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TECHNICAL EVALUATION OF THE SAFETY OF HYDROTECHNICAL STRUCTURES--ETC(U)
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V.S. Kuznetsov

May 1978

CORPS OF ENGINEERS, U.S. ARMY
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

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At present, an extensive national program of hydrotechnical (Hydraulic) construction is underway in the Soviet Union. This program is associated with the development of the energy base of the country, waterway management, irrigation and transport. The industrial resources of regions in the Far North, Siberia and the Far East are being assimilated. As in the entire world, an important place in hydrotechnical construction in the USSR is taken by earthen

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A TECHNICAL EVALUATION OF THE SAFETY OF HYDROTECHNICAL (HYDRAULIC) STRUCTURES

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The Ministry of Energy and Electrification of the USSR

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At present, an extensive national program of hydrotechnical (hydraulic) construction is underway in the Soviet Union. This program is associated with the development of the energy base of the country, waterway management, irrigation and transport. The industrial resources of regions in the Far North, Siberia and the Far East are being assimilated. As in the entire world, an important place in hydrotechnical construction in the USSR is taken by earthen dams. The modern conditions of building hydrotechnical structures are becoming more and more complicated, at the same time as the scale of structures is vigorously growing. Today, a veritable series of dams over 200 m high are being built in the USSR: the Chirkey and Ingursk arched dams; the Sayano-Shchushensk arch-gravitational dam; the Nurek earth dam, which is 320 m high. Dams of approximately the same dimensions are in the design stage. The construction of facilities must be more and more often carried out under complex engineering-geological conditions, in regions with a high seismic activity, a severe climate and permafrost. In this regard, the role and importance of field control of the work and the safety of modern dams significantly increase. In addition to monitoring functions, field investigations are called upon to solve many problems of scientific and practical significance. This report examines certain aspects of monitoring the work and condition of earthen dams, including those built in northern regions.

The composition of the control field observations of earthen dams is determined to a great extent both by the design features and class of the structure and by the characteristics of its foundation, as well as the climatic conditions of the construction site. However, according to the normative documents in force in the USSR (1, 2), all earthen dams at a high capital investment level and all dams of a lower investment level but higher than 25 m, as well as dams built under complicated geological conditions must satisfy the following field observations:

a) geotechnical control of the quality of soils placed in the body of the dam, the dam's antifiltration components and drainage; b) control over settlement and displacement of gravel and berms; c) control over filtration in the body of the dam, the dam foundation and the shore abutments; d) control over the stress state of the dam body and its antifiltration components (the core, screen, and diaphragm); e) control over the consolidation process of the soil in water pressurized dam components. A component part of the control observations of earthen dams is also visual observations conducted both during construction and in the operating period. In addition to this, observations are made of the temperature regime of the dam body, the dam foundation and shore abutments at dams erected in regions with a severe climate and permafrost, while in regions with high tectonic activity seismic observations are made. The field observations and investigations conducted on earthen dams, as a rule, are combined and are carried out according to a special program and the appropriate requirements of the project, which in fact establish the composition, quantity and types of monitoring-measuring instruments and devices. The placement of instruments in the dam body, the dam foundation, the dam crest and in the berms is carried out in the most important or characteristic control cross-sections of the structure's segments.

Geotechnical control is maintained during the construction of all types of earthen dams. Its purpose is to determine the actual physico-mechanical characteristics of the soil in the structure, to establish their degree of correspondence to project requirements, and also to identify deficiencies in the technology of laying and packing the earth and in construction on the whole. The results of geotechnical control are processed in the form of digital tables of characteristics, graphs, distribution diagrams and curves of their value conformance. These serve to evaluate the quality of the erected structure and its correspondence to the project and reliability requirements. In case of unfavorable operation of the dam, the results of the geotechnical control are used to estimate the degree of danger of the structure's condition (in the test calculations) and serve to develop measures which improve its reliability and lifetime. It is felt that the structure corresponds to reliability requirements with respect to soil stability characteristics if the characteristics correspond to the values used in the project or exceed these values.

Filtration control holds the main place in the combination of field observations of earthen dams. This control establishes the following: the position of the depression curve in the dam body; values of the filtration flow rates of flows passing through the structure and foundation; values and the distribution of the hydrodynamic head and the hydraulic gradients in dam components and the foundation; the presence or absence of suffosion phenomena; indices of the effectiveness of operation of antifiltration components (the core, screen, diaphragm, cement screen, etc.) and drainage, etc. Particular significance in maintaining control over the filtration regime of earthen dams is given over to studying the character and analyzing the change of the monitored parameters in time by means of accumulating data of observations and comparing their values. the problem of filtration control of earthen dams under field conditions has met significant success recently in the USSR. Besides improving well known methods of control, a combined method is undergoing greater and greater development. This combined method is based on the joint use of principally different methods of determining the parameters of filtration and of combining field observations with theoretical and laboratory analysis. A comparatively new method of investigating filtration with the use of thermometry (3) has appeared. This method has been successfully tested at a number of structures and has proven to be very effective, especially in cases when it is necessary to establish concentrated foci of filtration in a dam or in a foundation.

The primary control-measuring apparatus for monitoring filtration are the following: unpressurized and pressurized piezometers, wire membranous sensors - piezodynamometers, metered spillways, radiometric apparatus (during work with isotopes), telethermometers (in the thermometric method), etc. The designation of the composition, quantity of apparatus and placement of apparatus in the dam are determined on the basis of design features, the structure, the configuration of the subterranean contour and the hydrogeological characteristics of the foundation. The following should be obtained as the result of conducting control observations of filtration: pressure values at monitored points in the filtration region; the total filtration flow rate and flows with respect to individual sectors and concentrated sources; filtration rates; pressure gradients; the position of the depression curve, etc.

On the basis of analyzing the indicated indices, and based as well on the results of other observations (settlement, cracking, etc.), carried out with consideration of the character of change of the indices in time, one draws a general conclusion about the function of the structure in a filtration regard and estimates the degree of its reliability according to the given indices.

The task of control observations of deformations of earthen dams includes determining settlement of the crest, slopes and foundation (when one is dealing with compressible soils); the measurement of horizontal displacements; a study of local deformations of slopes, the crest and the foundation; observing the formation and opening of cracks. It is obligatory to observe settlement for all dams of the higher categories of capital investment; it is also obligatory to make observations of planned displacements of points located on the crest, slopes and in the body of the dam.

Methods of geometrical and hydrostatic levelling are employed for observing settlement; planned displacements are measured by siting methods according to special visual signs, geometrical triangulation, stereophotogrammetric methods, with the aid of plumb bobs located in special shafts, and with the aid of inclinometers using the "wire tension" method. The problem of monitoring the process of crack formations is presently a complicated one in earthen dams. At present, in the USSR, extensometers or wire indicators are used to detect cracks. These are similar to the carck detectors used in the United States. Instrumental observations over crack formation are obligatorily supplemented by systematic visual inspections of the structures, whose highest frequency falls toward the end of the construction period and the beginning of the reservoir filling period. The opening of detected cracks is monitored by observations made according to the simplest kinds of marks placed along both sides near cracks.

Appropriate graphs of the change of measured values in time are plotted according to the results of control observations of settlement and displacement. Stress-strain diagrams of settlement and displacements of the structure as a whole are also drawn, i.e., those pertaining to the entire length and height of the dam.

The results of observing deformations are analyzed in combination with the results of other kinds of observations and are also used to evaluate the reliability of the structure. Observations terminate only after the settlement and displacement of the dam are totally finished.

Observations of the stress state of earthen dams determine the values and character of distribution of stress components in the antifiltration components, the pressure prisms and the structural foundation. Observations are made for the purpose of estimating the stability and strength of the dam, to estimate the degree of completion of the earth consolidation process, and to determine its pressure on the surface of the adjacent concrete structures. Stresses in the soil are determined with the aid of rigid or elastic soil dynamometers which are laid in the dam itself during construction. Normal stresses in three directions are subject to measurement: horizontal, vertical, and at an angle of 45° to the horizontal. In dams with earthen cores it is considered necessary to measure the vertical stresses in peripheral zones of the core in contact with the pressure prisms. These measurements are made in combination with measurements of relative deformations of cores and pressure prisms. When the dam has a rigid screen or diaphragm, the latter are equipped with extensometers to monitor their stress state.

In addition to all of the observations which were discussed above, earthen dams erected in permafrost, whether of the frozen or melted type, have as one of the primary aspects of monitoring their reliability the problem of controlling and regulating the thermal regime of the structures and structural foundations. During construction, the foundation, which includes the shore abutments and the body of the dam, are equipped with an extensive system of extensometers; systematic observations of the thermal regime of the structure and foundation are organized. These continue into the operating period. The results of the thermal observations which can be presented in the form of detailed charts of isotherms are used when predicting and analyzing the filtration regime and deformations of the structure.

Visual observations are made on all types of earthen dams regardless of their height and construction site. The purpose of these observations is to identify defects of the dam, whose possibility of appearance cannot be foreseen in advance. Visual observations identify the following: visible deformations of slopes and the dam crest; damages to reinforcing structures and the water draining channels; various kinds of exit points of filtration water, ice, erosion channels, etc. The results of visual observations are entered in special logs; defective locations are fixed on diagrams, drawings and photographs. In points where defects have been identified or where unforeseen phenomena have been found, necessary instrument observations are organized.

In addition to the control observations conducted on earthen dams and mentioned above, other special observations and investigations are carried out according to need. The results of these are also taken into account when evaluating the function and condition of structures.

It seemed expedient to the author to dwell briefly below on the approach to evaluating the safety of earthen dams. At present, both in the USSR and in other countries (judging by publications), the question of developing strictly determined criteria which define the work and condition of different types of hydrotechnical structures remains unanswered, with respect to those that could be used uniformly to estimate structural safety. Therefore, the evaluation of the safety of earthen dams is presently made according to the totality of a veritable number of monitored parameters, among which, depending upon structural characteristics, one or several primary ones are chosen which determine structural reliability to a greater extent than others. The values of the controlled parameters determined in the individual most stressed points or cross-sections are integrally extrapolated to the entire structure. The results of current control are compiled with certain values of measured indices which are assumed to be the permissible ones. Several of the permissible indices are regulated by normative documents while others are regulated by the requirements of their project and still others are determined by their developmental dynamics in time.

Practically speaking, the control of safety of earthen dams begins already in the initial period of their construction. During preparation of the foundation beneath the dam, and during its construction, one pays primary attention to studying and monitoring satisfaction of the values of physico-mechanical characteristics of soils in the foundation, the body of the dam, in its antifiltration components, back filters and transition zones as guaranteeing values assigned by the project. The density of soils, their granulometric composition, permeability to water, resistance to deformation, deformativity during compression, etc. (Figure 1) are controlled. Tests are carried out under conditions which correspond to the actual structure. If it becomes clear during control that the physical values of the characteristic soils cannot be ensured within the framework of project specifications because of objective factors, then one quickly makes the necessary changes in the project which are backed-up by verification calculations.

In the construction period itself, systematic control is also maintained over deformations and displacements of the dam. An analysis of studying the given types of settlement enables one to draw a conclusion concerning the homogeneous nature of the dam with respect to density and to identify existing defective areas. It is considered that the normal condition of operation of the structure corresponds to settlement levels which increase proportional to the increase in loads (the height of the dam), but which diminish with the course of time after their stabilization (Figure 2). The types of settlement in different dam cross-sections should be identical in nature. The observation of different types of settlement along the length of the dam indicates its nonuniform packing and the possibility of cross cracks appearing in the body of the dam which are hazardous with respect to filtration. This circumstance requires establishing focussed attention on the indicated parts of the dam. The condition of the dam can be considered satisfactory (according to this parameter) if the course of settlement is uniform throughout the dam. If the settlement course is unexpectedly disrupted, then a combined working analysis is carried out to identify the causes of this disruption: the change in the filtration flow rate, the possibility of the appearance or presence of suffosion processes, the behavior of slopes, the presence of "buried" frozen ground, etc. in the dam are taken into account.

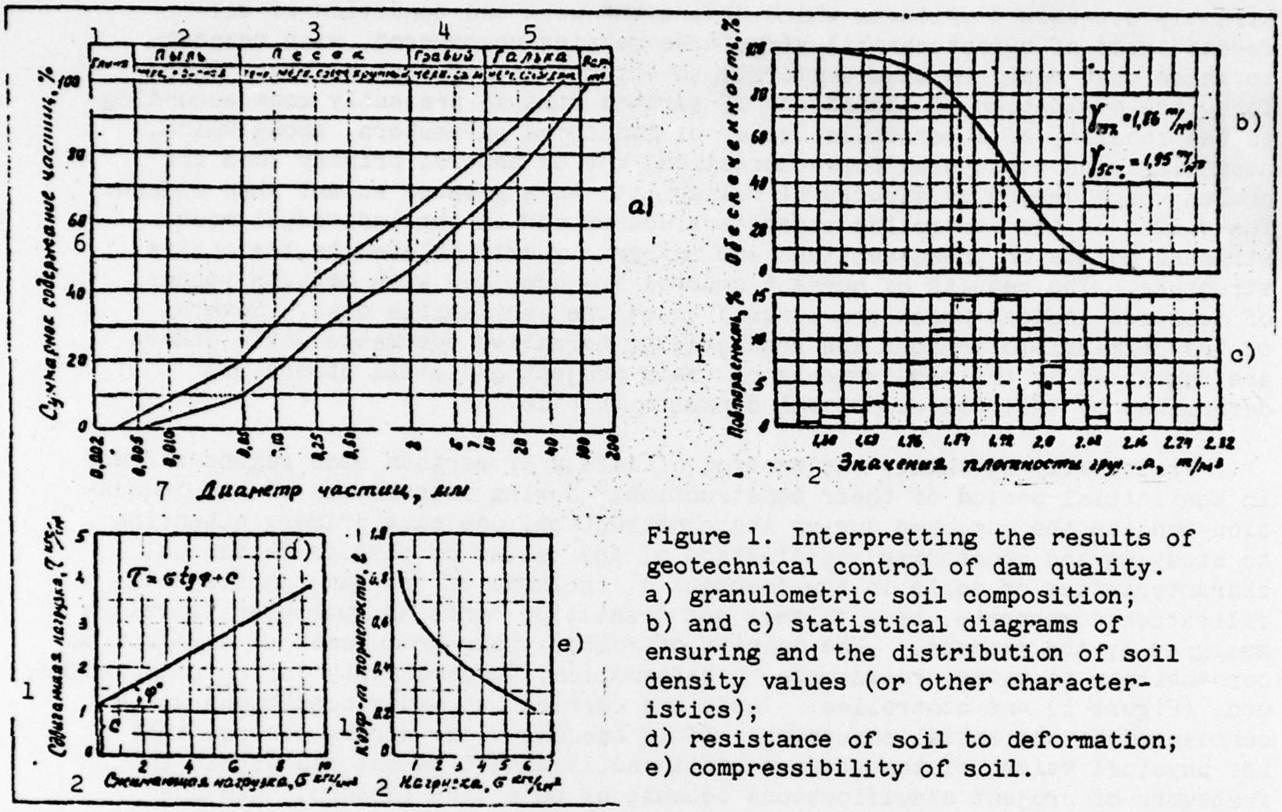

Figure 1. Interpretting the results of geotechnical control of dam quality.
a) granulometric soil composition;
b) and c) statistical diagrams of ensuring and the distribution of soil density values (or other characteristics);
d) resistance of soil to deformation;
e) compressibility of soil.

Key:

left-hand side of figure

1 - clay
2 - dust
3 - sand
4 - gravel
5 - crushed rock

6 - total particular content, %
7 - particulate diameter, mm

upper right-hand side of figure:

1 - repetition, %, guarantee level, %
2 - density values of soil, a, m/m^3

lower-left-hand side of figure:

1 - stress load
2 - compressing load
1 - coefficient of porosity, ε
2 - load

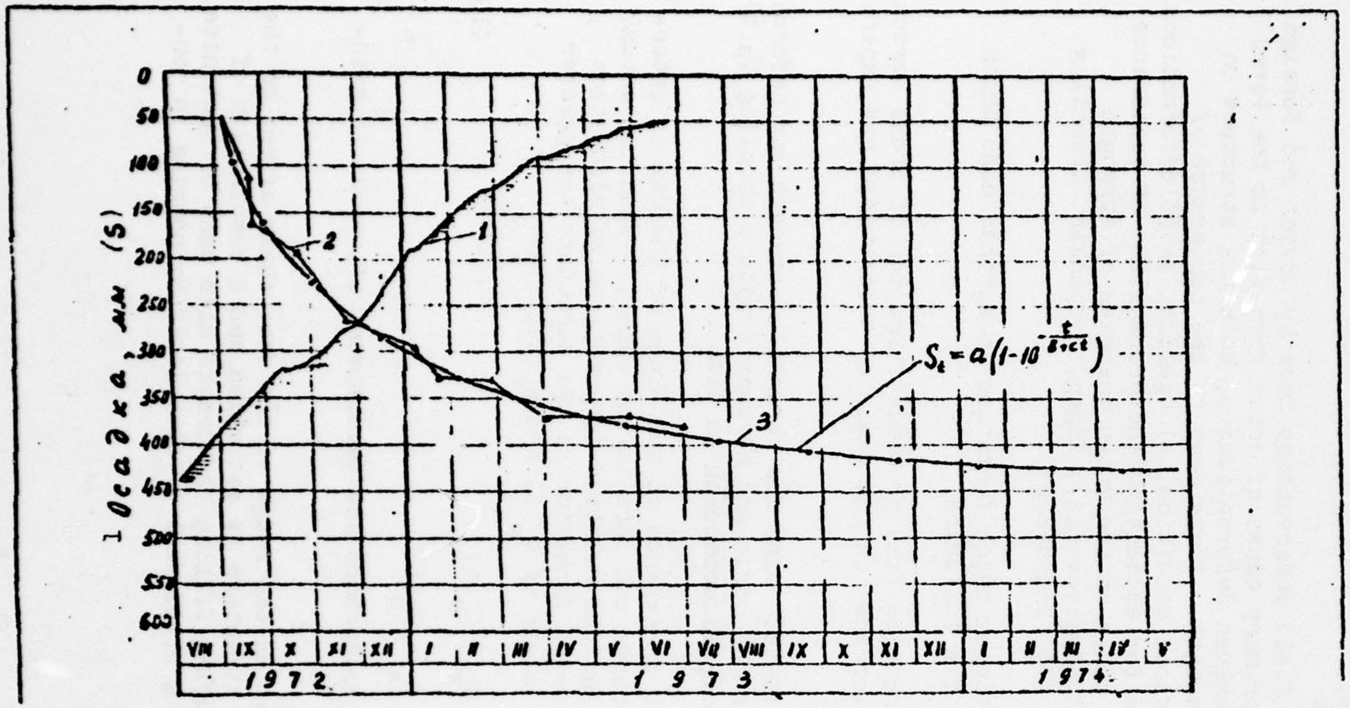

Figure 2. Control graph of the course of dam settlement.
1 - graph of backfilling; 2 - full-scale settlement curve;
3 - predicted settlement curve.

Key:

1 - settlement, mm (s)

In order to predict dam settlement in the future, the following empirical relationship will be frequently used: $S_t = a(1 - 10^{-\frac{t}{b+ct}})$, where S_t is dam settlement at a moment of time t; a, b, c - coefficients calculated on the basis of results of the initial values of measured settlement at different moments of time t_i. Final settlement ($t = \infty$) can be calculated according to the formula: $S_\infty = a(1 - 10^{-\frac{1}{c}})$.

Analysis of the results of field observations made by Soviet and foreign specialists has shown that the primary cause of crack formation in the cores and screens of earthen dams is uneven deformations of both the structure on the whole and its separate components. These lead to the appearance of weakened zones, areas of a threshold condition, elongation, shift deformations, etc. Sufficiently many criteria for estimating the probability of appearance of cracks are known. These are based on the known theories of strength (Teitelbaum, Mel'nik, Savvin (7), Svatyev (13), Kogan, Ovsyankin, Chernilov (6), Dolezhalova (4), Vasil'yev (5), and others).

The general scheme of monitoring crack formation in earthen dams which is used in the USSR consists in the following:

a) zones of a threshold condition (the probable formation of cross scracks on the ridge of the dam) are determined on the basis of theoretical and experimental investigations;

b) special tests are used to determine the threshold strength and deformative characteristics of soils in the cores and screens (rupture coupling $C_p(t)$ and maximum relative elongation $E_p(t)$ depending on time);

c) the probability of crack appearance on the ridge of the dam is determined. It is felt that ridge cracks can form in the case (7) when the actual maximum elongating stresses G_x and the relative deformations of elongation E_x by the time of hypothetical crack formation in the structure are greater than the corresponding maximum values of $C_p(t)$ and $E_p(t)$, i.e.,

$$G_x > C_p(t) \quad (1)$$

$$E_x > E_p(t)$$

d) field control over the appearance and development of cracks is maintained.

In case cross cracks appear on the ridge of the dam, their effect on the operation and condition of the structure is estimated and a combination of repair measures is taken, including filling the cracks with sand or bentonite, cross-blocking the cracks with a blind wall or clay lock, by pouring in concrete, etc.

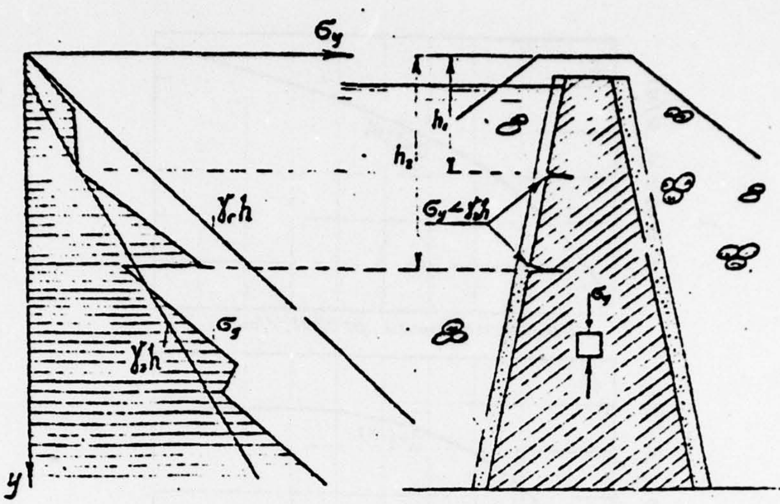

Figure 3. A diagram of the appearance of internal fault cracks in the core of a dam.

Crack formation within the dam (in zones of coupling of the core with filters and the transition zones is monitored both by piezometric observations and measurements of the layer and overall vertical settlements of the supporting prisms and core as well as by measurements of vertical stresses in contact zones of the core. The probability of formation of internal cracks in the core of the dam is estimated with respect to the magnitudes of settlement of the core and prisms and the degree of lowering (if such exists) of the vertical compressing stresses in the core opposite $\gamma_r h$. It is considered hazardous with respect to crack formation if the compressing stresses in the core comprise a value equal to (or less than) (Figure 3) water pressure at the corresponding point, i.e., if $G_y < \gamma_r h$. One of the radical measures of preventing hazardous consequences of crack formation in earthen dams is the fact that within the USSR the design of transition zones and filters is carried out in most cases with observance of the requirements which ensure "automatic healing" of filtering cracks if such cracks form (8, 9). Moreover, requirements of equality of deformative properties are levied on the earthen materials of supporting prisms and antifiltration components in the most important cases. Thanks to this, the manifestation of the arch effect in the core is prevented because of this during settlement of the dam.

In view of the fact that the development of horizontal displacements of earthen dams is chiefly associated with their being affected by hydrostatic pressure, displacements should significantly diminish after the build-up of water level in the reservoir. Monitoring observations record this process. If it is established that the displacements practically totally diminish following reservoir filling, then one has grounds to consider the condition of the dam to be normal.

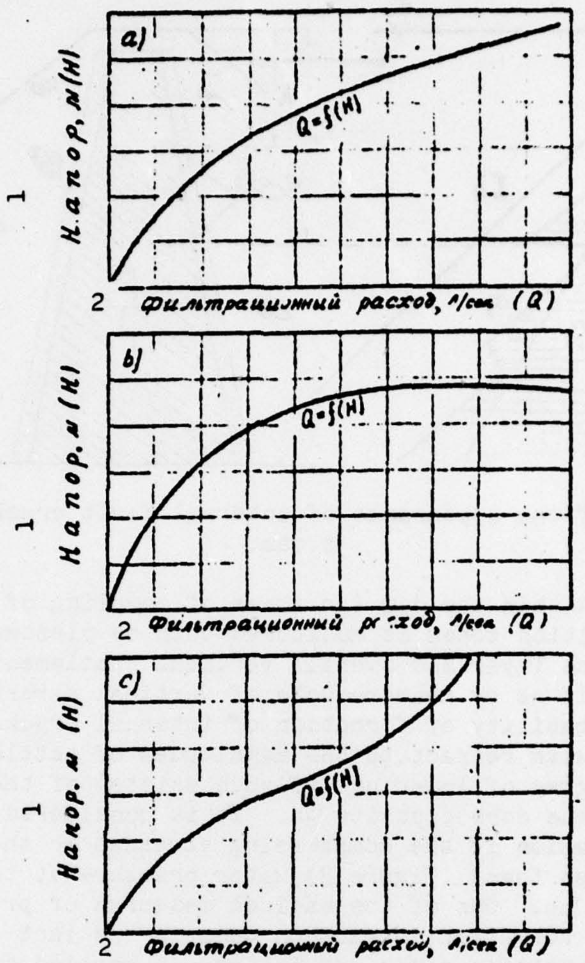

Figure 4. Control graphs of filtration flow rates
a) normal filtration regime;
b) increased filtration (suffosion, cracks);
c) reduced filtration ("colmatage").

Key:

1 - pressure, m (H)
2 - filtration flow rate, l/sec (Q)

With a continuing process, a combined analysis is made of the stability of slopes taking into account the actual strength characteristics of the soil, the position of the depression curve, the degree of consolidation of the soil in the core and the foundation, if it (they) consist of weak, argillaceous soils, as well as other indicators.

The filtration regime of earthen dams and their foundations is monitored according to several parameters: the filtration flow rate, piezometric pressure heads, the position of the depression curve, the pressure gradients, and suffosion phenomena. The homogeneity of the body of the dam, the operation of antifiltration devices and drains are evaluated according to the character and position of the depression curve. The functioning of the dam is evaluated as normal if the depression curve has a sharp drop after the antifiltration components (the core, the screen, and the diaphragm), does not extend to the surface of the low water slope, and is buried beyond it at a distance greater than the depth of soil freezing.

A special place in the evaluation of the filtration resistance of earthen dams is given over to field monitoring measurements of filtration flow rates. According to the data of these measurements (according to specific flow rates per one running meter), one identifies weakened stretches of the dam with respect to filtration and records phenomena of suffosion or colmatage. The results of the flow rate measurements according to separate stretches and the structure as a whole are presented in the form of control graphs $Q = f(t)$ and $Q = f(H)$, (Figure 4) where t is time and H is pressure. It is known that during the normal operation of the dam the filtration flow rate strictly depends upon the pressure affecting the structure. An increase in the filtration flow rate with an unknown pressure head acting on the dam is evaluated as a sign of the manifestation of suffosion; if the flow rate itself diminishes, one should assume that a colmatation process exists in the structure which reduces the structure's permeability to water. The condition of an earthen dam cannot be considered safe if the condition of ensuring the filtration resistance of the earth in the body and foundation of the dam is not satisfied. A check of the casual (random) strength of the soil making up the dam and the foundation was carried out according to the controlling gradient (T_k) method according to Professor R. R. Chugayev (10). The necessary condition of ensuring the filtration strength of the dam is considered to be the fact that at a certain average value of the actual operative pressure gradients both for the entire filtration region and for its separate components, values do not exceed the permissible values of the controlling gradients for the given types of soils $(T_k)g$, i.e., with the condition that

$$\mathcal{J}_k \leq (\mathcal{J}_k)_g \quad (2)$$

The permissible controlling pressure gradients $(T_k)g$ are governed in the USSR by the normative documents (1). Values ranging from 0.18 (fine sand) to 0.70 (dense clay) have been defined in the USSR for soils of the foundation of a dam classified in the higher capital significance category $(T_k)g$. These range from 0.45 (fine sand) to 1.5 (argillaceous concrete and clay) for the bodies of earthen dams.

A check of the normal (calculated on the basis of the laws of mechanics using previously known boundary and initial conditions) filtration-suffosion strength of dam components (the front part of the dam spillway, the core, the reinforcements, grains, etc.) is made according to the following condition (11):

$$T_{\phi n} \leq T_{cr.} \frac{1}{k_3}, \text{ where} \quad (3)$$

$T_{\phi n}$ is the pressure gradient in the region of the examined dam component or the dam foundation; T_{cr} is the critical pressure gradient at which suffosion of the soil, contact erosion or local overflow occur; k_z is the reserve coefficient.

Having the results of field observations of the filtration regime as well as specific quantitative values of the characteristics of soils in the dam components, one determines (according to the calculation formulas) the critical pressure gradients (T_{cr}) at the points of interest to us. After this procedure, one checks the strength condition (3).

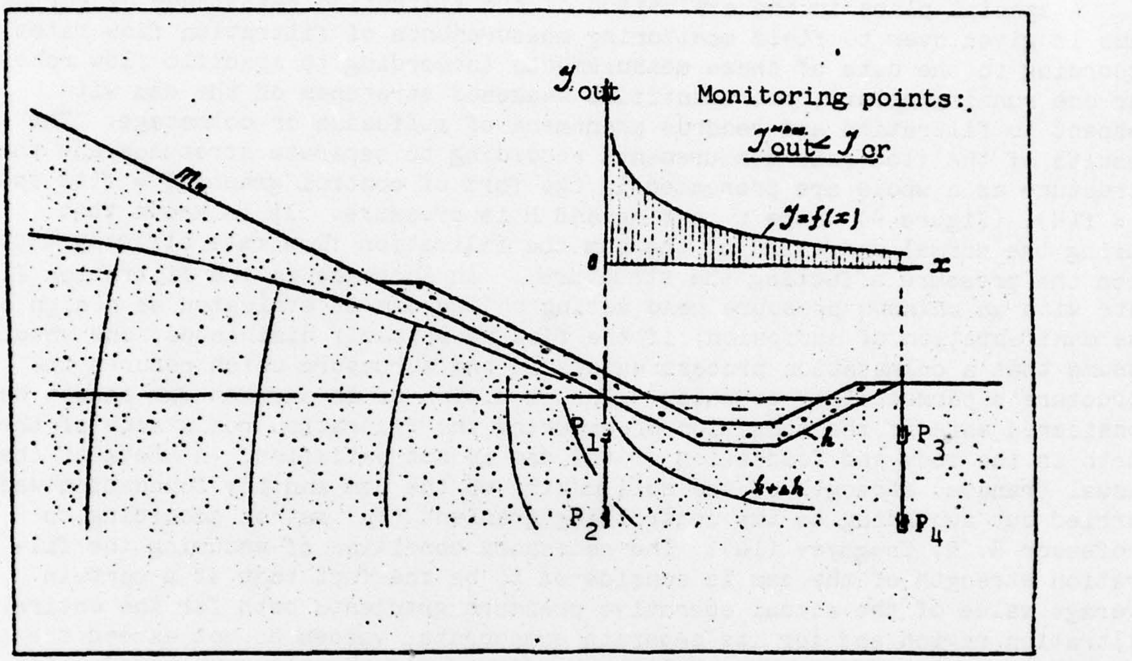

Figure 5. Monitoring the filtration pressure of foundation soil. P_1, P_2, P_3, P_4 are the piezometric monitoring points.

In those cases when condition (3) is not satisfied, the necessary engineering-design measures are carried out to strengthen the structure or the separate structural components in order to ensure their reliability and long-lived operation. The structure is considered to meet the requirement of reliability according to filtration-suffosion strength if following satisfaction of the indicated measures the condition (3) is satisfied (Figure 5).

In cases when foci of concentrated filtration appear in the dam or the foundation, the degree of their danger for the structure is estimated by whether the filtration is accompanied by suffosion; by the probability of appearance of suffosion at this point (established on the spot according to measurements of the pressure yield gradients); by the total tendency of development of filtration foci. If suffosion is absent, its probability of appearance is small and the filtration is stable in time, then local filtration foci can be considered safe. However, in both this case and upon detecting even slight suffosion, efficient measures are taken to ensure constant control of filtration and to prevent its development: the area of filtration water escape is clear; the area is loaded with a layer of sand and gravel selected according to the back filter principle; systematic observations are organized over the flow rate and turbidity; careful measurements are made of the filtering water temperature and the temperature of the water in the reservoir for the purpose of identifying the location of the inlet stretch of filtration and for taking effective measures to eliminate it, or in order to be certain that filtration is occurring because of ground water filtration.

The combination of parameters for estimating the reliability of earthen dams also includes data which characterize the effectiveness of the cement screen in the foundation (for example, when erecting dams on a rock slope).

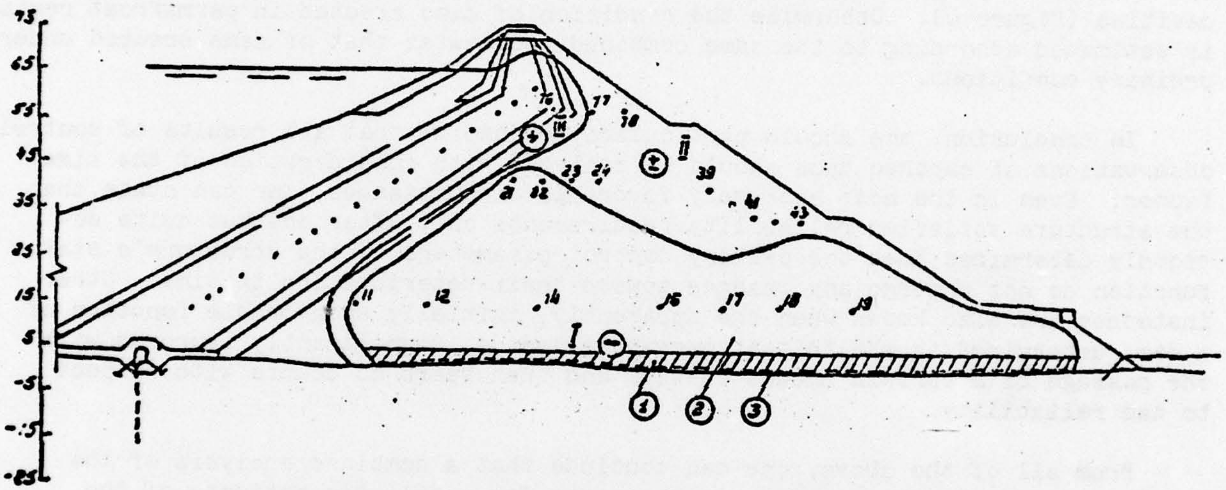

Figure 6. Thermal control of a dam on permafrost. I - zone of negative temperatures; II - zone of alternating freezing and thawing; III - melt zone; 1 - ice formation zone.

One estimates the effectiveness of the cement screen in the foundation of the dam based on the magnitude of the pressure loss in it and specific water absorption in the cement zone. According to the standards (12), the following requirements are made on the cement screen: a) specific water absorption in the zone of the cement screen at pressure heads higher than 30 m should not exceed 0.01 - 0.03 l/sec; b) pressure losses on the screen should range from 30 to 60% with a strongly cracked stone base and up to 50 - 80% with a stone base having slight permeability to water. The function of the screen is considered to be normal if its initial parameters do not change for the worse in time.

Control over the development of threshold pressure and the process of soil consolidation is important in wash dams as well as the clay cores of dams. The former are factors responsible for the value of internal pressure on the pressure prisms of the dam and, to a significant degree, for the stability of the structure. One cannot fail to reckon with the magnitude of excessive threshold pressure if its value exceeds 25% of the hydrostatic pressure.

Experience shows that the chief causes of disruption of the normal function of earthen dams constructed on permafrost are crack formation and the associated concentrated filtration due to settlement of the permafrost when it thaws. Melting of the ice layers in the foundation and the shore abutments leads to the formation of cavities which are hazardous with respect to filtration. Control observations of the thermal regime of the foundation ensure timely accomplishment of injection operations and the prevention of settlement phenomena proportional to foundation thawing. Upon evaluating the condition of permafrost-type dams, one primarily directs attention to the condition of the internal frozen zone, which plays the role of an antifiltration component and significantly ensures the reliability of the structure. When estimating stability of the lower-water slope, one takes into account the nature of the process of ice formation in earthen cavities (Figure 6). Otherwise the condition of dams erected in permafrost regions is estimated according to the same combined indices as that of dams erected under ordinary conditions.

In conclusion, one should particularly emphasize that all results of control observations of earthen dams should be analyzed with consideration of the time factor. Even in the most extremely favorable circumstances, one can state that the structure satisfies reliability requirements only after one has quite obviously determined that the primary control parameters of the structure's static function do not undergo any changes toward their deterioration in time. Other instances are also known when the apparently, initially unfavorable function of a dam, determined in the initial operating period, significantly improves with the passage of a certain amount of time and then bears no doubts with respect to dam reliability.

From all of the above, one can conclude that a combined analysis of the results of control observations is necessary for a reliable estimate of the function and safety of earthen dams. The isolated evaluation of separate indices of the static function of a structure can result in an erroneous conclusion concerning the reliability of the structure. It is necessary subsequently to continue work to devise criteria for evaluating the safety of earthen dams on an engineering and scientific basis.

At present, in the USSR, attempts are being made to predict the reliability and lifetime of hydrotechnical structures based on computerized mathematical modeling of their operating processes (M. I. Gogoberidze*, R. G. Kakauridze, N. G. Dularidze, Yu. N. Mikashvili, D. Ts. Mirtskhulava)*. In this case, the probability of the occurrence of any particular condition of the structure in time (normal, threshold, emergency) is determined on the basis of a system of linear differential equations which derive from the classical reliability equation:

$$P_i(t) = e^{-\lambda_{i,j} t}, \text{ where} \qquad (4)$$

$P_i(t)$ is the probability of finding the structure in a condition of S_i (normal, threshold, etc.) at a moment of time t;

*Illegible.

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$\lambda_{i,j} = \lim_{\Delta t \to 0} \frac{P_{i,j}(\Delta t)}{\Delta t}$ is the probability density of transition from one state to another;

$P_{i,j}(\Delta t)$ is the probability of the structure's transition from a state S_i over an interval of time Δt to a state S_j.

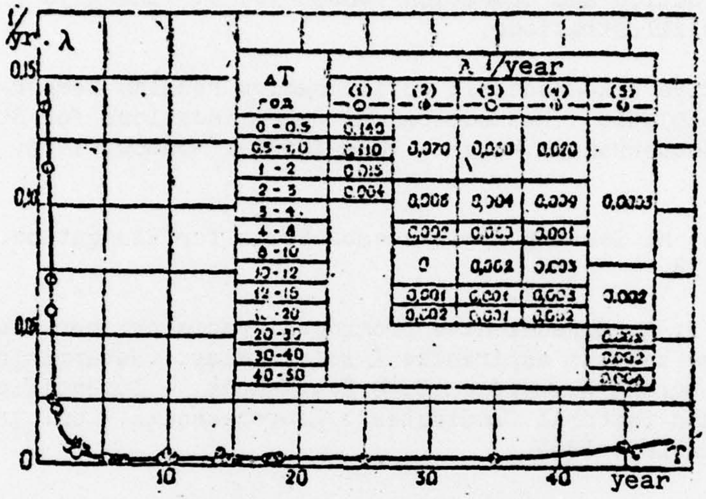

Figure 7. A graph of the intensity of emergencies and incidents at dams: 1 - crack formation in the body of the dam; 2 - nonuniform settlement; 3 - filtration in the body and foundation of the dam; 4 - design errors; 5 - structural damage with time.

The question of establishing the transitional probability density for hydrotechnical structures (λ) from one state to another (for example, from normal to threshold) is a complicated problem. This is because these structures are not distinguished by a standardization of components and by clarity of the relationships which exist among them. The difficulties also consist in identifying the internal factors which act on the structures. One can therefore state that the modern method of mathematical modeling of processes which occur in hydrotechnical structures presently under operation are more and more remote from perfection. One way or the other, one of the methods of improving this remains the one with whose aid one ensures a maximally complete and comprehensive systematic data base regarding the function of structures, emergencies and incidents which occur in such structures. Based upon the results of processing statistical data about emergencies and incidents, one can plot integral intensity graphs (λ) of the transition of structures from one state to another (Figure 7), and following this one can establish the probability of safe functioning (P) of modern structures by calculation. It is natural that the estimate of structural reliability thereby obtained should be viewed as an approximate one.

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