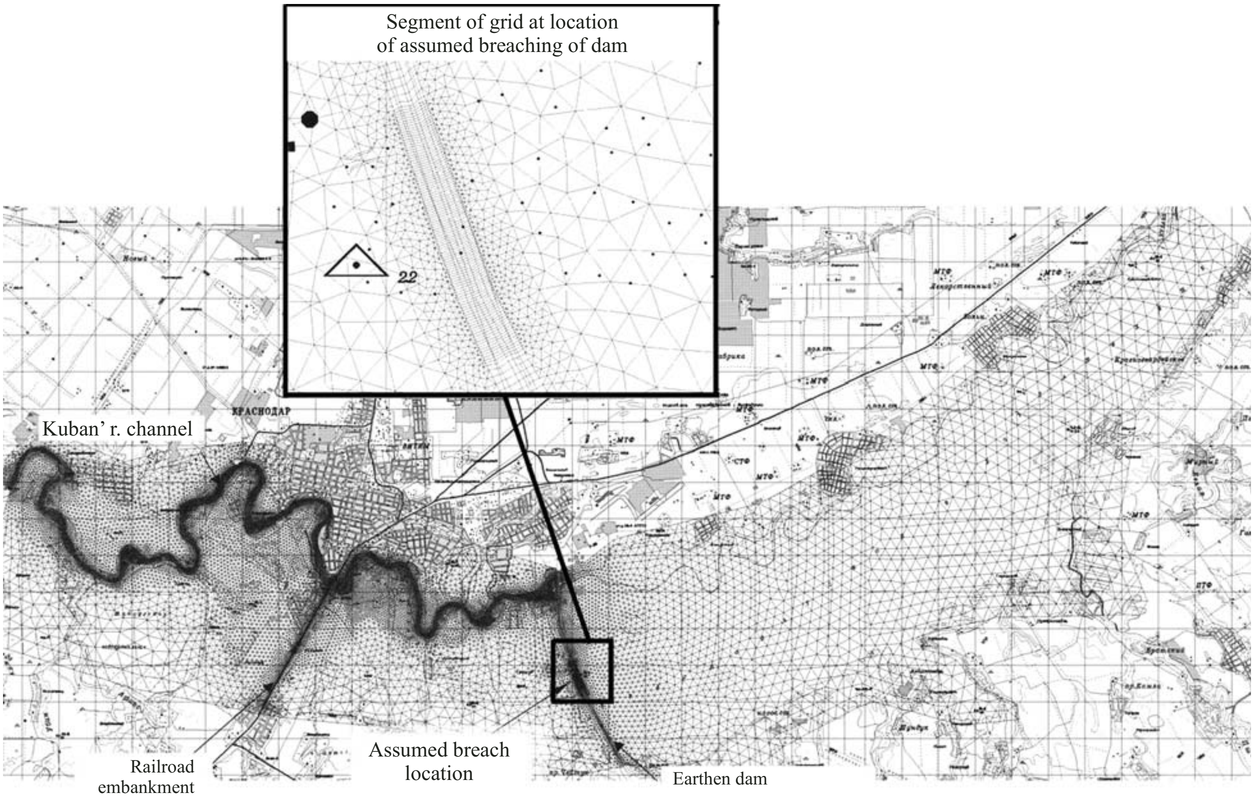


Fig. 6. Hybrid grid in computational domain (52,356 cells).

The following conclusions were drawn on the basis of results derived from the 2004 analyses:

1. Scenarios were developed and analyzed for possible emergency situations associated with breaching of the thrust front at the Krasnodar hydroproject. High levels and large areas of flooding are characteristic of all scenarios. During breach formation in the bottomland section of the dam at the FOL, the maximum flow rate through the breach attains 30,200 m^3/sec, the width of the gap 1100 m, the maximum flood levels above the railroad embankment from 27.0 to 25.5 m, and 22.5 and 22 m, respectively, downstream from the bridge and in the Novaya Adygeya District. The velocities of the current in the channel are negligible in the neighboring zone, while those in the opening beneath the bridge are up 7 m/sec. Flood depths attain 5 – 7 m in the bottomland between the dam retaining the reservoir and the railroad embankment, and 3 – 4 m below the embankment. This indicates a major influence exerted by the railroad embankment on the level of flooding in the locale between it and the dam retaining the reservoir. During a breach at the NBL, the rate of outflow through the breach reaches a maximum value of 23,500 m^3/sec 9 h after initiation of the failure. This flow rate exceeds by 15 times that of a natural 100-year flood.

2. During a breach in the channel section, a breach wave will advance forward along the Kuban' River channel and gradually emerge into the bottomland, and back-up against the railroad embankment, causing flooding in the outskirts of Krasnodar. After 18 h, the wave will reach the Elizavetinskii channel. During a breach in the bottomland section of the dam, the wave propagates along the bottomland at first, and then reaches the channel, a back-up occurs against the railroad embankment, and the outskirts of Krasnodar are flooded. The wave will reach the Elizavetinskii channel after 20 h.

3. Moderate and sever destruction and loss of life are possible only in the vicinity where the breach wave forms in the near-channel section, and also in the left-bank bottomland. Individual districts of Krasnodar will experience primarily a rise in ground-water table at low current velocities; this will not result in catastrophic destruction, but will bring about extensive social and economic losses.

4. The investigations conducted indicated that measures must be developed to protect flood-prone areas of Krasnodar from a breach wave.

In planning solutions to problems associated with safety assurance of the Krasnodar hydroproject, attention has been focused on the undesirability of overflow across the diking of the Kuban' River channel (near-channel embankments) during a significant influx of water to the reservoir; this is to be provided for by limiting drawdown from the reservoir to 1200 and 1500 m^3/sec in the winter and summer, respectively. Such a restriction is possible, if the possibility of accumulating a prisms of water to a level of 36.5 m in the reservoir over and above the level not to exceed 28.0 m is specified. The analyses conducted in 2006 allow for the possibility of evaluating conditions for breaching of the dam

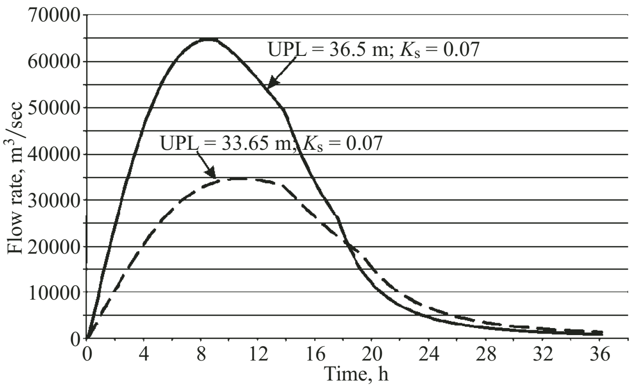


Fig. 7. Hydrographs of flow rates through breach with the Krasnodar Reservoir at various levels: UPL, upper pool level.

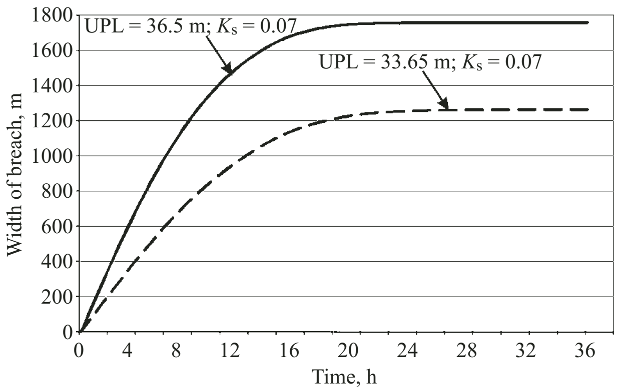


Fig. 8. Width of breach over time with Krasnodar Reservoir at various levels: UPL, upper pool level.

without altering its design when the initial water in the reservoir is raised to 36.5 m.

As a result of these analyses, relationships between flow rates through the breach and the increase in its dimensions over time were determined in the first phase in accordance with the procedure outlined in [8]; these relationships are shown in Figs. 7 and 8. It is apparent from Fig. 7 that the outflow of water attains a maximum value equal to 65,000 m^3/sec nine hours after initiation of breach development, i.e., exceeds by more than two times the flow rate during a breach at the FOL for the existing conditions. The maximum length of the breach is 1770 m.

For combined analysis of the headrace and tailrace on the basis of two-dimensional St. Venant equations (in the second phase), the maximum outflow is reduced to 60,000 m^3/sec; it remains extremely high, however, resulting in catastrophic flooding of the tailrace, whereupon the left-bank bottomland and also the city of Krasnodar are inundated. Maximum flood levels in the near zone (to the railroad embankment) range from 27 to 29 m, resulting in the flooding of a significant area of Krasnodar. These levels are 1.5 – 2 m higher than the flood levels obtained in the 2004 analyses for a breach at the NBL, where the depths of flooding in the outskirts of Krasnodar reach 3 – 5 m. Villages situated on the left bank of the Kuban' River are also inundated. On average, the velocities of the current over the bottomland attains 2 – 3 m/sec; the velocity of the current under the railroad bridge, however, reaches 8 m/sec, resulting in destruction of the bridge crossing.

The 2006 analyses of the conditions under which a dam with a homogeneous body is breached indicates the extreme gravity of these conditions. It is therefore suggested that were the crest level of the dam to be raised, the possibility of its break-through would be eliminated, even when serious causes for its damage exist. For this purpose, it is recommended to stabilize the crest of the dam with a thick reinforced-concrete slab, the strength of which would be ensured, for example, were an aircraft to plummet into the crest by transfer of support to the slopes of the dam.

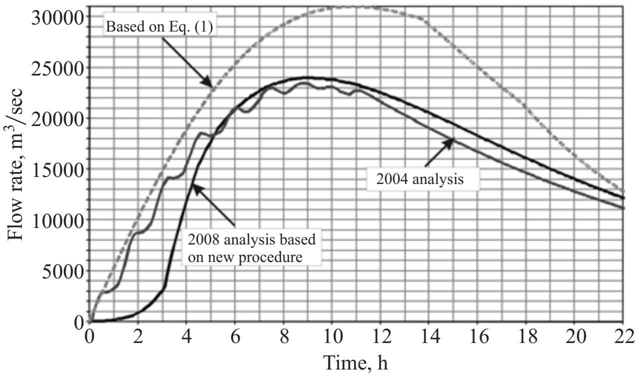


Fig. 9. Hydrographs of flow rate through breach in bottomland section of dam at Krasnodar hydroproject, calculated by various methods.

Results of 2008 analysis. These analyses were conducted in accordance with a new procedure for direct mathematic modeling of breach development [5]. Moreover, the level of the upper pool was assumed equal to the design NBL. The earthen dam retaining the Krasnodar Reservoir and the railroad embankment were deemed prone to scouring over their entire length. The site of the breach in the bottomland section of the dam was defined by an initial funnel with dimensions of 20 × 20 m and depth of 5 m.

Figure 9 shows hydrographs of the outflow through the breach, which were calculated: directly from the procedure outlined in [8] with the flow rate through the breach calculated from the formula for a spillway with a broad threshold; from the modified procedure in which the law governing expansion of the breach was assigned from [8], and the breach wave was analyzed with respect to two-dimensional St. Venant equations; and, in accordance with the new procedure. It is apparent that the analysis based on [8] yields flow rates significantly on the high side. The two other analyses yield very similar maximum outflows; the analysis based on the new procedure, however, takes into account the initial phase of breach development (cutting through the depth), which continues for approximately three hours. During that

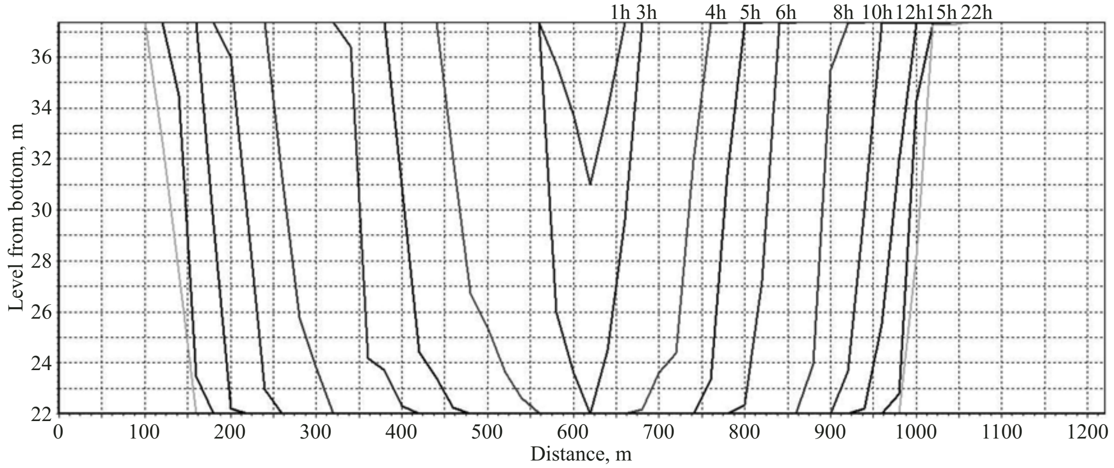


Fig. 10. Longitudinal section through site of breach in dam at Krasnodar hydroproject.

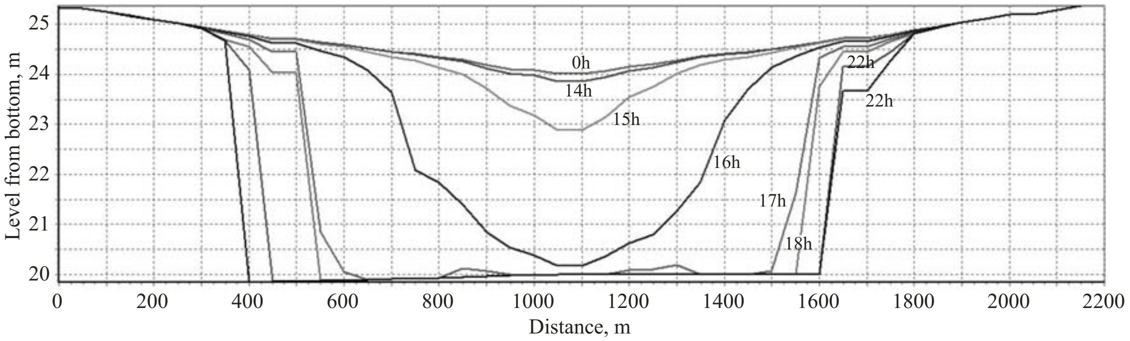


Fig. 11. Section of breach along destroyed railroad bed.

time, it may be possible to warn the populace, thus avoiding loss of life.

Figure 10 shows a section through the breach in dam at the Krasnodar hydroproject. “Cut-in” of the breach to the base of the dam occurs in the first three hours after which the breach expands only in width, the maximum opening attaining 940 m after 16 h. The breach wave, which gradually consumes the left-bank bottomland and rolls down into the channel, develops as the breach opens. A back-up develops against the railroad embankment nine hours after initiation of the breach, while overflow of the railroad takes place as early as four hours in areas where its elevation is depressed. The embankment begins to wash-away over the entire length of the overflow section, and a breach is formed, reaching a maximum width of 1.5 km. Figure 11 shows the longitudinal section of the destroyed railroad.

Consideration of the scouring of the railroad embankment yields a more realistic scenario of breach-wave propagation in the tailrace. This leads to a certain reduction in the maximum levels and depths of flooding above the railroad, but to an increase in maximum depths of flooding in the bottomland downstream. Figure 12 shows the dynamics of the breach wave, as calculated in accordance with the new procedure. Results of the analyses are in rather good agreement with those previously obtained, but do not make it possible to account for such effects as the initial stage of breach development and scouring of the railroad embankment. Consideration of the latter situation is essential for hydroprojects in the tailraces of which bridge crossings that partition bottomland are situated.

CONCLUSIONS

1. Various schemes of analysis of a breach wave through the thrust front of the Krasnodar hydroproject, which were conducted in accordance with modern approved procedures, indicated that for the scenarios of hydrodynamic failure considered, a breach forms in the earthen left-bank dam with a gap ranging from 940 to 1100 m wide, a maximum flow rate of from 23,500 to 30,200 m^3/sec through the breach, and maximum flood levels of from 27.0 to 25.5 m above the railroad embankment, and 22.5 and 22 m downstream from the bridge and in the Novaya Adygeya District, respectively, under the existing conditions.

2. The parameters of an outflow wave through a breach will ultimately depend on the initial water level in the reservoir. The designation of 36.5 m for the maximum level of the upper pool weighs heavily on the consequences of the pas-

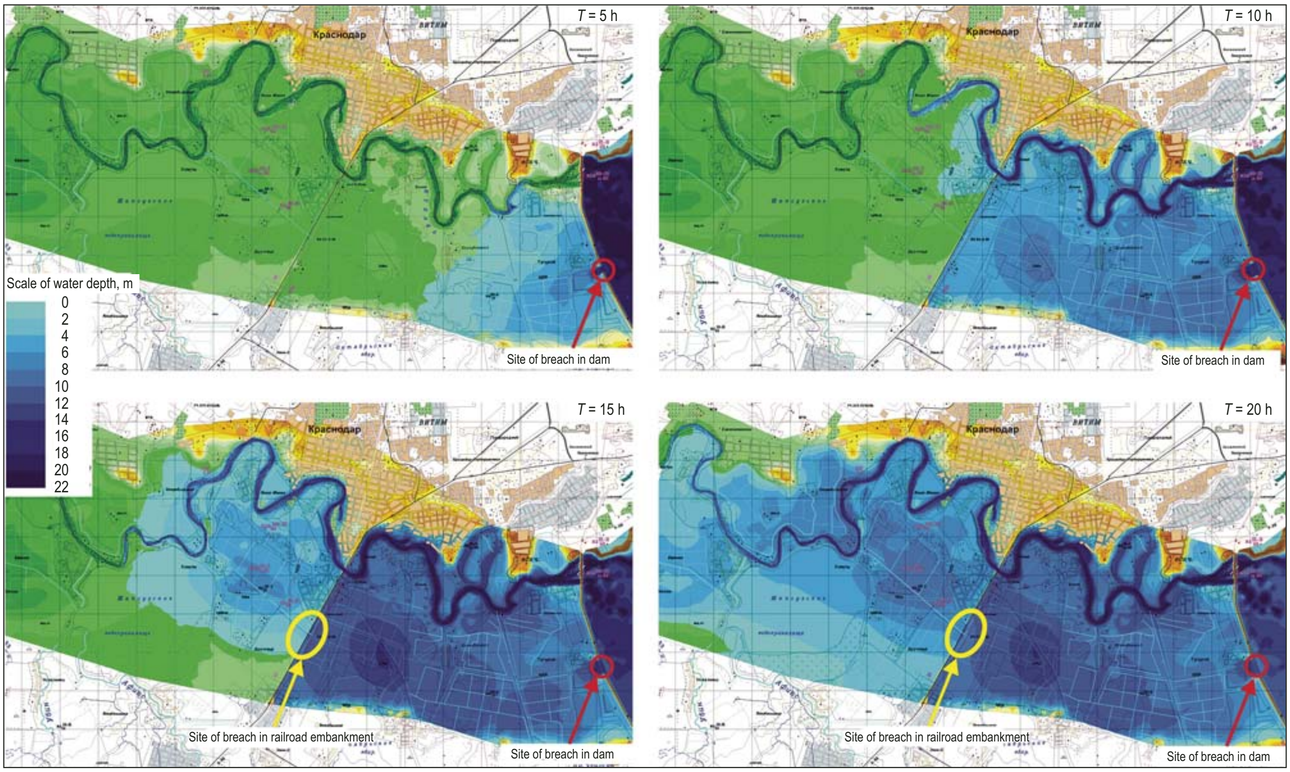


Fig. 12. Depths of flooding in tailrace of Krasnodar hydroproject at various times.

sage of the outflowing high water. Moreover, the size of the breach is increased to 1770 m, and the maximum outflow rate reaches 60,000 m^3/sec. Maximum flood levels in the near zone (up to the railroad embankment) range from 27 to 29 m, resulting in inundation of a large area of Krasnodar. These levels are 1.5 – 2 m higher than those of the flooding obtained in the 2004 analyses for a breach at the NBL, while the depths of flooding in the vicinity of Krasnodar reach 3 – 5 m. Villages situated on the left bank of the Kuban’ River are also inundated.

3. In view of the extreme gravity of breach conditions for the dam at elevated upper-pool levels, it is proposed to eliminate the possibility that the dam will be breached, even when serious causes of its damage exist, by raising the crest. For this purpose, it is recommended to stabilize the crest of the dam with a large reinforced-concrete slab, the strength of which is ensured in the event of a plummeting aircraft with transfer of support to the slopes of the dam.

4. The probability that the spans of the railroad bridge across the Kuban’ River will collapse, and the embankment in the bottomland broken-through is high owing to the formation of a discontinuous wave. In this connection, it is expedient, in our opinion, to examine the question concerning the installation of a trestle for the railroad track, thereby considerably reducing the depths of flooding in Krasnodar.

5. The correctness of the methods developed by the JSC NIIÉS for analysis of breach development in dams formed from noncohesive materials is confirmed by data gleaned from similar experiments. Moreover, the advantage of the method of direct numerical modeling of breach development (2, 3) over empirical relationship (1), including the possibility of evaluating the outflow from the breach in the initial stage of its formation, is noted.

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