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Variation of stress-strain state of rockfill dam affected by creeping

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Abstract. Rockfill is subject to creeping and this phenomenon has negative consequences for rockfill dam stress-strain state (SSS). Recently, rockfill creeping attracts more and more attention in China where a great number of embankment dams are constructed. Chinese scientists fulfilled tests of rockfill in stabilometers. However, for SSS numerical modeling, there are used other empirical rheological models whose parameters are determined by the method of SSS back analysis of existing rockfill dams. For studying the effect of creeping on rockfill dam SSS, the authors fulfilled back analysis for Tianshengqiao-I dam in China. Modeling the dam SSS was carried out with the aid of software package MIDAS. Two analyses were performed: without consideration of creeping and with consideration of it. Mohr–Coulomb model was used for description of rockfill deformation. For consideration of creeping, it was added by Maxwell–Kelvin rheological model. Reliability of SSS modeling was provided by selection of soil model parameters from condition of approximate correspondence between design and field displacements. Comparison of two design alternatives of analysis permitted making conclusions on the role of rockfill creeping in formation of the dam SSS. There was determined the share of displacements reached during construction due to time-dependent component of rockfill deformation. For settlements, it was amounted to approximately 20–30 %, and for horizontal displacements, it was higher. Creeping affects the character of settlement distribution in a complicated way. This is related to the fact that it causes growth of deformation of two types: shear deformations toward the downstream side and deformations of lateral expansion. In the lower part of the dam, deformations of lateral expansion prevail and in the upper part – share deformations. Such character of displacements may affect reinforced concrete face. Effect of creeping on rockfill stress state is not great and it is mainly related to rather small increase of tangent stresses.

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1. Introduction

Subject of research

Soil deformation occurs not instantly but during a long period of time. Slow increase of soil deformations in the course of time at the action of constant external load is called creeping. Creeping is a characteristic feature of coarse soils (rockfill) used for construction of rockfill and rock-earthfill dams.

Formulation of relevance of research

Rockfill creeping causes constant increment of the dam deformations both during construction and operation periods; these deformations may have negative consequences for the dam safety.

Due to additional settlements, the dam crest elevation may become sufficiently lower than the design value. At the existing rock-earthfill and rockfill dams, which were constructed before 1960s with use of methodology without rockfill compaction by rollers, the crest settlement during operation period could exceed 1 % of the dam height [1]. There are cases of high settlements also at modern dams. For example, the crest settlement of ultra-high Atatürk rock-earthfill dam (Turkey, H = 184 m high, 1990) over the 7 years of operation exceeded 2.5 m [2]. Constant settlements of the embankment dam of Boguchany HPP (Russia, H = 77 m, 2012) cause permanent problems in operation of its conjugation with the concrete dam.

Creep deformations may be also dangerous for integrity for the rockfill dam concrete face. There are well-known cases of emergency situations related to formation of large structural cracks in the face [3].

At present, more and more high dams are constructed. By 2023 in China, there had been constructed 406 concrete faced rockfill dams, including 94 dams with height exceeding 100 m [4]. With growth of the dam height, the danger of creep deformations increases. Russian norms envisage that the design validation of high dam structures should be carried out with consideration of creeping.

All this conditions urgency of study and prediction of rockfill creep deformations.

Literature review

Creep of materials has been studied from the 19th century. Studies of creeping are directed on development of rheological models of materials, which permit making predictions of deformations.

The simple theoretical models of viscoelastic behavior of materials are J.C. Maxwell model and W.T. Kelvin – W. Voigt model. Mechanical scheme of Maxwell model presents sequential relations of the elastic element (spring) and the viscous damper: total deformation is composed of deformations of these two elements. In Kelvin–Voigt model, the spring and the damper are connected in parallel (Fig. 1a); at perception of load, they are deformed jointly. However, experiments are required for determination of parameters of rheological models.

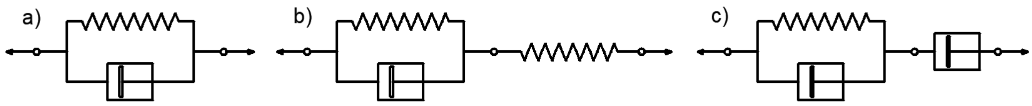


Figure 1. Mechanical schemes of rheological models:
a – Kelvin–Voigt model; b – Merchant model; c – Maxwell–Kelvin model.

Up to the middle of the 20th century, rockfill creeping had been studied only based on the experience in operation of the constructed rockfill dams. Later, due to appearance of large-scale instruments allowing development of great forces, study of rockfill creeping in laboratory conditions became possible.

In 1960–1970s, for the constructed Mica dam (Canada, H = 243 m, 1973), tests of coarse soils were carried out. R.J. Marsal during studies marked two characteristic stages of soil deformation in odometer [5]. These stages differ by the form of the diagram of relationship between deformations and time. The first stage is characterized by active growth of deformations; at the diagram plotted in semilogarithmic scale (time logarithm is put on the horizontal axis), this stage is presented in the form of “S-shaped” curve. The second stage is characterized by damping of creep deformations. In semilogarithmic system of coordinates, it may be presented in the form of a straight line, therefore, at this stage, the logarithmic relationship between deformations and time may be assumed. In [6], it is shown that, based on the results of in-kind measurements, the dam settlements change over time according to a logarithmic curve.

Fuller understanding of soil deformation mechanisms is obtained from the tests in stabilometer in conditions of triaxial compression. Large volume of such experimental studies was performed by the Chinese scientists [7–14] as a great number of high and ultra-high dams were constructed in this country. Experimental studies of rockfill were carried out using large-scale instruments. [12] describes the results of tests in a compression instrument with a diameter of 502 mm and a height of 252 mm. [10] describes the results of tests of granite rock mass in a triaxial compression device with a diameter of 150 mm and a height of 300 mm. [7–9, 13–14] describe tests in triaxial compression devices with a diameter of 300 mm and a height of 600–700 mm under high compression pressures (up to 2 MPa). These tests show that rockfill deformations are durable in time. The less is the ratio between axial and lateral stresses, the more share of deformations will be revealed in the form of creeping.

The authors of experimental studies [7–9, 12, 14] recommended to use exponential function for description of time dependent variation of deformations. In the function of this type, the rate of deformation also varies by exponential law. In [8], it is substantiated that logarithmic and exponential functions cannot be used for description of the creeping process.

However, laboratory tests do not give full understanding of rockfill creeping because they cover only the first day after load application.

Experimental data cannot provide thorough information on damping of rockfill in the dam body because it may take place in a more complicated way. Growth of creep deformations may have damping, stable (at constant rate), or progressive character.

Therefore, starting from the end of the 20th century the other method of rockfill creeping study, i.e., “back analysis,” began to be used. It envisages selection of such soil mathematical model, which can properly describe deformation of the existing dam.

In [11], a linear model supplemented with a creep model was used for stress-strain state (SSS) modeling. In China, the Duncan–Chang hyperbolic model, supplemented with a creep model, is used to model SSS dams. Several creeping models are applied.

In 1998, the Chinese scientists Z. Shen and K. Zhao proposed [15] use of the creep model (Shen-Zhujiang model) whose mechanical scheme corresponds to W. Merchant model. In it, Kelvin–Voigt model is sequentially joined with the elastic element (Fig. 1b). In Shen-Zhujiang model, there was adopted exponential relationship between deformations and time. During refinement, the number of this model parameters increased from 3 to 7. Different alternatives of this model were used in [3, 16–20] for modeling SSS of a number of dams. It should be noted that in the study in [3], use of the model alternative with 4 parameters did not permit reaching good agreement of the design data with the field measurements.

In 2004, Chinese researches Z. Cheng and H. Ding based on experiments proposed a similar model of creeping, but with exponential function [7]. This model with 9 parameters was used for modeling behavior of Shuibuya dam (China, H = 233 m, 2008) [21–23]. In [24], a different soil model was used to calculate the Shuibuya dam, but also with an exponential creep function.

Later, the Chinese researches also began to use more complicated rheological models (for example, Burgers model). Composite models not only contain a greater number of parameters but are also based on more complicated mechanical scheme, with more complicated structure and greater number of elements. At that, different functional relationships may be adopted for the elements of one type.

In [25, 26], there was applied the model with J.M. Burgers mechanical scheme. In [27–30], the model was used whose mechanical scheme contains 3 elastic elements, 3 dampers, and 1 element of dry friction.

Variety of rheological models evidences that rockfill creeping was insufficiently studied. Therefore, effect of creeping on rockfill dam workability also remains unstudied.

Aims and tasks of study

The aim of our study consists of investigating the effect rockfill creeping on the dam SSS.

However, there are several obstacles in reaching this aim. One of them is in the fact that in Russia, there are no suitable software permitting use of complicated rheological models. Therefore, one of the tasks of studies was selection of a rheological model, which, on the one hand, could be available, and on the other hand, could rather accurately represent creep deformations of a rockfill dam.

2. Materials and Method

Soil model

Software package MIDAS permits to carry out creep modeling. In it at use of Mohr–Coulomb elastic-plastic model, there is a possibility to apply integrated empirical model of creeping. This creep empirical model corresponds to mechanical scheme of Maxwell–Kelvin. As Merchant model, the model of Maxwell–Kelvin also presents a sophisticated Kelvin–Voigt model. But in its mechanical scheme, to the model of Kelvin–Voigt there sequentially connected not an elastic element but one more damper (Fig. 1c). At such a scheme, Kelvin–Voigt model is intended for simulation of damping creep, and the second damper – for representation of continuous deformations.

Maxwell–Kelvin model is simpler than the other models (for example, Burgers model), but composition of its elements may be quite sufficient for designing.

Mathematical model of Maxwell–Kelvin in software package MIDAS is written in the form of the following formula:

$$\varepsilon = a \cdot \sigma^{b}\left[1-\exp\left(-c \cdot \sigma^{d} \cdot t\right)\right]+e \cdot \exp\left(f \cdot \sigma\right) \cdot t, \quad (1)$$

where ε – relative deformation; σ – stress; $a,\ b,\ c,\ d$ – empirical parameters for description of damping creep; $e,\ f$ – empirical parameters for description of constant creeping.

As we can see, the empirical model of creep (1) contains 6 parameters. However, as compared to Shen-Zhujiang model, it includes not a single but two components. The first component represents the damping character of creeping and the second one – the undamped character.

In formula (1), the rate of deformation variation depends not only on time but also on stresses, i.e., it considers the effect, which was found in laboratory experiments.

Subject of study

As a subject of study, there was selected Tianshengqiao-I concrete faced rockfill dam (China, H = 178 m, 1999) because the results of field measurements during construction and operation periods were published for this dam [3].

Tianshengqiao-I dam was constructed of sedimentary rocks and has a heterogeneous structure (Fig. 2). In the dam upstream zone (IIIB), there was placed limestone rock mass from the quarry (maximum size 800 mm), and in the downstream zone (IIIC) – rock mass of mudstone with size up to 1600 mm (zone IIID).

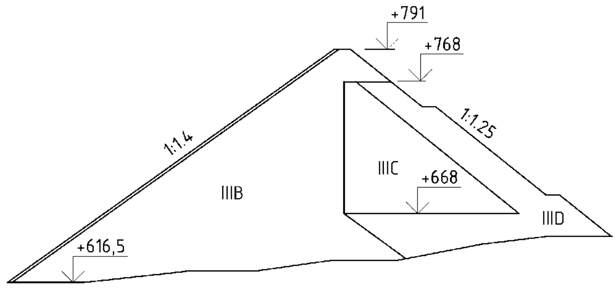


Figure 2. Scheme of the structure of the Tianshengqiao-I dam profile (China): IIIB – limestone fill up to 800 mm in size, IIIC – argillite and sandstone fill from useful excavations, IIID – limestone fill up to 1600 mm in size.

The dam was constructed in the period of 1996–1999. In September 1999, the reservoir was impounded to the level of 768 m. The diagram of the dam height growth and the reservoir level is shown in Fig. 3; it was plotted in compliance with [3].

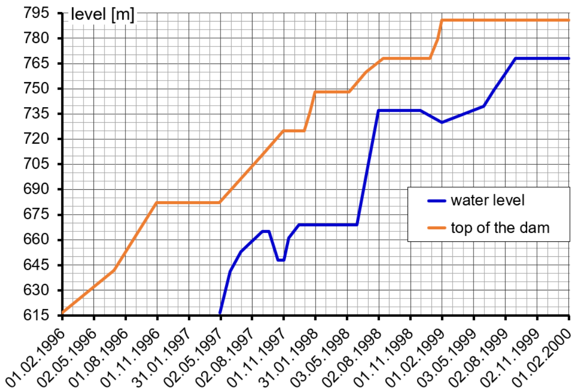


Figure 3. Graph of changes in dam crest and reservoir level.

A number of sensors was located in the dam for measuring displacements (Fig. 4). Analysis of natural displacements show that the dam had high deformations during the construction period. Maximum construction settlement (in 1999) amounted to 3.2 m (Fig. 4), i.e., 1.8 % of the dam height. The crest horizontal displacement after the reservoir impoundment comprised about 0.4 m.

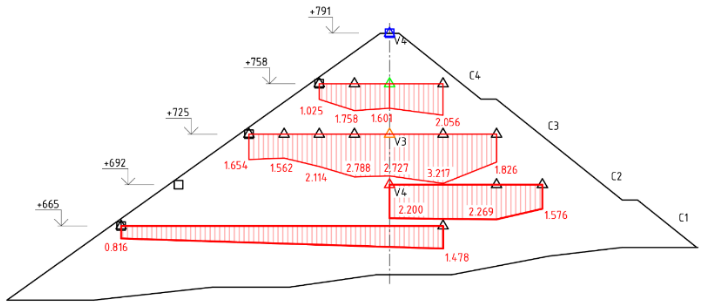


Figure 4. Settlement (m) of Tianshengqiao-I Dam points in August 1999.

High deformation of rock mass became the cause of emergency situations related to break of integrity of the reinforced concrete face. In the zones of conjugation of different construction stages, horizontal cracks appeared in the face [3].

Finite element model was performed for maximum by height cross section of the dam. It included only the rockfill shell; the reinforced concrete face was not taken into account. Dividing the section into finite elements considers the presence in the structure of soils of various quality, as well as sequence of the dam filling. The finite element model consists of 2562 finite elements of solid type (Fig. 5).

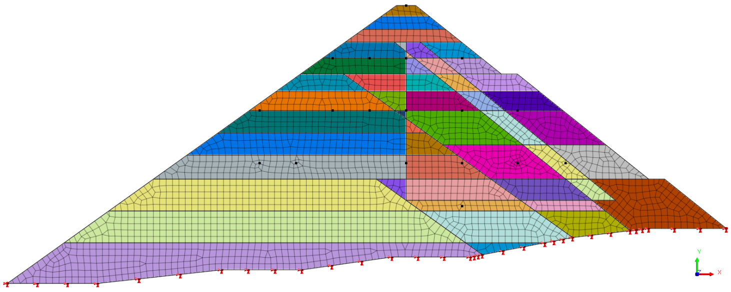


Figure 5. Finite element model of a dam cross-section.

Design procedure

The study was conducted by “back analysis;” the aim of analysis was selection of parameters for Mohr–Coulomb and Maxwell–Kelvin models. They were selected in such a way to obtain proper conformance of the design and natural displacements of the dam body.

Analysis was performed for loads from the dead weight and hydrostatic pressure on the dam upstream face; at each stage, the load was applied instantly. The construction period included 23 stages of the dam body filling and 13 stages of the reservoir level variation. Non-stationary problem was solved: there were sequentially considered SSS variation during several thousands of time intervals; the time interval was 1 day.

Density (specific weight) of the dam body soils was taken by data [3]. Selected as a result of studies, parameters of Mohr–Coulomb and Maxwell–Kelvin models are given in Tables 1 and 2.

Table1. Design physical and mechanical properties of rockfill.

Profile zones	Specific weight, кN/m^3	Elastic modulus, MPa	Poisson’s ratio
Upstream zone	21.2	50	0.27
Downstream zone	21.5	40	0.27
Downstream slope cover	20.5	40	0.27

Table 2. Design parameters of creep model.

Parameter	a	b	c	d	e	f
Value	$2 \cdot 10^{-5}$	0.5	$1.5 \cdot 10^{-8}$	0.015	$1 \cdot 10^{-11}$	$1.5 \cdot 10^{-15}$

Of interest is the fact that the parameter is not equal to 1, which evidences that the selected empirical model provides non-linear relationship between stresses and deformations.

The indicated model parameters correspond to the design alternative 1. For evaluation of creeping effect, there was accomplished the design alternative 2, where the creeping model is not used and calculation is carried out by initial Mohr–Coulomb model.

3. Results and Discussion

As a result of studies, for each design alternative, there was obtained the dam SSS at all the design stages.

Checking adequacy of the dam numerical model

For checking adequacy of the obtained results, the comparison was made of design displacements of the dam points with the measured ones at the existing dam. Fig. 6 shows comparison of settlements for four points located along the dam axis at different heights; Fig. 7 shows comparison of the crest horizontal displacements. Data of field measurements are given for these points in [3]. From the diagrams of Fig. 6 and 7, it is seen that on the whole the numerical model satisfactorily represents both displacement values of the existing dam points and their variation in time.

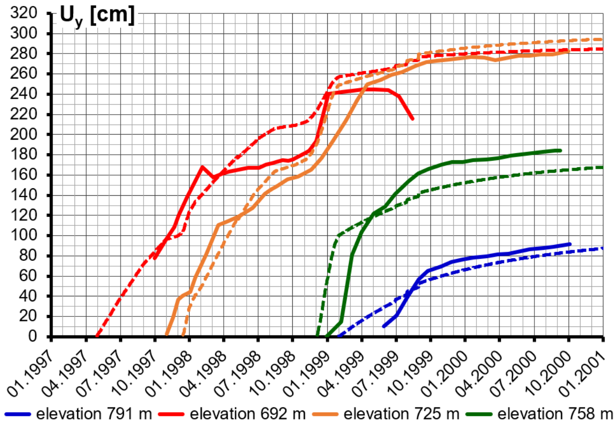


Figure 6. Change in time of settlement of dam points.
The solid line indicates measured settlement, the dotted line indicates calculated settlement.

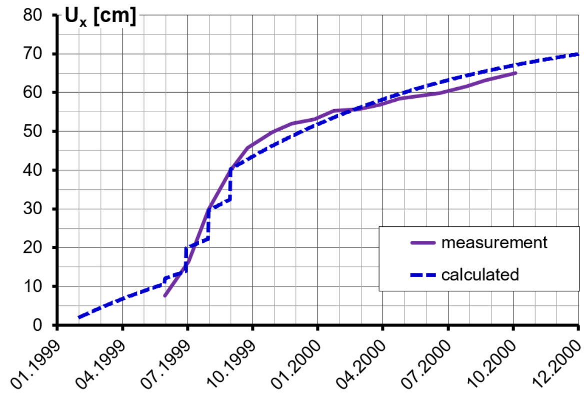


Figure 7. Time evolution of horizontal displacements of the dam crest.

Reliability of the numerical model permitted analyzing time-dependent variation of the dam SSS and effect of rockfill creeping on this process.

Analysis of dam SSS

Figures present SSS for three moments of time. The first moment corresponds to completion of the dam filling in January 1999, the second – to the time of the reservoir level elevation in August 1999. These two moments of time correspond to the completion stage of the construction period. The third moment of time corresponds to November 2006, i.e., 7 years of operation.

Analysis showed that at the completion stage of the dam construction, considerable SSS variations took place. They were caused by increase of hydrostatic pressure on the upstream face and rockfill creeping. Maximum settlements of fill increased from 270 cm (Fig. 8a) to 280 cm (Fig. 8b), and horizontal displacements towards the downstream side increased from 125 cm (Fig. 9a) to 145 cm (Fig. 9b).

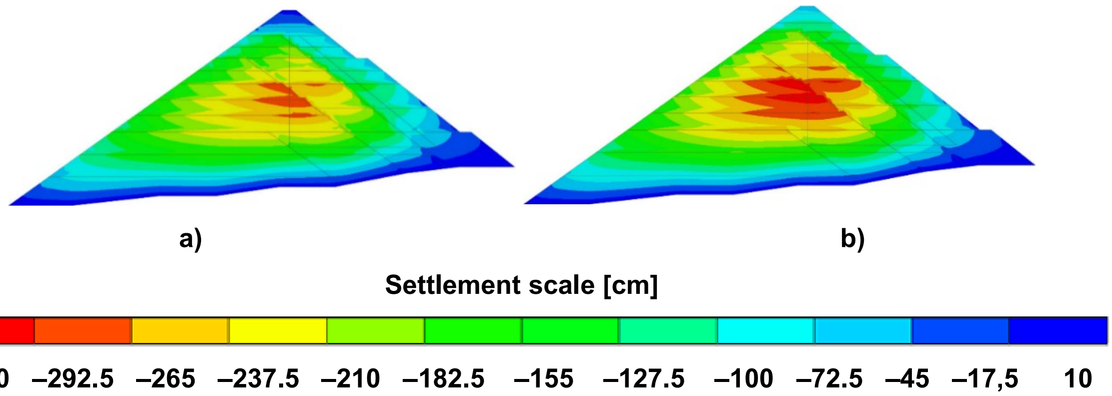


Figure 8. Dam settlements based on numerical modeling results taking into account creep:
a – January 1999, b – August 1999.

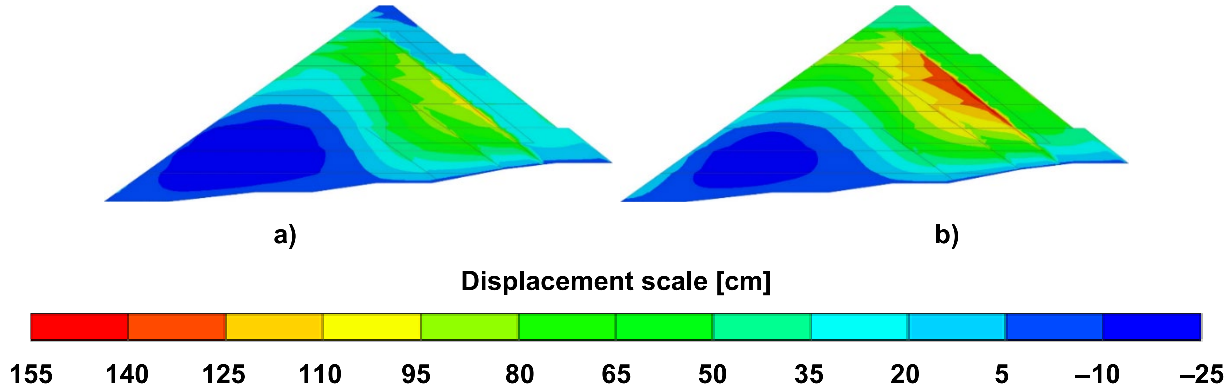


Figure 9. Horizontal displacements of the dam based on the results of numerical modeling taking into account creep: a – January 1999, b – August 1999.

During operation, creeping causes further growth of the dam displacements (Fig. 10). In the first 3 years of operation, it is rather intensive. By November 2006, maximum settlements U_y increased to 320 cm (Fig. 10a), and maximum displacements to 155 cm (Fig. 10b). In percentage terms, maximum settlement increased by 14 %, and maximum displacement by 7 %.

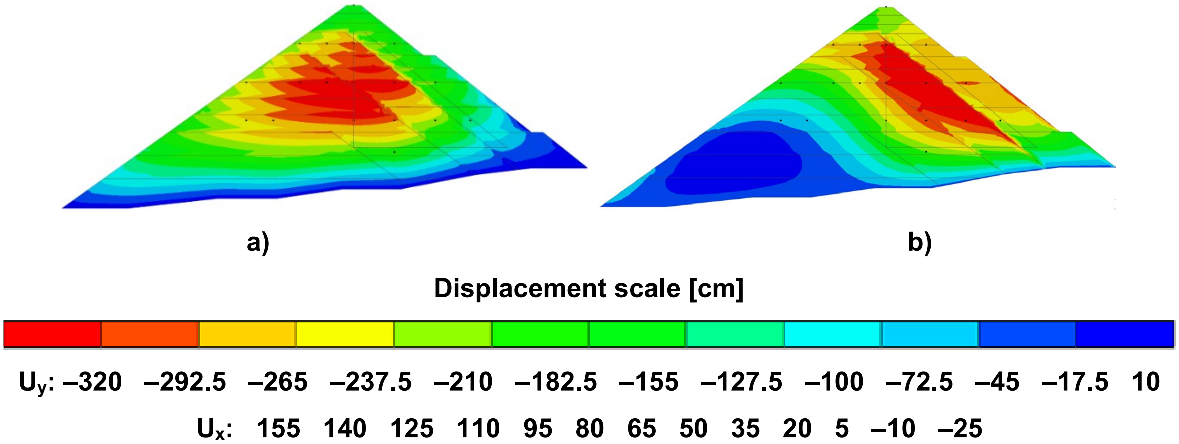


Figure 10. Dam displacements based on numerical simulation results (November 2006) taking into account creep: a – horizontal displacements, b – vertical settlements.

Evaluation of creeping effect on dam displacements and deformations

In order to evaluate the effect of creeping on the dam displacements during construction period, there were compared the displacements calculated with use and without use of the creeping model. The displacements obtained from Mohr–Coulomb model without use of the creeping model are shown in Figs. 11 and 12. It is well noticed that settlements (Fig. 11) and horizontal displacements (Fig. 12) of the dam in this case are much less than at consideration of development of creeping deformations.

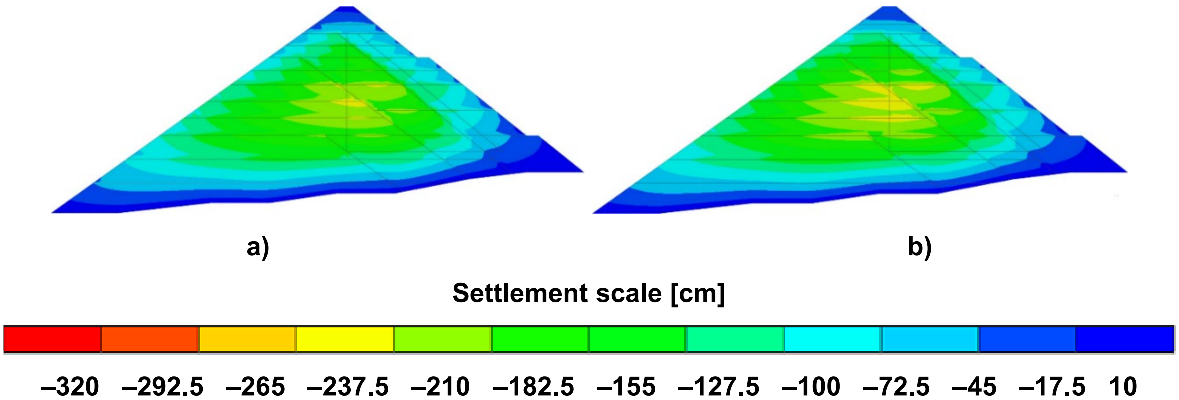


Figure 11. Dam settlements based on numerical modeling results without taking into account creep: a – January 1999, b – August 1999.

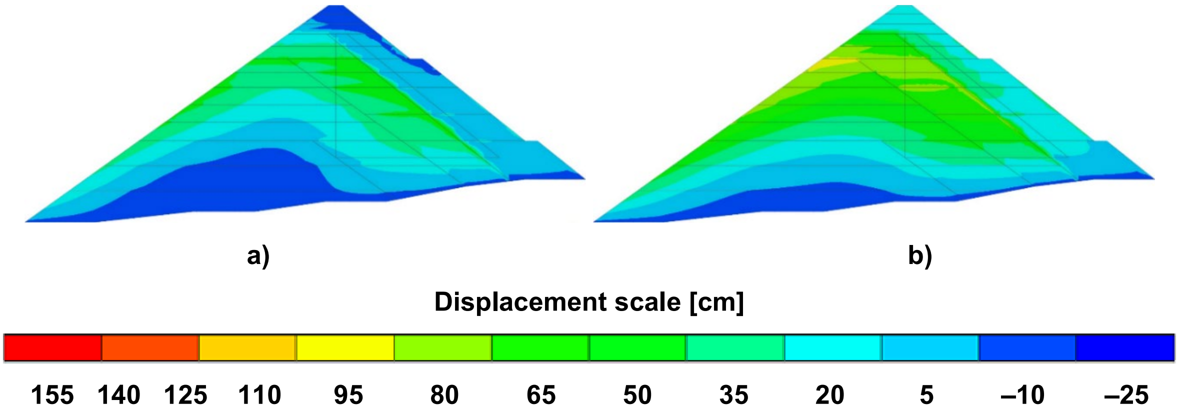


Figure 12. Horizontal displacements of the dam based on the results of numerical modeling without taking into account creep: a – January 1999, b – August 1999.

Difference in displacements obtained for two indicated design diagrams reflects the effect of creep deformations. However, these displacements correspond not to total creep deformations (which are developed from the moment of load application) but only to their part for which durable time was required (more than design step for time of 1 day). The durable part of creep deformations represented by the empirical model creeping will be called cumulative (with time) deformations.

Comparison showed that in settlement values, the share of cumulative deformations is not large. For the moment of the dam filling completion (January 1999), it does not exceed 33 %; its maximum is a characteristic feature for the dam upstream part in the middle of the height. In the other dam zones, this share decreases to 15 %. With time, the share of cumulative deformations increases mainly in the upper part of the dam. In the crest settlement, this share amounts to: for the moment of dam filling completion (January 1999), it is about 20 %, and at the start of operation (August 1999), it is already 70 %.

In formation of horizontal displacements, the role of cumulative deformations is much greater; it is revealed both in the values of displacements and in the pattern of distribution along the dam profile. This is related to the fact that the dam is subject to two types of loads: the dead weight and hydrostatic pressure on the upstream slope. Under the action of the dead weight, deformations of lateral expansion take place and under the action of hydrostatic pressure, it displaces towards the downstream side. Complicated character of horizontal displacements is the result of these two types of deformations.

Two zones may be distinguished in the dam: the near-crest zone (approximately higher than ∇745 m) and the lower zone. In the near-crest zone, shear deformations prevail; here with time, the displacements increase towards the downstream side. For example, for the moment of start of operation period (August 1999), the crest displacement by Mohr–Coulomb model amounts to 23 cm, and by calculation with consideration of creeping, it is 40 cm.

In the lower part of the dam, deformations of lateral expansion prevail. With time, increase of the dam upper part displacements towards the upstream side takes place and in the lower part – towards the downstream side. The more is the distance from the dam axis, the higher are increments of accumulated displacements. Increments of displacements are comparable by value with displacements by Mohr–Coulomb model (without consideration of creeping) or even exceed them.

With time, the described character of displacements is remained, but in view of cumulative deformations in values of displacements. For example, over the first 3 years of operation, the crest displacement increased from 40 cm to 83 cm.

Of special interest is the effect of cumulative deformations on the values and distribution of displacements of the upstream face because the reinforced concrete face is located there. In the lower part, accumulation of creep deformations leads to decrease of displacements of the upstream face towards the downstream side and in the upper part – to their increase (Fig. 13). This result is indirectly confirmed by the data of field measurements at the dam. By [3], maximum face displacements were observed in the dam upper part and amounted to 70 cm. Such pattern of the face displacements has adverse effect on the face strength because it increases its bend.

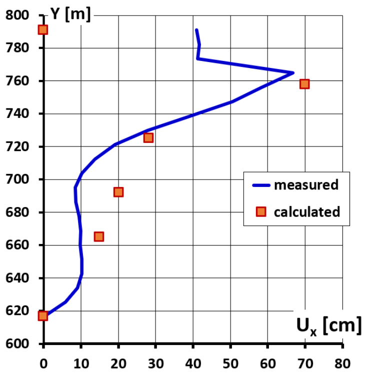
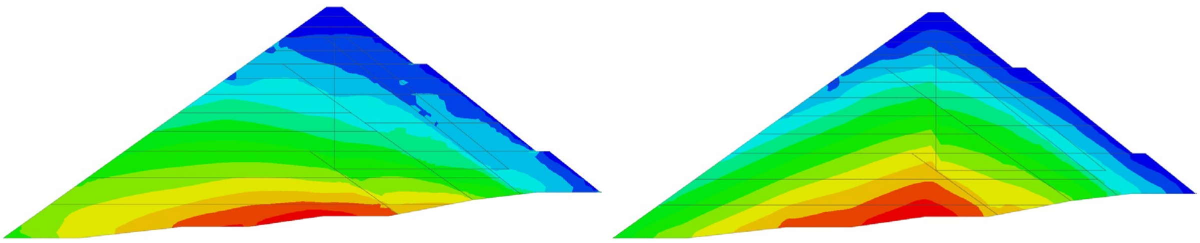


Figure 13. Horizontal displacements of the upstream face of the dam.

Evaluation of the effect of accumulated with time deformations on the dam stress state

For evaluation of the creeping effect on stresses, comparison of stresses was made for two moments of time: for start of operation (August 1999) and after 7 years of operation (November 2006).

Analysis showed that in spite of the existing growth of displacements due to creeping, stresses in the dam body vary to a small extent. Variations in distribution and values of normal stresses (horizontal σ_x and vertical σ_y) during operation are actually unnoticed. For distribution of stresses σ_y, the characteristic feature is weak hanging-up of the dam downstream part over its upstream part (Fig. 14b). For distribution of stresses σ_x, the typical feature is development of the zone of concentration of compressive stresses at the contact with the rock foundation (Fig. 14a).



a) **b)**

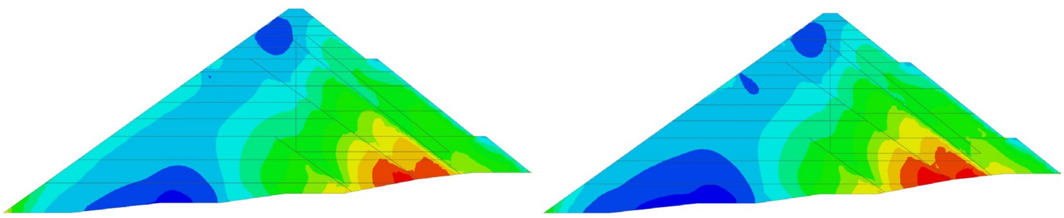
Stress scale [MPa]

σ_x: –1.8 –1.65 –1.5 –1.35 –1.2 –1.05 –0.9 –0.75 –0.6 –0.45 –0.3 –0.15 0

σ_y: –3.0 –2.75 –2.5 –2.25 –2.0 –1.75 –1.5 –1.25 –1.0 –0.75 –0.5 –0.25 0

Figure 14. Normal stresses in the dam body based on the results of numerical modeling (August 1999) taking into account creep: a – stresses σ_x, b – stresses σ_y.

According to the shear stresses τ, some increase in values is noted in the first 3 years of operation (Fig. 15), which is explained by the increase in shear deformations due to creep.



a) **b)**

Stress scale [MPa]

–0.6 –0.54 –0.47 –0.41 –0.35 –0.29 –0.22 –0.16 –0.1 –0.04 –0.025 0.09 0.15

Figure 15. Shear stresses in the dam body based on the results of numerical modeling: a – August 1999, b – November 2006.

4. Conclusion

1. Maxwell–Kelvin rheological model with sufficient accuracy permits simulation of time-dependent character of growth of rockfill dam deformations due to rockfill creeping. Its adding to linear Mohr–Coulomb model allows solving the problem on dam SSS formation with consideration of non-linear character of rockfill deformation.
2. By the results of analysis, a large share of the dam displacements during construction period was accumulated with time due to creeping. In settlements, the share of cumulative with time deformations reaches 33 % of the total ones. The indicated deformations consider the part of creep deformations, which accumulated over durable time after application of load.
3. Rockfill creep deformations affect accumulation of horizontal displacements in a complicated way. The character of the dam deformation due to creeping is the result of summation of two processes. On the one hand, creeping contributes to further dam displacement (shear) towards the downstream side under the action of hydrostatic pressure. On the other hand, it leads to increase of the dam expansion to both sides under the action of the dead weight. In the dam lower part, the deformations of lateral expansion prevail while in the upper part, shear deformations prevail. Such character of the dam deformation may affect the SSS of the reinforced concrete face located on the dam upstream slope because it increases its bend deformations.
4. For the considered dam, the increment of maximum displacements over the first 3 years of operation (from displacements of construction period) amounted to: settlements – 15 %, horizontal displacements – 7 %.
5. Creep deformations have small effect on the stress state of the rockfill dam body; growth of shear deformations results in some increase of tangent stresses in the first 3 years of operation.

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