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Pore pressure in the core of ultra-high earth core rockfill dam at consideration of stress-strain state

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Abstract. In the clayey core of the rockfill dam, pore pressure always appears, which may present a serious threat to the dam safety. Therefore, in the middle of the 20th century, there started the development a theory of clayey soil consolidation in cores of earth core rockfill dams; analytical methods were developed to calculate pore pressure. However, these methods are approximate; they do not permit modeling complicated processes of soil consolidation in the structure. The published data of field measurements at the ultra-high dam of Nurek HPP give evidence about the fact that the processes of accumulation and dissipation of pore pressure in the core soil have a complicated character. At the initial stages of construction, there observed a gradual growth of pore pressure due to the weight of the overlying soil layers. But at the completion stages, pore pressure rapidly decreased, and its values approached the values, which are characteristic for the regime of steady seepage. These effects cannot be explained and simulated by a traditional method of analysis. The rate of seepage is too small to provide occurrence of so rapid processes. Therefore, for study of the processes of pore pressure formation in the core of Nurek dam, a more complicated and accurate method was used, i.e. the method of numerical modeling. Numerical modeling permits joint solving the tasks related to stress-strain state and seepage regime in the structure. Use of numerical modeling permitted us with sufficient accuracy to simulate the pore pressure formation process in the core of Nurek dam, as well as to analyze the causes of the observed effects. It was revealed that the main role in pore pressure formation is played not by the process of water seepage but by the process of the dam stress-strain state formation. Decrease of increased pore pressure due to dead weight loads takes place due to the dam lateral expansion. Increase of pore pressure before the seepage pressure is due to soil deformation under the action of force loads from the upstream side. The considered analytical method of analysis does not take into account the peculiarities of formation of stress-strain state of the rockfill dam earth core, it does not consider appearance of pore pressure from the upstream loads. Therefore, the real processes of the core soil consolidation cannot be simulated with its aid.

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1. Introduction

Pore pressure is pressure in the liquid phase of soil. It may exceed the hydrostatic pressure corresponding to groundwater level at the steady seepage regime. Such pressure we will cause increased pressure (or surplus pressure).

It is known that increased pore pressure may present a serious danger for safety of embankment dam structures. Namely, it was pore pressure in the clayey soil layer, which became the cause of failures of embankment dams Chingford (1937) and Muirhead (1941) in Great Britain. At these dams immediately after completion of construction, there happened the loss of clayey soil bearing capacity and break of integrity of the dam structure [1].

Special urgency in study of pore pressure in structures of embankment dams aroused in the middle of the 20th century with use of earth core rockfill dams (ECRDs), whose core was constructed of clayey soil. Many of them had considerable height, therefore, the clayey soil in them was subject to great loads. In 1939, the height of an ECRD for the first time exceeded 100 m. This is 131.7 m high Mud Mountain dam in the USA.

The danger of increased pore pressure in the cores of high ECRD is related to the fact that it may cause crack formation in them. Numerical modeling of stress-strain state (SSS) shows that pore pressure creating a wedging action, contributes to formation of separation cracks in the core [2] or shear surfaces [3]. Pore pressure may be one of the causes of the core hydraulic fracturing, which happened at several dams.

In the 21st century, a number of high ECRDs was built : Karkheh (H=127 m, Iran, 2001) [4–6], Masjed-e-Soleyman (H=177 m, Iran, 2002) [3], San Roque (H=210 m, Philippines, 2003), Tehri (H=260.5 m, India, 2006), Qiaoqi (H=125.5 m, China, 2006) [7], Pubugou (H=186 m, China, 2010) [8], Maoergai (H=147 m, China, 2011) [7], Nuozhadu (H=261.5 m, China, 2012) [9–11], Upper Gotvand Dam (H=180 m, Iran, 2012), Changheba (H=240 m, China, 2017) [9]. Dams San Roque, Tehri, Nuozhadu, Changheba refer to ultra-high dams; their height exceeds 200 m. At construction stage is the dam of Rogun HPP (Tajikistan), which should be the highest in the world.

To provide safety of high ECRDs, it is necessary to carry out studies of pore pressure in the core clayey soils. Approximately from the 1950s, pore pressure started to be studied experimentally, in field conditions at the constructed structures. In [12], there published the data of field measurements of pore pressure at several dams constructed in the 20th century. Monitoring of pore pressure is carried out at all high ECRDs [3, 11, 13].

Analysis of field measurements shows that processes of the core soil consolidation on different dams take place in different ways. In some dams (Aswan, Pachkamar), pore pressure did not exceed hydrostatic pressure and the processes of soil consolidation were quick [12]. In the clay core of Talbingo dam, pore pressure reached considerable values and dissipated slowly [12].

Therefore, it is urgent to develop methods of calculating the process of soil consolidation in ECRD core, so that they can predict formation of pore pressure.

In this connection, of special interest are studies of pore pressure in the core of the highest embankment dam in the world, i.e. the dam of Nurek HPP. Sensors were installed in the core of this dam, which permitted carrying out monitoring of pore pressure during construction and operation. The results of field measurements were published in [14]. With this regard, it is interesting to compare the results of calculations with the results of field measurements and estimate accuracy of calculation methods.

The theory of forming pore pressure and soil consolidation has been developed over the last one hundred years.

The pioneer in study of pore pressure is K. Terzaghi, who provided the basis for the theory of soil consolidation [15]. K. Terzaghi proposed to consider soil as a multi-phase system consisting of solid, liquid, and gaseous phases. And in 1925, he proposed to solve a one-dimensional problem of soil water saturated layer compaction due to the process unsteady seepage.

For development of consolidation theory of great importance was solving the problem of the effect of presence in soil pores of compressible gaseous phase on the value of pore pressure. In 1939, American researchers J. R. Bruggeman, C. N. Zanger, J. H. A. Brahtz proposed determining pore pressure based on the assumption of equality of pore pressure in liquid and gaseous phases using equations of R. Boyle and E. Mariotte law (on air compressibility) and W. Henry law (on dissolubility of air in water). In 1948, J. W. Hilf published the equation based on Boyle–Mariotte law, which permitted determining pore pressure without consideration of consolidation process. This equation became the basis for analytical methods of analysis. A.W. Skempton introduced the methodology of calculating coefficients of pore pressure, which reflects connection between the total stresses and pore pressure with consideration of pore liquid compression and the degree of pore water saturation [16].

The consolidation theory was developed in the works of N.M. Gersevanov, V.A. Florin, M. Biot et al.

In 1937, a Russian scientist V.A. Florin proposed the equation for solving a 2D problem of seepage consolidation applicable to the case of non-compressible liquid. Then, he developed the methods of solving consolidation problems also with consideration of solid phase creep.

In 1941, M. Biot published the proposed by him system of equations of seepage consolidation for a more common case, i.e. for the case of compressible skeleton of soil and compressible liquid [17].

Analytical methods of analysis propose creation of closed analytical solution of the indicated equations, permitting calculation of the pore pressure value and its variation with time.

Analytical solving of the problem related to formation and dissipation of soil pore pressure in the dam core was obtained by A. A. Nichiporovich and T.I. Tsybulnik. They mark two types of pore pressure: pore pressure from the weight of overlying soil layers and pore pressure from water filtration (penetration of the upstream water in the core). A. A. Nichiporovich and T.I. Tsybulnik proposed mathematical formulae, which permits determining distribution pore pressure in the core for each moment of time [18, 19].

In this analytical method, the initial pressure from the weight is determined based on J. W. Hilf equation (via pore pressure coefficient), and the process of pore pressure dissipation is described by V.A. Florin equations. However, at that, a number of simplifying assumptions was accomplished, which makes this method of analysis approximate.

From the middle of the 20th century, the methods of numerical modeling started to be used for solving the problems on soil consolidation. They permit solving joint static-seepage problems simultaneously modeling the process of forming SSS of the structure and its seepage regime. Numerical methods permit solving complicated tasks of soil consolidation not only for particular, previously assigned conditions.

Already in the 1970s, the numerical analyses of pore pressure by the finite element method were carried out at designing Mica dam (Canada, 1973, 243 m high) [20]. It was shown that the results of numerical modeling greatly differ from the results of analyses by the analytical method due to variation of mass stress state in the process of consolidation.

In the 1980s, Yu.K. Zaretsky and V.N. Lombardo[1] fulfilled prognostic modeling of pore pressure in the core of Nurek dam (1980, the USSR, – Tajikistan, 300 m high). The finite difference method was used for solving a joint static-seepage problem for the dam cross section.

At present at designing high ECRD, numerical modeling of processes forming pore water pressure (PWP) and SSS is always fulfilled. Publications [3, 11, 21–24] are devoted to this issue. Rater often analysis has the aim of checking the core crack resistance [11, 21, 23].

For fulfilling analyses, there were used different software packages: FLAC 3D [3, 21], PLAXIS [22, 24], GeoStudio [23]. With the aid of software package FLAC 3D, there was fulfilled numerical modeling of SSS and PWP for several dams in Iran: Masjed-e-Soleyman [3], Siah Sang [21]. Calculations in [13] and [3] were carried out in 3D formulation. Not always for determining pore pressure there modeled the process of soil consolidation, in [22], a simplified approach is used for determining pore pressure.

Publication of [21] is devoted to numerical modeling of SSS and PWP for Siah Sang dam (33 m high) in Iran. Analyses showed rapid dissipation of pore pressure.

Of the most interest are publications [11, 3], devoted to studies of ultra-high ECRD.

The article [11] is devoted to numerical modeling of SSS and PWP for Nuozhadu dam in China. Analyses were conducted based on consolidation theory of M. Biot with use of parabolic model of soil. For obtaining results, adequate data of field measurements, calibration of the structure model was required. At the soil seepage factor value $(2{\div}5)\cdot10^{-6}$ cm/s, measured in laboratory and field conditions, at numerical modeling, the pore pressure quickly dissipated, which were not observed in real dam. Correspondence to the field data was reached at seepage factor value $(1.5{\div}5)\cdot10^{-9}$ cm/s [11].

The article [3] is devoted to studies of PWP and SSS for Masjed-e-Soleyman dam in Iran. By the results of field measurements, there observed high pore pressure in the dam core, and its dissipation was sufficiently slow. At the end of the first reservoir impoundment, the crest settlement amounted to 2,2 m. numerical modeling of SSS and PWP showed that due to pore pressure, there is a danger of the core soil shear strength.

These examples demonstrate urgency of study of pore pressure formation and dissipation, as well it shows that they have not been sufficiently studied by present.

The aim of our study is estimation of adequacy of pore pressure analyses results, obtained by different methods, estimation of adequacy of representation by them of the processes in core soil consolidation, which are observed in a real structure.

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[1] Zaretsky Yu.K., Lombardo V.N. Statics and dynamics of embankment dams. M.: Energoatomizdat, 1983. 255 p.

Analysis will be conducted by two methods: analytical method and the finite element method. They will be shown on the example of Nurek HPP, where field measurements of pore pressure in the core have been conducted for already 40 years.

Consequently, the tasks of the study are as follows:

- fulfill analysis of data on field measurements of pore pressure in the core of Nurek dam;
- fulfill analysis of pore pressure in the core of Nurek dam by the analytical method;
- carry out numerical modeling of Nukek dam SSS and seepage regime;
- compare the results of analysis obtained by different methods, formulate conclusions and recommendations on peculiarities of pore pressure formation and for reliability of the analysis results.

2. Materials and Methods

2.1. Subject of Study

The subject of study, i.e. Nurek dam, is an ECRD. It has a 269 m high core made of sandy loam (Fig. 1). The core rests on a thick concrete block. The dam shells are made of gravel-pebble soil.

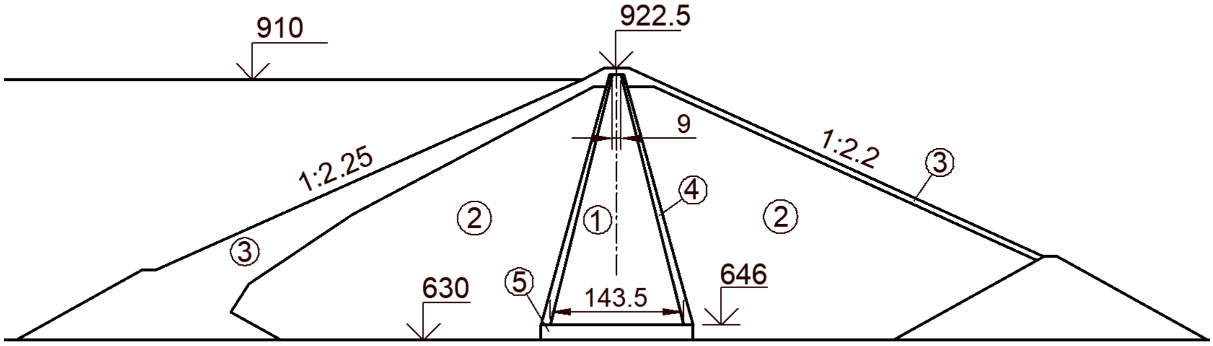

Figure 1. Design scheme of earth core rockfill Nurek dam structure in vertical section: 1 – sandy loam core; 2 – shells of gravel-pebble soil; 3 – protection against rockfill; 4 – transition zone; 5 – concrete plug.

2.2. Description and Analysis of Results of Pore Pressure Field Measurements

Several dozens of sensors were installed in the core for measuring pore pressure. Multiple sensors were installed on the surface of concrete block. Besides, vibrating wire piezometers were installed inside the dam core in 7 vertical measuring sections at different elevations. For example, in the riverbed section (measuring section 5), the sensors are installed at elevations 686, 774.5, 799 m.

Measurements were carried out from the start of construction (since 1973). In [14], there given the data of pore pressure field measurements during the period of construction. In 1973, when the core was constructed for the height of 104 m, pore pressure reached 1,8 MPa (Fig. 2a), and in 1977, when the core was constructed for the height of 209 m, it reached 2,99 MPa (Fig. 2b). For these moments of time, the vertical pressure from the soil weight amounts to 2.4 and 4.8 MPa respectively. This means that on the liquid phase of soil (pore liquid), there transferred accordingly 75 and 62 % of maximum possible pressure (for pressure coefficient α=0.75 and 0.62).

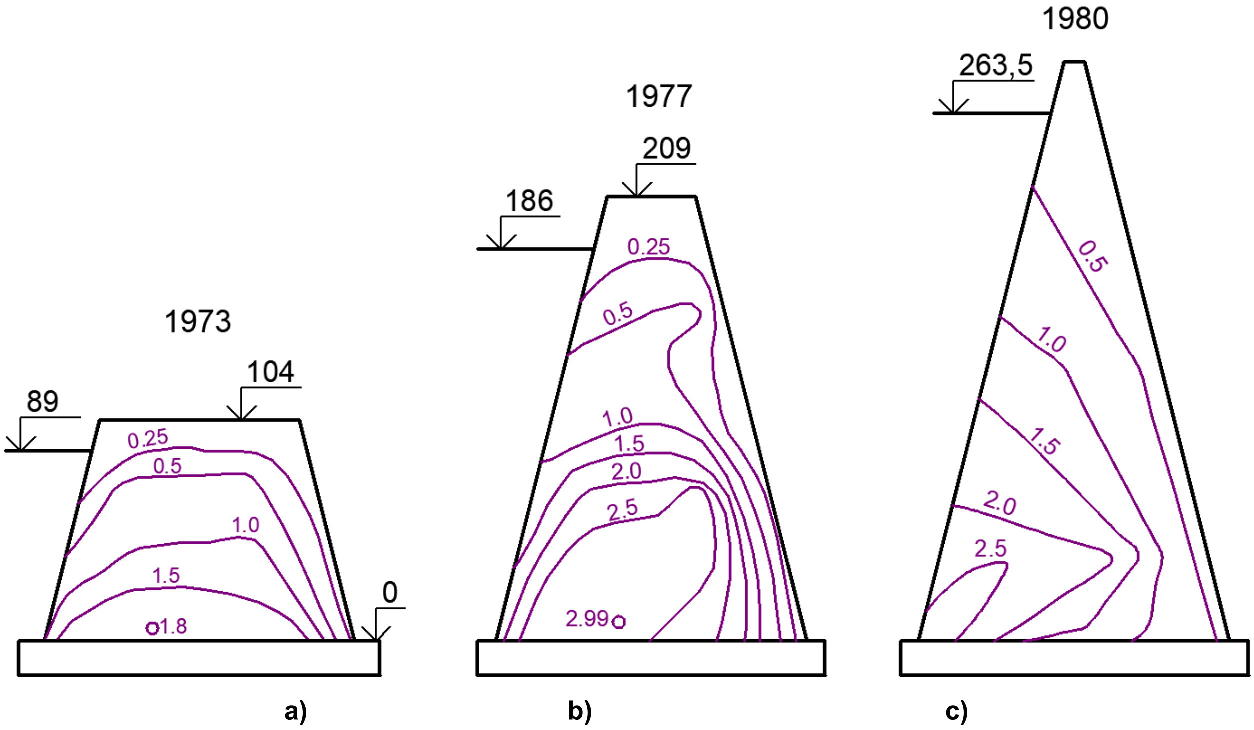

Figure 2. Pore pressure in the dam core by the data of field measurements (values are in MPa): a – after 2 years from the start of construction; b – after 6 years from the start of construction; c – after 9 years from the start of construction. Relative elevations are indicated.

For us, of the most interest is the riverbed vertical cross section No. 5, having maximum height. After completion of the dam construction and the reservoir impoundment (in 1981) in this section, the maximum value of pore pressure was reached in sensor No. 1314 [14]. In this sensor at ∇686 m, it amounted to 2.48 MPa (Fig. 2c). As compared to maximum possible value (5.4 MPa), the pore pressure is 46 %.

This simple analysis evidences that during the period of construction, intensive dissipation of pore pressure and soil consolidation took place. During the operation period, these processes continued. In the same sensor No. 1314 by 2014, pore pressure decreased to 1.47 MPa [14], i.e. by 40 %.

The data of field measurements show complicated character of pore pressure distribution in the dam core. In the core, upper part considerably less portion of load is transferred to water than in the lower part. Already during construction period (1977), piezometric levels in the upper sensors turned to be less than in the lower one; in future this tendency maintained.

Plotted by the data of field measurements, distribution of pore pressure for the moment of construction completion (Fig. 2c) proves that by the start of operation period, dissipation of the most part of surplus pore pressure took place, and it approached the values, which corresponded to the steady seepage flow.

The described above pattern of distribution and variation of pore pressure obtained in the field is abnormal from the point of view of theoretical concepts, and the causes of such rapid soil consolidation are debatable. In publication [14], it is affirmed that rapid dissipation of pore pressure in the core lower part may be explained by permeability of the concrete block. By the results of numerical modeling of the process of non-steady seepage in the core of the ultra-high dam, fulfilled by N.A. Aniskin [25], the process of water penetration inside the dam core should usually occur very slowly, i.e. during several decades the boundary of seepage area should advance only for several meters from the upstream face. Consequently, consolidation process should take place for decades or hundreds of years.

Our study is an attempt to explain the causes of effects in distribution of pore pressure in the core of Nurek dam, revealed by field measurements during construction period.

Specially mentioned should be the results of field measurements of the core soil permeability, which are also published in [14]. Values of the core soil seepage factor were determined by calibration of the mathematical model. It was obtained that with time, the values of the core soil seepage factor decreased. If in 1984, it amounted to $(0.4 \div 4) \cdot 10^{-6}$ cm/s, afterwards, it decreased approximately by an order [14]. However, the value of seepage factor $1.2 \cdot 10^{-6}$ cm/s =0.001 m/day seems to be very high for the clayey soil.

2.3. Analytical Method of Analysis

Design formulae of the analytical method, proposed by A. A. Nichiporovich and T.I. Tsybulnik, are given in [2, 18, 19, 25]. They permit determining two types of pore pressure: pore pressure appearing under the action of weight of overlying layers and seepage pore pressure of water from the upstream side penetrating inside the core.

This analytical method is approximate; it is based on a number of assumptions. The following assumptions may be distinguished:

- the core operates independently from the dam shells, it is independently subject to the load from the weight of overlying soil layers;
- total stresses in the core in vertical direction are equal to the pressure from the weight of overlying soil layers;
- soil deformations occur only in vertical direction; soil is a linearly deformed material;
- initial pore pressure (in the initial moment of time) is determined by total stresses with the aid of J. W. Hilf equation, corresponding to conditions of fluid efflux ("closed system");
- dissipation of pore pressure occurs due to water seepage in horizontal direction;
- the rate of the structure construction height-wise, the rate of the upstream level growth at the reservoir impoundment are constant.

Due to the made assumptions, the analytical method is approximate. Therefore, we used the method of numerical modeling.

2.4. Method of Numerical Modeling

Numerical modeling of the structure was accomplished based on the finite element method in the software package MIDAS. The problem of soil consolidation was solved by M. Biot equations.

These calculations are also approximate because only the dam vertical section is considered and the dam soil is assumed to be linearly deformed.

The used for analyses finite element model of the dam section is shown in Fig. 3. It comprises 6975 nodes and 6906 finite elements.

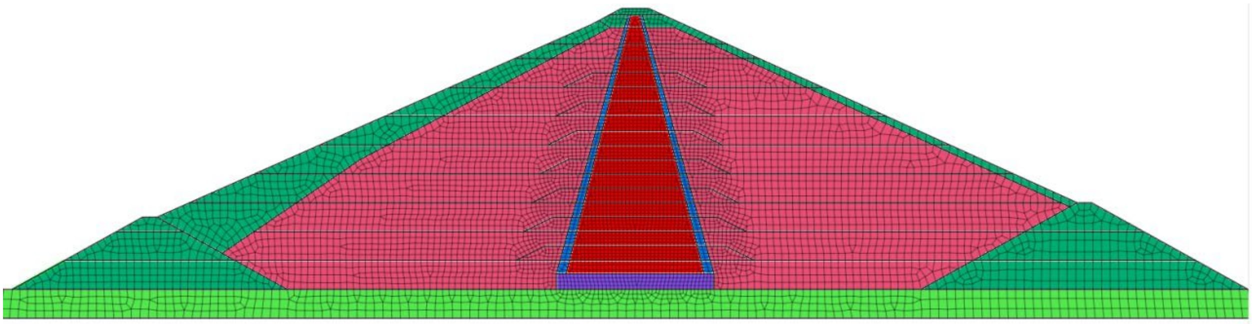

Figure 2. Finite element discretization of the designed section.

During analyses, the following types of loads were considered:

- loads from the structure dead weight;
- loads on soil from the buoyant action of water;
- volumetrically distributed loads from filtering water.

Only construction period was considered, whose duration was 9 years.

The sequence of dam construction was simulated (with consideration of its construction by horizontal layers) and the reservoir impoundment. It is shown in Fig. 3 as a diagram, reflecting growth with time of the dam top elevation and the upstream level.

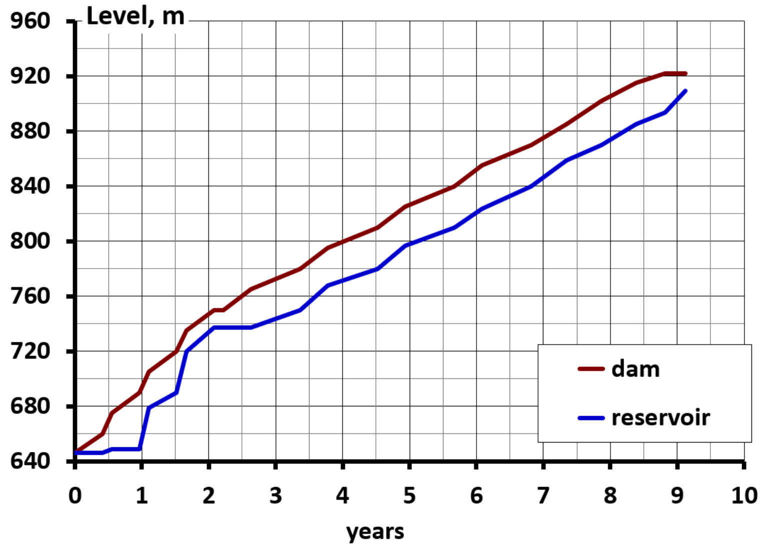

Figure 3. Design diagram of sequence of the dam construction and the reservoir impoundment (for numerical modeling).

At modeling behavior of soil, Coulomb–Mohr model was used envisaging linear deformation. Physical-mechanical properties of soils adopted in the analysis are in Table 1. The core soil seepage factor was assumed to be several times less than that by data of [14].

Table 1. Design physical-mechanical characteristics of soils.

Material	ρ_d t/m^3	ρ_{sat} t/m^3	E MPa	ν	k_f m/day
Sandy loam	2.10	2.28	40	0.32	$8.64 \cdot 10^{-5}$
Soils of transition zones	2.10	2.20	55	0.3	20
Gravel-pebble soil of shells	2.16	2.35	150	0.27	100
Weightening rock mass	1.96	2.22	150	0.27	100

Designations: ρ_d – density in dry state, ρ_{sat} – density in water saturated state, E – modulus of linear deformation, ν – Poisson's ratio, k_f – seepage factor.

3. Results and Discussions

3.1. Results of Analysis by Analytical Method

At analysis by the analytical method of A.A. Nichiporovich and T.I. Tsybulnik for a number of moments of time, there was determined pore pressure from soil dead weight and from the seepage flow, out of which the greatest was selected. The rate of the dam growth height-wise and the rate of the reservoir impoundment were assumed to be constant due to peculiarities of this method.

Analysis results on pore pressure in the core by the analytical method are presented in Fig. 4. They show that pore pressure is mainly caused by the dead weight of the overlying soil layers, while the seepage pore pressure is small.

The results of analysis are in bad correlation with the data of field measurements at the initial stages of the dam construction (Figs. 4a, 4b), though design values slightly exceed the field values. For example, for the moment of time for the year of 1977, the maximum value of pore pressure according to calculation amounts to 3.5 MPa, and by field data it is 2.99 MPa (Fig. 4b). It should be stressed that by the results of analyses, made by Yu.K. Zaretsky and V.N. Lombardo, the maximum pore pressure comprised 2.77 MPa. Thus, the results of analyses are in satisfactory correlation.

However, for the time of construction completion (1980), divergence of design and field data is considerable. The difference is not only in absolute values of pore pressure but also in the pattern of their distribution and variation with time. In the data of field measurements, the most part of pore pressure due to the soil dead weight has already dissipated, and by the results of analysis, it is not decreased but increases. By field data, the maximum value of PWP is about 2.5 MPa (Fig. 2c), and by the results of analysis, it reaches 4.5 MPa (Fig. 4c).

Such difference in the results of field measurements and calculations testifies about disadvantages of the design model. Therefore, it is interesting to estimate the results of analysis with the aid of numerical modeling.

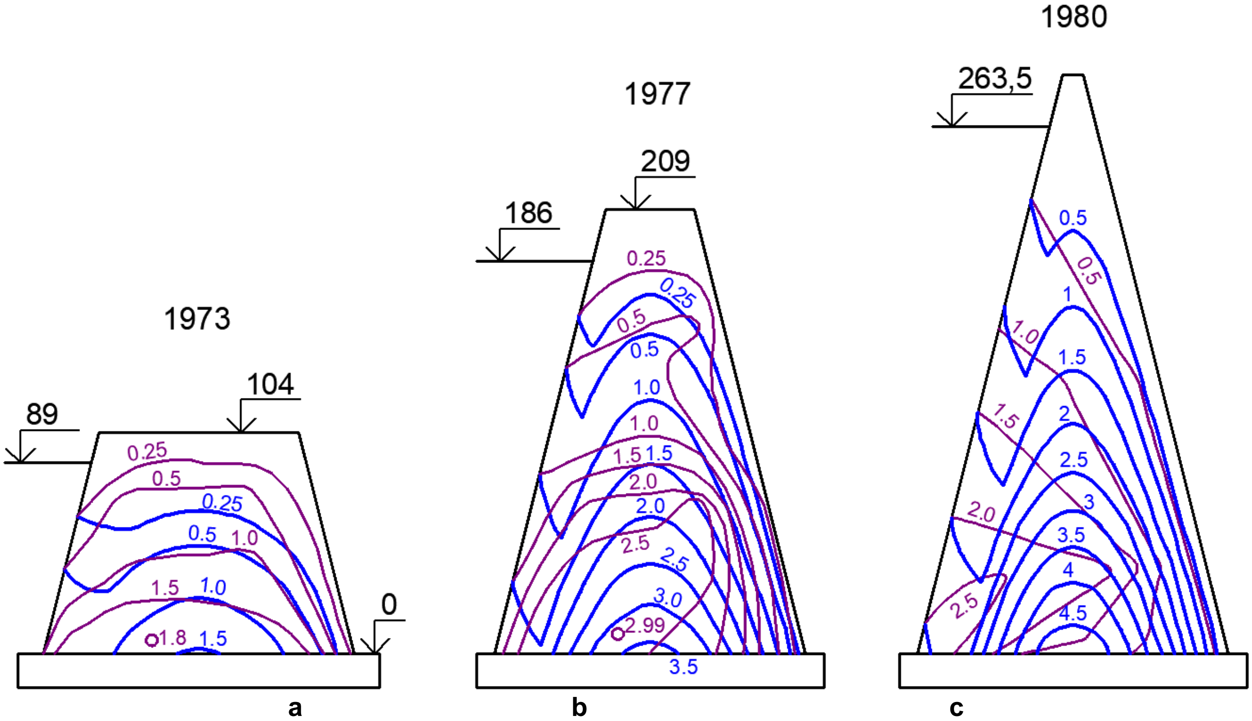

Figure 4. Pore pressure in the dam core by the results of analyses by the analytical method (values are given in MPa):
a – after 2 years from the start of construction; b – after 6 years from the start of construction; c – after 9 years from the start of construction. Violet color shows isolines of pore pressure by the results of field measurements, blue color – by the results of analyses with use of the analytical method. The indicated elevations are relative.

3.2. Results of Numerical Modeling

The dam stress state for the moment of construction period completion, obtained by numerical modeling, is shown in Figs. 5–10. Construction settlements and displacements of the dam are shown (with consideration of construction sequence), as well as distribution of vertical and horizontal stresses.

Obtained in the analysis construction settlements reach maximum in the core central part (Fig. 5). The maximum settlement amounts to 3.35 m, which is slightly more than by the results of field measurements (3.0 m).

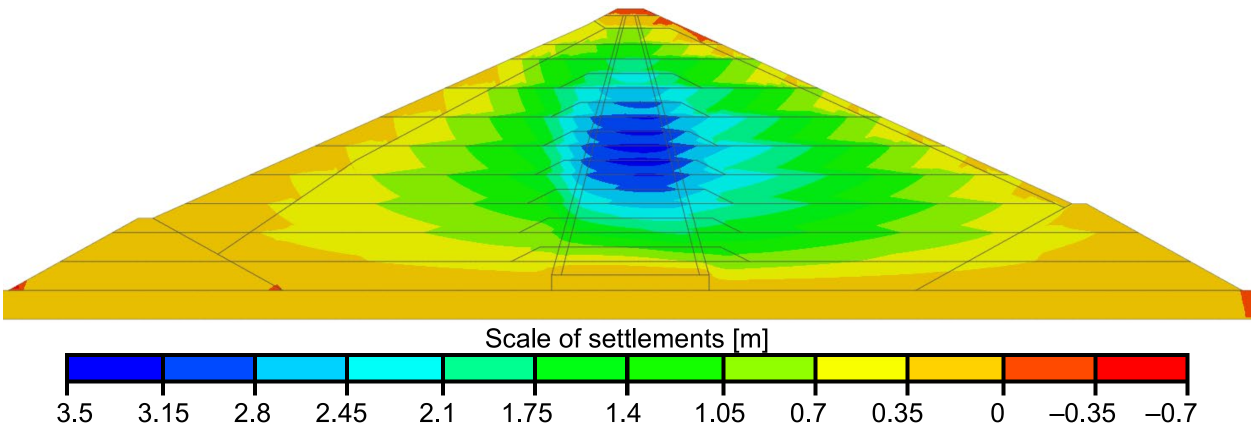

Figure 5. Dam settlements by the results of numerical modeling (for the moment of construction completion).

Design horizontal displacements are directed towards the downstream side. Their maximum value 2.5 m is in core central part (Fig. 6). It is several times more than field settlements (0.8 m). This difference is explained by the fact that analyses were conducted in 2D formulation for the dam vertical section, while SSS of a real dam was formed in spatial conditions.

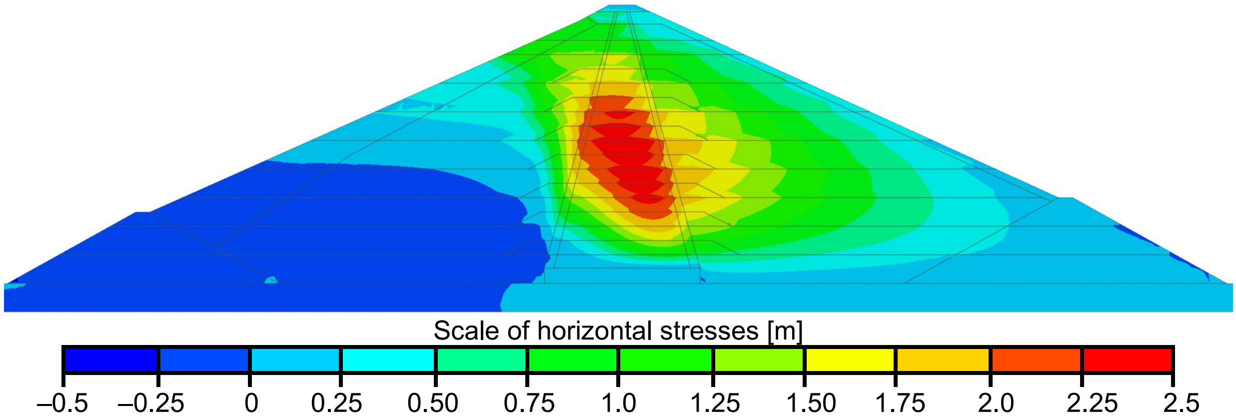

Figure 6. Dam horizontal displacements by the results of numerical modeling (for the moment of constriction completion).

Arch effect is characterized for distribution of vertical total stresses (Fig. 7). Compressive stresses in the core do not reach 2.5 MPa, while in the shells, they exceed 8 MPa. As compared to maximum possible pressure from the soil weight (6.3 MPa), compressive forces amount to only 40 %. Thus, the effect of the core “hanging up” on the shells takes place.

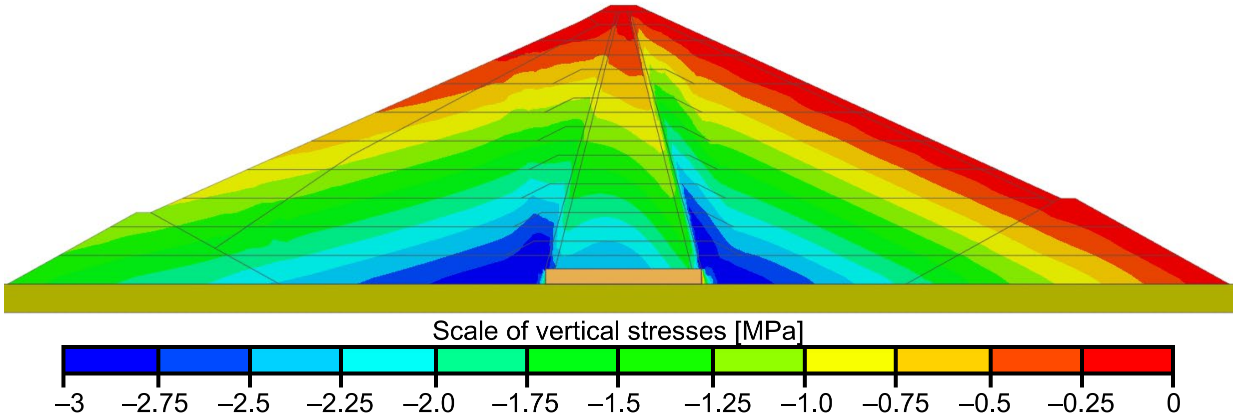

Figure. 7. Vertical total stresses in the dam body by the results of numerical modeling (for the moment of constriction completion).

Horizontal stresses are considerably lower than the vertical ones. They do not exceed 4.3 MPa (Fig. 8). The level of compression gradually decreases in the direction from the upstream slope to the downstream one. The most intensive drop of compressive stresses occurs in the core lower part.

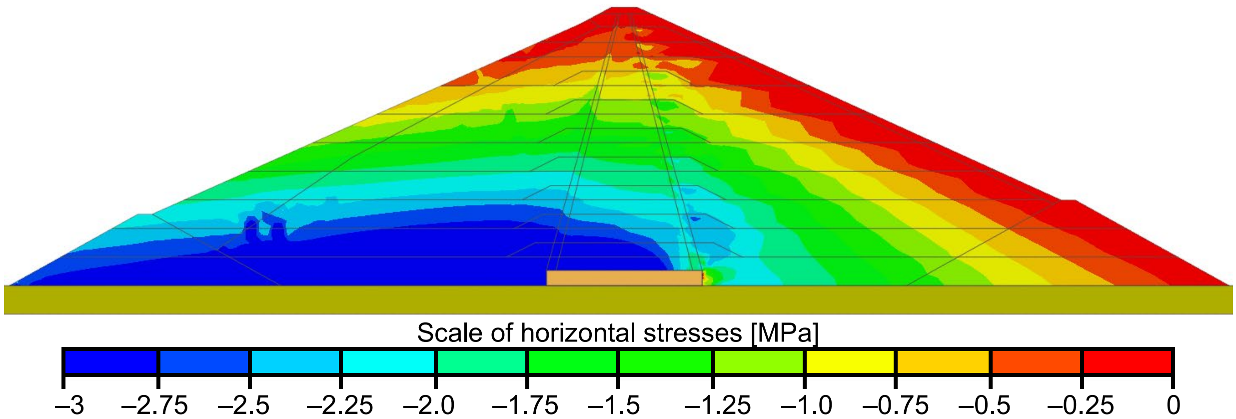

Figure. 8. Horizontal total stresses in the dam body by the results of numerical modeling (for the moment of constriction completion).

Fig. 9 shows distribution of pore pressure in the core for three characteristic moments of time obtained by numerical modeling. For convenience of comparison, Fig. 10 shows isolines (isobars) of pore pressure, obtained by analysis and field measurements.

The pattern of pore pressure distribution at the initial stages of construction, obtained with aid of numerical modeling, is similar to that obtained by the analytical method. It is formed mainly by pressure of the overlying soil weight. PWP maximum is reached closer to the center of the core lower part. PWP maximum values are also similar. For example, for the moment of time for the year of 1977, it amounts to: by the method of numerical modeling, it is 2.7 MPa (Fig. 9b), by the analytical method, it is 3.5 MPa (Fig. 4b). These values are close to the values obtained in the field conditions (2.99 MPa, Fig. 2b). PWP decrease, obtained by numerical modeling, among others is explained by the effect of the core "hanging up" on the shells.

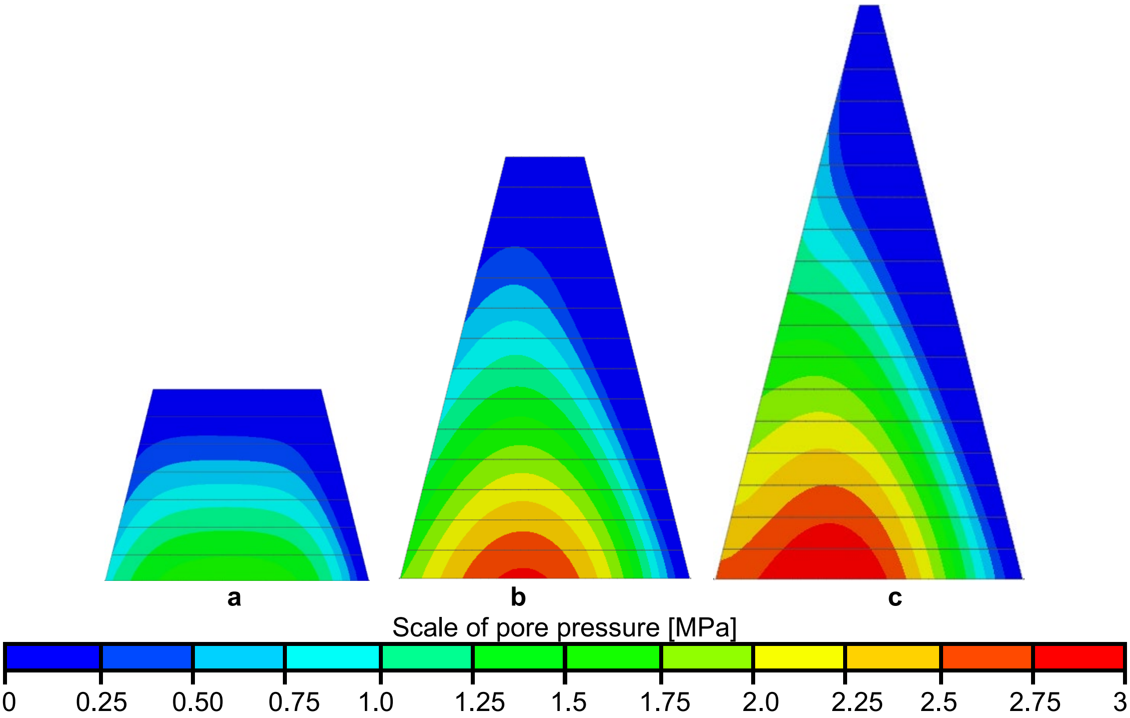

Figure 9. Pore pressure in the dam core by the results of numerical modeling (with consideration of the reservoir impoundment):
a – after 2 years from the start of construction; b – after 6 years from the start of construction; c – after 9 years from the start of construction.

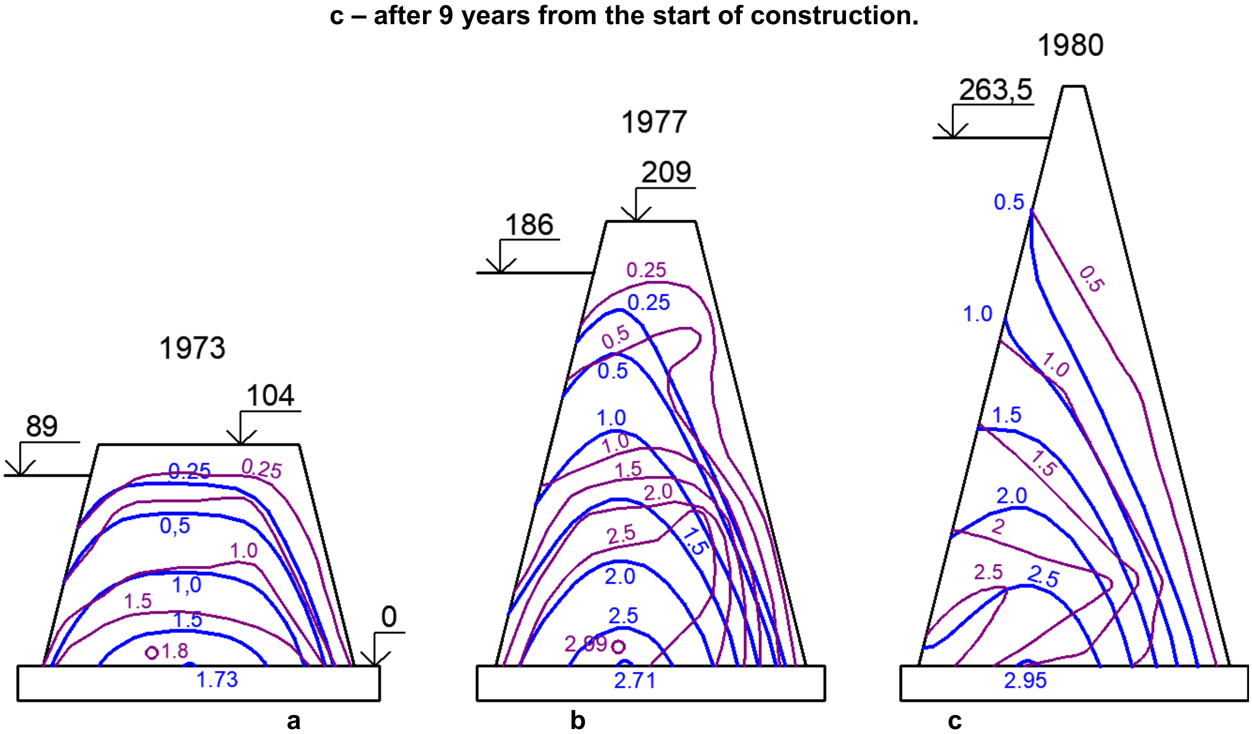

Figure. 10. Comparison of the results of numerical modeling with the results of pore pressure field measurements in the dam core:
a – after 2 years from the start of construction; b – after 6 years from the start of construction; c – after 9 years from the start of construction. Violet color shows isolines of pore pressure by the

results of field measurements, blue color – by the results of numerical modeling. The indicated elevations are relative.

For the moment of construction completion (1980), the results of numerical modeling greatly differ from the results of analysis by the analytical method. The pattern of PWP distribution is much closer to that, which corresponds to the seepage pressure (Figs. 9c, 10c). PWP maximum value according to the analysis amounted to 2.95 MPa (Fig. 10c), which is less that by the analytical method (4.5 MPa, Fig. 4c). Obtained by numerical modeling pattern, pore pressure is much closer to that, which was obtained by field measurements. Maximum value of designed PWP is approximately by 15 % higher than by field data.

In order to determine the mechanism of pore pressure formation, reveal its rapid variation at the completion stage of construction, additional analysis was carried out. This SSS analysis was performed at loads only from the dead weight, without consideration of the reservoir impoundment. The obtained for this design scheme PWP distribution is shown in Fig. 11. It principally differs from that, which was obtained with consideration of the reservoir impoundment.

At the completion period of construction, the pore pressure does not increase with time but decreases. Namely, the maximum value of PWP after 6 years from the start of construction amounts to approximately 2.2 MPa (Fig. 11b), and after 9 years, it is about 1.8 MPa (Fig. 11c). PWP decrease is well illustrated in Fig. 12, where variation of pore pressure is shown for several points (where sensors are installed).

The pore pressure value under loads is much less then with consideration of the reservoir impoundment. Under loads from only the dead weight at the completion stage of construction, PWP maximum value was only 1.8 MPa (Fig. 11c), and with consideration of the reservoir impoundment, it was 2.95 MPa (Fig. 10c).

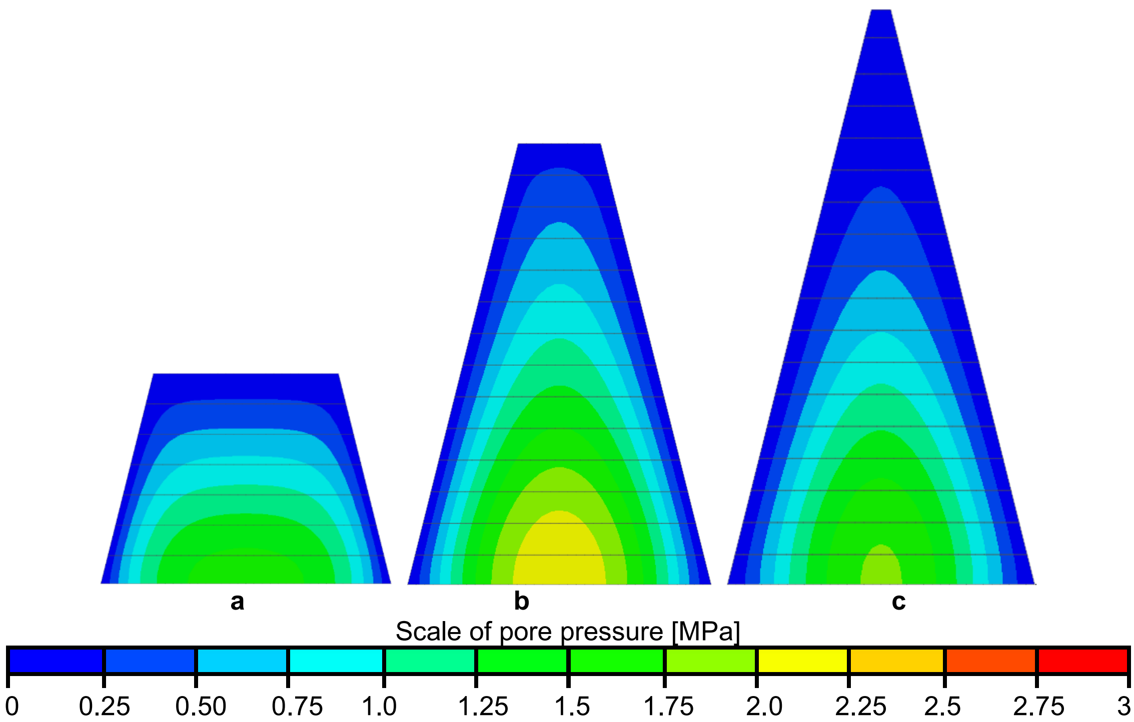

Figure. 11. Pore pressure of the dam core by the results of numerical modeling (without consideration of the reservoir impoundment):
a – after 2 years from the start of construction; b – after 6 years from the start of construction; c – after 9 years from the start of construction.

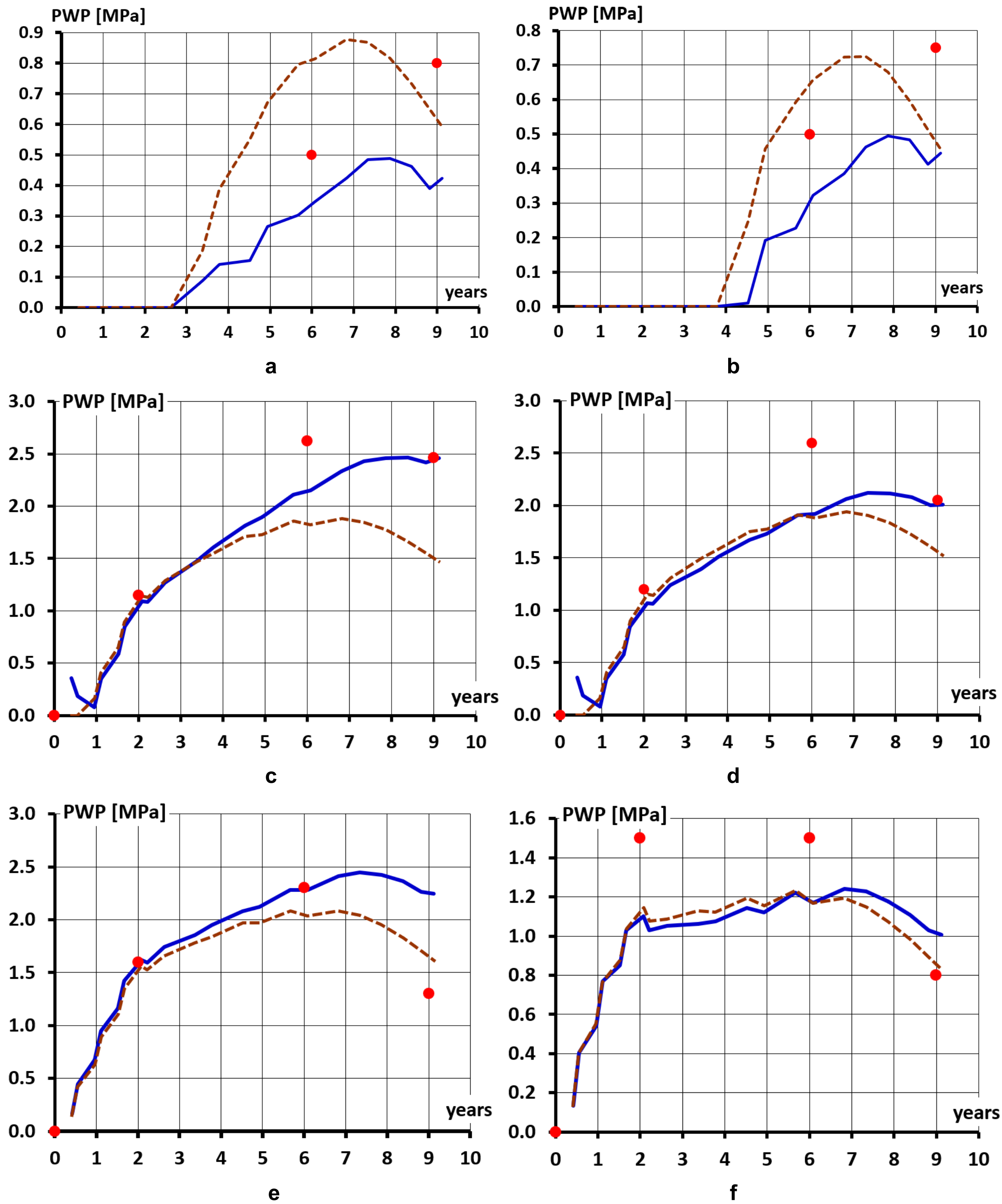

Figure. 12. Pore pressure variation with time in several points: a – sensor 1370; b – sensor 1357; c – sensor 1314; d – sensor 1315; e – sensor 1304; f – sensor 1305. Red points show the results of field measurements; the blue continuous line shows the results of numerical modeling with consideration of the reservoir impoundment; the brown dotted line shows the results of numerical modeling without consideration of the reservoir impoundment.

This comparison testifies that:

- in pore pressure formation, the role of pressure from the dead weight is much less, and the role of the reservoir impoundment is much greater than it is proposed in the analytical method of analysis;
- growth of seepage pressure in the core is sufficiently rapid.

These effects are explained by specific features of the dam SSS formed by the action of external forces.

Decreased values of pore pressure from dead weight, obtained by numerical modeling, are explained by several reasons. One of the causes is the effect of the core “hanging up”, as a result of which the load on the core decreases. The main cause is the dam lateral expansion at perception of loads, which leads to increase of porosity and, consequently, to decrease of PWP. This is the evidence due to the studies, which we have conducted earlier and described in [26].

Rapid increase of PWP at the reservoir impoundment occurs not just due to the process of water filtration inside the core but more due to compression deformations, to which the dam is subject at perceiving horizontal loads. To the two known types of PWP in the dam (PWP from the dead weight, filtration PWP) the third one may be added, i.e. PWP from horizontal loads.

Comparison of the character of core pressure variation in time, obtained by the results of numerical modeling (Fig. 12) and by the results of field measurements, shows their satisfactory conformity (with consideration of the fact that other factors also affect the processes of PWP formation in field conditions).

4. Conclusion

Analysis of field observations of Nurek dam state evidences that formation of pore pressure in the core soil was not always in the way predicted by the analytical methods of analysis of consolidation process. In real conditions, the soil consolidation process is more rapid than it is prognosed by analytical methods.

1. At the initial stages of construction, pore pressure increased, mainly due to weight increase of the overlying soil layers. At these stages, the process of soil consolidation is well described by analytical methods. At the completion stages of construction, the surplus pore pressure dissipated and filtering water penetrated inside the core. However, it happened much quicker than analytical methods predict. Already by the moment of construction completion, pore pressure from the dead weight already dissipated to a great extent and became close to seepage pressure. These effects cannot be explained only by long duration of construction and the reservoir impoundment (9 years).
2. Numerical modeling of the dam SSS jointly with modeling the seepage regime permitted to simulate rather accurately the process of pore pressure formation in Nurek dam core during construction period. In spite of proximity of the design scheme, we managed to reflect a special character of soil consolidation process, which was recorded by field measurements.
3. Analysis of numerical modeling results permits disclosing mechanisms of pore pressure formation in the core of ECRD, revealing the effect of the most important factors. Rapid decrease of pore pressure from the dead weight occurs not only due to its dissipation but mainly due to deformations of the dam lateral expansion. Due to these deformations in spite of dam height growth, cubic deformations do not increase but decrease. Rapid penetration of seepage pressure inside the core occurs not due to water filtration but due to those horizontal loads, to which the core is subject from the upstream water.
4. Analytical method of the core soil consolidation analysis does not take into account the enumerated above peculiarities in formation of the rockfill dam earth core SSS, therefore, it is applicable only for approximate estimations.
5. Results of numerical modeling are approximate because there were not considered non-linearity of soil deformation and special character of the dam SSS formation.

References

1. Penman, A.D.M. On the embankment dam. Geotechnique. 1986. 36(3). Pp. 303–348.
2. Sainov, M.P. Assessment of crack resistance of ultra-high earth core rockfill dam by pore pressure. Magazine of Civil Engineering. 2022. 114(6). Article no. 11411. DOI: 10.34910/MCE.114.11
3. Akhtarpour, A., Salari, M. The deformation mechanism of a high rockfill dam during the construction and first impounding. Scientia Iranica A. 2020. 27 (2). Pp. 566–587. DOI: 10.24200/sci.2018.20778
4. Hosseini, S.M.M.M., Fard, R.A. Pore pressure development in the core of earth dams during simultaneous construction and impounding. Electronic Journal of Geotechnical Engineering. 2003. 8. Pp. 1–13.
5. Razavi, B., Parehkar, M., Gholami, A. Investigation on Pore Water Pressure in Core of Karkheh Dam. International Journal of Civil and Environmental Engineering. 2011. 5(11). Pp. 539–542.
6. Balanji, S.G., Davoudi, S., Merufinia, E. Investigation the Effects of Pore Water Pressure and Arching on Karkheh Earth Dam Considering the Instrumentation Results. Advances in Environmental Biology. 2014. 8(12). Pp. 1345–1353
7. Feng, R., He, Y.-L., Cao, X.-X. Different Deformation Patterns in High Core Wall Rockfill Dams: A Case Study of the Maoergai and Qiaoqi Dams. Advances in Civil Engineering. 2019. 2019(2). Article no. 7069375. DOI: 10.1155/2019/7069375
8. Guo, Q., Pei, L., Zhou, Z., Chen, J., Yao, F. Response surface and genetic method of deformation back analysis for high core rockfill dams. Computers and Geotechnics. 2016. 74. Pp. 132–140. DOI: 10.1016/j.compgeo.2016.01.001
9. Ma, H., Chi, F. Major Technologies for Safe Construction of High Earth-Rockfill Dams. Engineering. 2016. 2(4). Pp. 498–509. DOI: 10.1016/J.ENG.2016.04.001
10. Lv, X., Chi, S. Strain Analysis of the Nuozhadu High Rockfill Dam during Initial Impoundment. Mathematical Problems in Engineering. 2018. 2018(2). Article no. 7291473. DOI: 10.1155/2018/7291473

11. Wu, Y., Zhang, B., Yu, Y., Zhang, Z. Consolidation analysis of Nuozhadu high earth-rockfill dam based on the coupling of seepage and stress-deformation physical state. International Journal of Geomechanics. 2016. 16(3). Article no. 04015085. DOI: 10.1061/(ASCE)GM.1943-5622.0000555
12. Rasskazov, L.N., Yadgorov, E.K., Nikolaev, V.B. Field Observations of Soil Settlements, Displacements, and Pore Pressure in Dams. Power Technology and Engineering. 2018. 51(6). Pp. 611–620. DOI: 10.1007/s10749-017-0804-1
13. Salari, M., Akhtarpour, A., Ekramifard, A. Hydraulic fracturing: a main cause of initiating internal erosion in a high earth-rock fill dam. International Journal of Geotechnical Engineering. 2018. 15(6). DOI: 10.1080/19386362.2018.1500122
14. Rasskazov, L.N., Yadgorov, E.Kh., Burenkov, P.M. Pore Pressure Dissipation in the Core of the Nurek Dam. Power Technology and Engineering. 2016. 50(1). Pp. 54–56. DOI: https://doi.org/10.1007/s10749-016-0658-y
15. Verruijt, A. Consolidation of Soils. Encyclopedia of Hydrological Sciences. Chichester: John Wiley & Sons, Ltd., 2008. Pp. 1–16. DOI: 10.1002/0470848944.hsa303
16. Skempton, A.W. The pore pressure coefficients *A* and *B*. Geotechnique. 1954. 4(4). Pp. 143–147. DOI: 10.1680/geot.1954.4.4.143
17. Biot, M.A. General Theory of Three-Dimensional Consolidation. Journal of Applied Physics. 1941. 12(2). Pp. 155–164. DOI: 10.1063/1.1712886
18. Tsybulnik T.I. Opredeleniye porovogo davleniya v yadre vysokoy plotiny pri peremennykh znacheniyakh kharakteristik grunta [Determining pore pressure in the core of a high dam with variable soil characteristics]. Trudy VODGEO, Gidrotekhnika. 1965. 11. Pp.35-45.
19. Nichiporovich A.A., Tsybulnik T.I. Odnomernaya zadacha konsolidatsii glinistogo grunta pri napryazhennom sostoyanii, sootvetstvuyushchem sluchayu ploskoy deformatsii [One-dimensional problem of consolidating clay soil in a stressed state corresponding to the plane deformation case]. Trudy VODGEO, Gidrotekhnika. 1972. 34. Pp. 5–25.
20. Eisenstein, Z., Law, S.T.C. Analysis of consolidation behavior of Mica dam. ASCE Journal of Geotechnical Engineering Division. 1977. 103(8). Pp. 879–895.
21. Rashidi, M., Heidari, M., Azizyan, Gh. Numerical Analysis and Monitoring of an Embankment Dam During Construction and First Impounding (Case Study: Siah Sang Dam). Scientia Iranica A. 2018. 25(2). Pp. 505–516. DOI: 10.24200/sci.2017.4181
22. Soroush, A., Pourakbar, M., Nabizadeh, A. 3D numerical analyses of behavior of a high rockfill dam with clay core in narrow canyon. 16th Asian Region Conference on Soil Mechanics and Geotechnical Engineering, Taipei, 2019.
23. Komasi, M., Beiranvand, B. Study of Hydraulic Failure Mechanism in the Core of Eyvashan Earth Dam with the Effect of Pore Water Pressure and Arching. Journal of Stress Analysis. 2020. 4(2). Pp. 55–67. DOI: 10.22084/jrstan.2020.20022.1110
24. Undayani, C.S., Sri P.R.W., Suharyanto, Windu P. Influence of pore water pressure to seepage and stability of embankment dam (case study of Sermo Dam Yogyakarta, Indonesia). MATEC Web of Conferences. 2017. 101. Article no. 05007. DOI: 10.1051/matecconf/201710105007
25. Aniskin, N.A., Rasskazov, L.N., Yadgorov, E.K. Filtration, pore pressure, and settling from consolidation of an ultra-high dam. Power Technology and Engineering. 2017. 50(6). Pp. 600–605.
26. Sainov M.P., Boldin A.A. Formirovaniye porovogo davleniya v yadre kamenno-zemlyanoy plotiny ot sobstvennogo vesa [Formation of pore pressure in the earth-core rockfill dam due to the dead weight]. Gidrotekhnika. 2024. 2(75). Pp. 10–14.

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