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NUMERICAL SOLUTION OF THE FILTRATION-DEFORMATION PROBLEM IN THE CASE OF PHASED CONSTRUCTION OF A STORAGE DAM

Nikolay A. Aniskin, Stanislav A. Sergeev, Andrey V. Stupivtsev, Ilia A. Bokov

Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract. This paper presents the results of numerical modeling of the joint filtration-deformation problem for a storage dam taking into account its construction and filling of the pond bowl in 3 stages. Two variants of th e structure operation were considered: with the tubular drainage operating and excluded from operation. According to the results of researches the stability of the structure and parameters of filtration regime were evaluated. Recommendations on ensuring reliability and safety of the structure are formulated.

Keywords: numerical solution, finite element method, storage dam, filtration-deformation problem, depression surface, slope stability

ЧИСЛЕННОЕ РЕШЕНИЕ ФИЛЬТРАЦИОННО-ДЕФОРМАЦИОННОЙ ЗАДАЧИ ПРИ ПОЭТАПНОМ ВОЗВЕДЕНИИ ДАМБЫ НАКОПИТЕЛЯ

Н.А. Анискин, С.А. Сергеев, А.В. Ступивцев, И.А. Боков

Национальный исследовательский московский государственный строительный университет» (НИУ МГСУ), г. Москва, РОССИЯ

Аннотация. В данной работе представлены результаты численного моделирования совместной фильтрационно-деформационной задачи для дамбы накопителя с учетом ее возведения и наполнения чаши накопителя в 3 этапа. Рассматривалось два варианта работы сооружения: с действующим и исключенным из работы трубчатым дренажем. По результатам исследований дана оценка устойчивости сооружения и параметров фильтрационного режима. Сформулированы рекомендации по обеспечению надежности и безопасности сооружения.

Ключевые слова: численное решение, метод конечных элементов, дамба накопителя, фильтрационно-деформационная задача, депрессионная поверхность, устойчивость откоса

INTRODUCTION

For creation of accumulators of secondary material resources (“tailings” in the process of ore dressing, sludge in metallurgical production, fly ash in the operation of thermal power plants), dams from ground materials are used as enclosing structures. Also, industrial wastes can be used as materials for dam construction (as a rule, for building up the primary dam of the accumulator) if their properties allow it. As a rule, the construction of such storage dams is carried out in stages with their gradual filling. Such structures belong to hydraulic engineering structures and are subject to the same loads and impacts as earth dams. The peculiarity for the considered case is the gradual formation of stress-strain state of the erected soil massif. Also in the process of erection there is a change in the influence of water from the side of the storage bowl and the weighting and hydrodynamic pressure in the soil mass as a result of filtration flow. Operability of such structures depends to a great extent on the filtration regime. Certain requirements are imposed on the position of the depression curve, values of filtration flow rates, velocities and gradients [1, 2]. The results of filtration calculations are necessary to assess the filtration strength of dam soils, to calculate transition zones and return filters, to calculate the stress-strain state and stability of the slopes of the earth dam.

One of the important structural elements of storage dams are drains necessary for lowering of the depressive surface position and organized drainage of filtered water. During operation of the structure, the drainage failure is possible, which can be caused by its colmatization [3, 4]. In this case the depression surface in the downstream prism of the dam rises, which can lead to undesirable consequences: threat of ground freezing in the zone of filtration flow outlet to the downstream in winter period.

This paper presents the results of filtration and deformation studies on a numerical model of a storage dam being built up during operation. Joint calculations of filtration, stress-strain state and stability of the dam slopes were carried out using the software package "PLAXIS 2D" based on the finite element method [5]. The results obtained made it possible to draw conclusions about the reliability of the structure and propose measures to improve its operation.

METHODS

The solution of this problem involves a joint filtration problem and the problem of determining the stress-strain state of the gradually built-up body of the storage dam. At each stage, the problem of unsteady filtration is solved with determination of filtration regime parameters necessary for calculation of the stress-strain state: position of the depression surface, values of filtration gradients and filtration volume hydrodynamic load in the design area.

In the most complicated cases, the filtration flow can pass through areas with different degrees of saturation of soil pores with water. This is the case when the water level in front of the structure changes in time. Then it is possible to conditionally divide the design area into 2 zones in which the filtration flow motion will be described by different dependencies [6, 7].

The basic differential equation of filtration [7] is used for the part of the design area of filtration, where the filtration flow movement occurs in a fully saturated water medium:

$$\frac{\delta}{\delta x}\left[k_x\frac{\delta h_t}{\delta x}\right]+\frac{\delta}{\delta y}\left[k_y\frac{\delta h_t}{\delta y}\right]+\frac{\delta}{\delta z}\left[k_z\frac{\delta h_t}{\delta y}\right]=S_s\frac{\delta h_t}{\delta t} \quad (1)$$

where $h_t = f(x, y, z, t)$ - head function in the considered area, varying along coordinates x, y, z and in time t; k_x, k_y, k_z - filtration coefficients of saturated soil in directions of axes x, y, z; S_s - saturation of soil.

Saturation can be expressed as follows: $S_s = \gamma_w (m_v+n\beta)$, where γ_w - specific weight of water, n - porosity, β - compressibility of water, m_v - volumetric compressibility coefficient of the soil of the filtration area.

Since water is not very compressible ($\beta = 4.7 \cdot 10^{-7}$ kPa - for cases of filtration flows), we can take $S_s = \gamma_w \cdot m_v$ in equation (1).

In the case when filtration in a region with incompletely saturated ground pores with water is considered, equation [7] is used for the solution:

$$\frac{\delta}{\delta x}\left[k(h_m)\frac{\delta h_m}{\delta x}\right]+\frac{\delta}{\delta y}\left[k(h_m)\frac{\delta h_m}{\delta y}\right]+\frac{\delta}{\delta z}\left[k(h_m)(\frac{\delta h_m}{\delta z}+1)\right]=C(h_m)\frac{\delta h_m}{\delta t} \quad (2)$$

where $k(h_m)$ is the value of the filtration conductivity function; hm is the filtration head deficit (suction head); $C(h_m)$ is the slope of the soil volumetric water saturation curve.

At present, filtration problems are mainly solved using the finite element method (FEM) [8-13]. There are many program complexes (PCs) in which the solution of the steady filtration problem consists in solving the basic differential equation of filtration theory (1) using known boundary conditions. The position of the depression surface is determined by an iterative process.

Many studies conducted in recent years [14-18] have focused on the study of filtration processes, in a nonstationary state in incompletely saturated soils with a degree of water saturation $S_e < 0{,}8$. In this case, the complexity of the solution based on differential equation (2) consists in determining the parameters $k(h_m)$ and $C(h_m)$.

The model developed by Mualem in 1976 [19], which describes how the water permeability and water holding capacity of a soil depend on its degree of water saturation, is one of the widely used models in the field.

This model offers a relatively simple form for calculating the filtration conductivity of unsaturated soils. Additional research conducted by Van Genuchten in 1980 [20] compared the results based on Mualem's theory with direct measurements for a variety of differently characterized soils. The Van Genuchten model offers a way to describe the filtration characteristics for a wide range of soils, expressed through the relationship between the soil volumetric water saturation θ and the head deficit (suction head) h_m :

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h_m)^n\right]^m}, \tag{3}$$

where θ_s – volume content of saturated water in the soil pores; θ_r - residual volume content of water in the soil pores; h_m - filtration head deficit (suction head); α, n and $m=1-1/n$ parameters of soil property curves (determined as a result of soil laboratory tests).

Filtration permeability of unsaturated soil is determined in accordance with the Van Genuchten model as follows:

$$k(h_m) = k_s \sqrt{S_e}\left[1 - (1 - S_e^{1/m})^m\right]^2, \tag{4}$$

where k_s – filtration conductivity (filtration coefficient) of saturated soil; S_e – degree of soil saturation, which is determined by dependence [20]:

$$S_e = \left[1 + (a h_m)^n\right]^{-m}, \tag{5}$$

Within the framework of this work, filtration studies were performed using the “PLAXIS 2D” software package based on the finite element method. The filtration calculations module of this complex “PlaxFlow” uses differential equations of saturated and unsaturated filtration (1-2) for solution. In the case of filtration in unsaturated soils, the Van Genuchten model described above (3-5) is used to determine the soil properties [20].

As a result of solving steady-state and transient filtration problems, a picture of filtration development in the dike and the foundation in the process of stage-by-stage construction of the dike and filling of the storage bowl was obtained. The position of the depression surface, distribution of heads, filtration gradients and velocities, volumetric filtration hydrodynamic load were determined for each stage.

Based on the obtained results of solving filtration problems at each stage, the stress-strain state of the dam and foundation was also evaluated and critical slip surfaces with stability coefficients were determined.

To solve the coupled filtration-deformation problem, the Plaxis 2d software package uses the calculation type “Fully coupled flow-deformation” using equation [5]:

$$\begin{bmatrix} K & Q \\ 0 & -H \end{bmatrix}\begin{bmatrix} v \\ p_w \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ C & -S \end{bmatrix}\begin{bmatrix} \frac{dv}{dt} \\ \frac{dp_w}{dt} \end{bmatrix} = \begin{bmatrix} f_u \\ G + q_p \end{bmatrix} \tag{6}$$

where K is the stiffness matrix; H is the permeability matrix; Q, C is the coupling matrix and S the compressibility matrix; v is the displacement value; pw is the pore pressure; q_p is the flow function at the model boundaries; f_u is the loading vector; G is a vector that accounts for the effect of gravity on the flow in the vertical direction. This vector is part of the external flow.

On the basis of the joint unsteady deformation-filtration calculation, the stability coefficient of the upper slope of the dam was calculated.

To evaluate the stability of the slopes of the investigated soil structures in the PC “PLAXIS 2D” the “Safety” calculation is used, in which the strength characteristics of the soils (angle of internal friction, cohesion and shear strength) are successively reduced until the minimum value of the stability coefficient is reached. The results of the stability calculation are the determination of the possible shear surface - the most weakened surface along which failure is possible, and the calculated stability coefficient. The possible shear surface is characterized by the minimum possible tangential stresses. The minimum design stability factor is defined as the ratio of the actual surface strength to the fracture strength.

RESEARCH OBJECT

Filtration and deformation studies have been carried out in relation to the enclosing dam of a tailings storage facility constructed to accommodate and store residual products of primary hydrometallurgical processing of ores. The barrier dam is an earth hydraulic engineering structure constructed by layer-by-layer backfilling with subsequent rolling. The cross section of the structure is shown in Figure 1. The maximum height of the embankment is 36.5 m with a crest elevation of 760 m, crest width of 13 m, and length along the dam axis of 645.8 m. The top slope of the dam is 1:3.0, the bottom slope is variable and is 1:2.5; 1:3.0. Berms 5 m wide are provided along the entire height of the dike with a spacing of 10-12.5 m. The thickness of the reclamation layers in the bowl is 32 m, the bowl filling level is 753.5 m. In the downstream prism of the dam, drainage is provided to ensure that the depression curve near the downstream slope is lowered below the seasonal freezing level.

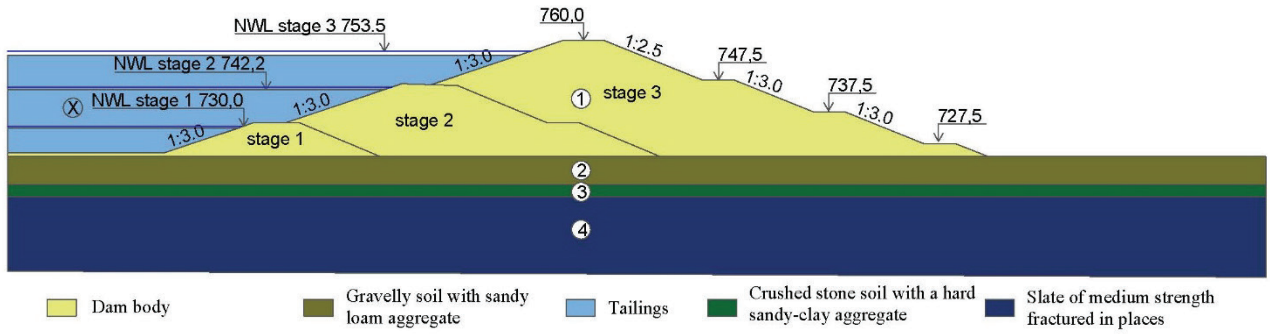

Figure 1. Cross-sectional profile of the tailings dam barrier

Table 1. Characteristics of soils

№ п.п	Soil type	Filtration coefficient m/day	Specific cohesion c, kPa	The angle of internal friction φ,°	Strain modulus E, kPa	Specific gravity ρ, kn/m^3
1	Sandy loam (dam body)	0,025	20	25	33500	21,3
2	Gravelly soil with sandy loam soil aggregate	0,08	16	33	29300	21
3	Crushed stone soil with a hard sandy-clay aggregate	0,09	15,0	20,3	30900	19,8
4	Slate of medium strength, fractured in places	0,00075	6535	35	50000	24,7
5	Tailings	0,003	21,1	19,5	7800	17,7

The volume of the technical reservoir at the design filling at the last stage is 10 million m3. The dam material is sandy loam. The base of the dam is predominantly gravel with sandy loam aggregate. There are interlayers of hard sandy loam up to 3 meters thick. At a depth of more than 13 meters there is medium strength shale, fractured in some places. Physical and mechanical characteristics of the soils used in the calculation are presented in Table 1.

Problem statement

The process of phased construction of the storage dam to full height and filling of its bowl in 3 stages was modeled (Fig.1). The time step between the dam construction stages is 3 years. The schedule of dam construction and filling of the tailings storage facility is presented in Figure 2.

At each step, after filling the corresponding stage of the storage capacity, an unsteady filtration problem was solved with the determination of filtration flow parameters. The results of these calculations were used in the calculation of the stress-strain state and stability of the downstream slope of the dam for this stage using the calculation type "Fully coupled flow-deformation" in the PC "PLAXIS 2D" [5].

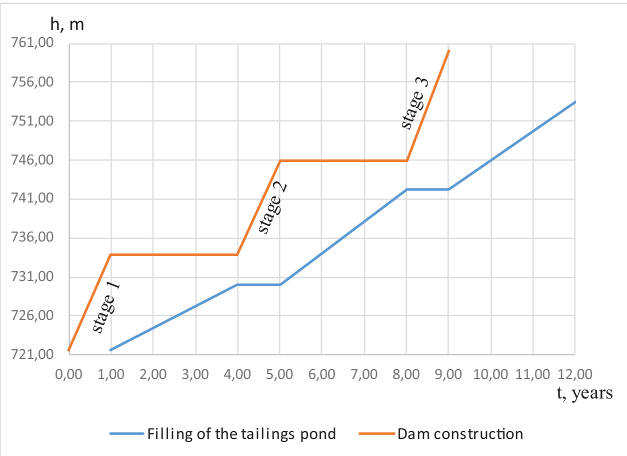

Figure 2. Schedule of dam construction and filling of the tailings pond bowl

Within the framework of the work two design cases were considered - the case of normal drainage operation and the case of drainage failure. The pipe drainage is located under the downstream prism at a distance of 64.0 m from the central axis of the dam (Fig. 1).

RESULTS

Filtration regime in case of full drainage operability.

Results of calculations of filtration regime for variant with full drainage operability are presented in Fig. 3-4.

Figure 3 shows the positions of the depression surface at the moments of time corresponding to the end of the filling stages (3, 6 and 9 years after the beginning of dam construction) and the moments of time 20, 25 and 30 years after the beginning of dam construction. It is possible to note gradual, rather long saturation of dam soil with water, which is caused by rather small value of dam soil filtration coefficient (k = 0.025 m/day). In case of normally operating drainage the soil of the downstream prism along the downstream slope is in dry condition. At that, its thickness up to the surface of the bottom slope all along exceeds the frost depth, which will ensure absence of ground freezing in winter period.

Figure 4 shows the distribution of filtration gradients in the dam massif at the time of stabilization of the filtration process (30 years from the start of construction). The maximum value of the gradient J_{max} = 1.48 was obtained at the outlet of the filtration flow into the drainage. To exclude filtration deformations at the outlet of filtration flow into drainage, this value should be used for calculation of drainage return filter and its device.

In accordance with the requirements to ensure the filtration strength of the soil [1] the inequality should be fulfilled:

$$J_{est,\,m} \le J_{cr,m} / \gamma_n \tag{7}$$

Where $J_{est,\,m}$ - average design head gradient of the seepage area; $J_{cr,m}$ - critical head gradient taken on the basis of laboratory studies of the dam soil or recommendations [1]; γ_n - reliability coefficient for the responsibility of the structure.

In our considered case $J_{est,\,m}$ = 0,29, $J_{cr,m}$ = 1,0 (according to [1] for sandy loam can be taken 2.0-

1.0), γ_n =1,25 (1st class of responsibility). Thus, the requirement (7) for this variant is fulfilled.

Results of filtration calculations of this variant testify to favorable filtration regime of the structure in case of proper operation of drainage.

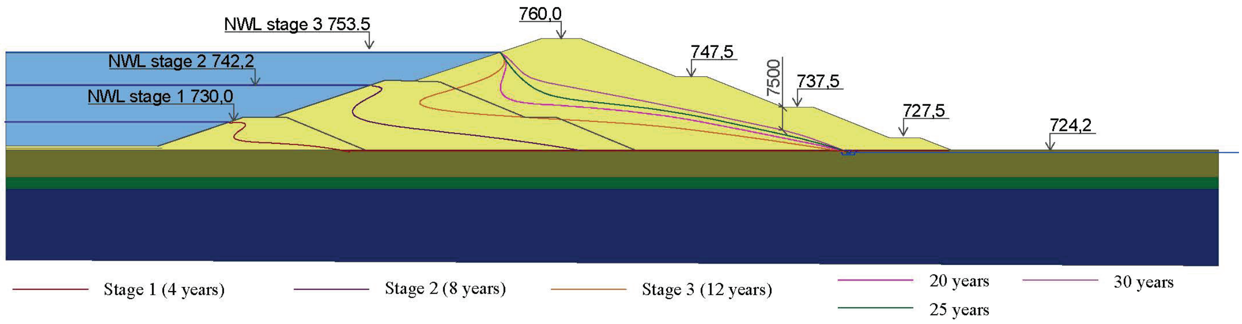

Figure 3: Position of the depression surface in the dam body in case of full operational capability of the drainage based on the results of unsteady calculation of filtration (transient flow) at stage filling and during the operation period

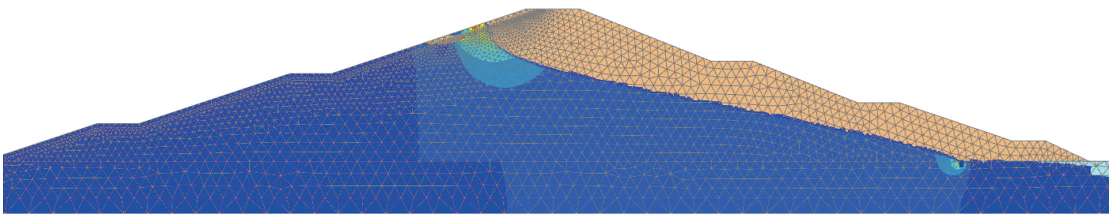

Figure 4. Distribution of head gradients in case of full serviceability of drainage according to results of unsteady filtration calculation (transient flow) at the moment of depression surface stabilization (30 years)

Filtration mode in case of complete drainage failure.

Drainage failure results in a significant increase in the position of the depression surface near the downstream slope of the dam (Figure 5-6). Over a significant length of the downstream slope, the distance from the slope surface to the depressional surface is less than the freezing depth. Operation of the structure under such conditions will result in freezing of the ground near the downslope slope and uplift of the depressional surface. If the frozen slope thaws in spring, it may lose its stability and collapse.

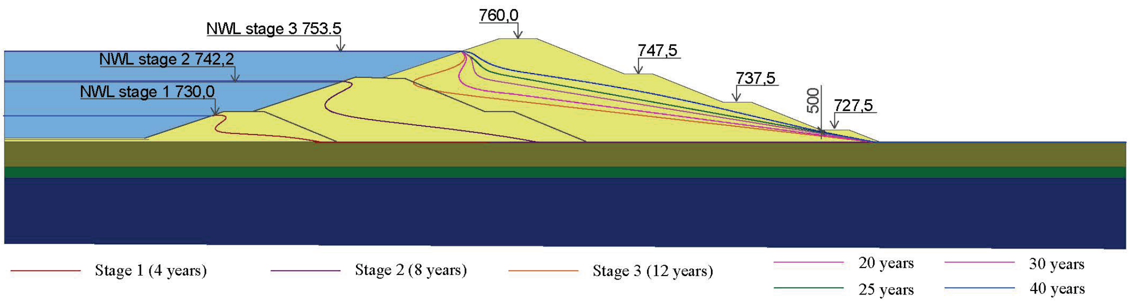

Figure 5. Position of the depression surface in the dam body in case of drainage failure based on the results of unsteady transient flow calculation during stage filling and operation period

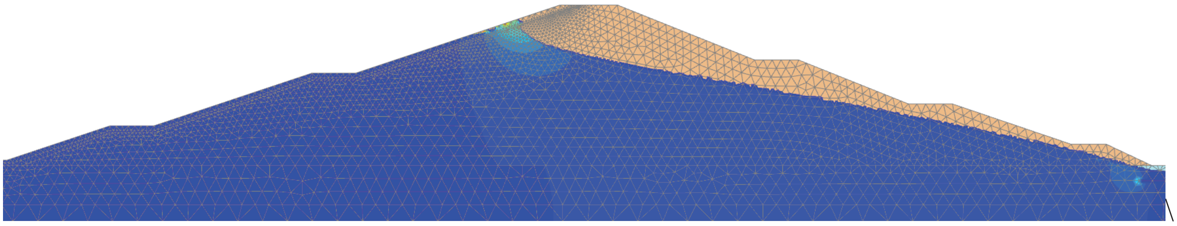

Figure 6. Distribution of head gradients in case of full serviceability of drainage according to the results of unsteady filtration calculation (transient flow) at the moment of stabilization of depressive surface (40 years)

Stabilization of dam soil saturation process comes for this variant in 40 years after the beginning of its construction. In order to ensure normal operation of the structure in case of drainage failure it is necessary to restore its serviceability or to pile additional soil massif on the part of the downstream slope, providing for the device of external drainage with a return filter. The value of maximum head gradient at the outlet of filtration flow, obtained for this option is equal to 1,67.

Requirements on average head gradient for this variant are also fulfilled ($J_{est,\ m}$ = 0,29).

Results of calculations of the stability of the downstream slope of the dam.

Using the results of the unsteady filtration calculations, the stability of the slopes of the dam body was calculated for the moments of time 10, 15, 20, 25, 30, 35, 40 years since the operation of the structure for each of the design cases. The results are presented in Figure 7,8 and Table 2.

For the variant with serviceable drainage during the operation period of the storage dam erected at full height, there is a gradual decrease in the stability coefficient over time from the value of 1.520 at the time of 10 years to the value of 1.351 at the time of 30 years, when the steady filtration regime is reached. The decrease is caused by gradual water saturation of the soil of the bottom prism and increase of hydrodynamic filtration force, which reduces the stability of the bottom slope. For this variant the stability requirements are fulfilled.

Table 2. Value of stability coefficients in unsteady filtration calculation.

Calculation option	Values of stability coefficients at service life						
	10 years	15 years	20 years	25 years	30 years	35 years	40 years
Operational drainage	1,520	1,406	1,383	1,369	1,351	1,351	1,351
Drainage failure	1,465	1,336	1,278	1,255	1,251	**1,249**	**1,247**

a) б)

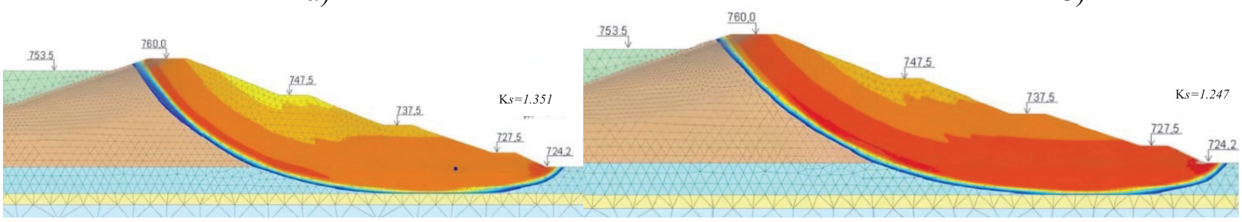

Figure 7. Slope shear surface: a - at the moment of stabilization of depression surface (30 years) in the dam body in case of proper operation of drainage, K_s= 1,351; b - at the moment of stabilization of depression surface (40 years) in the dam body in case of complete failure of drainage at non-stationary calculation of filtration, K_s= 1,247.

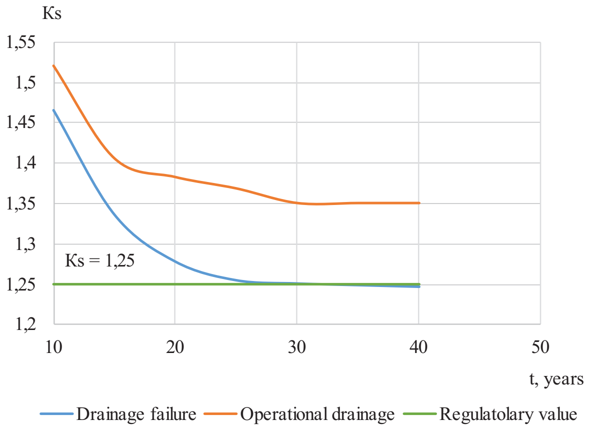

Figure 8. Graph of time dependence of dam slope stability coefficient in the process of operation

In case of non-working drainage at operation of the structure in time stability coefficient decreases from the value 1,465 (at the moment of time 10 years) to 1,249 - 1,247 (at moments of time 35-40 years). These obtained values are less than the normative stability coefficient K_s= 1,247 for this class of responsibility. Thus, operation of storage dam in considered variant with non-operating drainage is impossible.

RESULTS

Numerical solution of the joint filtration-deformation problem for the tailings dam being built up in stages is obtained. Two variants of the structure operation are considered: in case of normal operation of the pipe drainage and in case of its inoperability. The results of numerical investigations allowed to give an estimation of serviceability and safety of the structure during construction and operation.

Variant with working drainage satisfies all requirements to the structure on providing favorable filtration regime. In case of drainage failure the depression surface rises to the surface of the dam bottom slope, as a result of which the requirement to prevent freezing of the dam soil in winter period is not fulfilled.

Requirements on stability of the dam bottom slope in case of drainage failure are also not fulfilled: the value of slope stability coefficient at the moments of time 35-40 years is lower than the required normative value.

According to the results of solution of the joint deformation-filtration problem, it can be concluded that it is necessary to use tubular drainage or to change the design of the downstream prism of the dam

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Aniskin Nikolay Alexeyevich, Professor, DSc, Acting Director of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, phone +7 (495) -287-49-14 ext. 14-19, e-mail: Aniskin@mgsu.ru

Анискин Николай Алексеевич, профессор, доктор технических наук, исполняющий обязанности директора Института гидротехнического и энергетического строительства (ИГЭС) Национального исследовательского Московского государственного строительного университета (НИУ МГСУ), 129337, г. Москва, Ярославское ш., д. 26, тел. +7 (495)-287-49-14 доб.14-19. e-mail: Aniskin@mgsu.ru

Sergeev Stanislav Alexeyevich, PhD, Associate Professor of the Department of Hydraulics and Hydraulic Engineering, Researcher at the Scientific and Educational Center "Geotechnics" of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, phone +7 (495) -287-49-14 ext. 14-19, e-mail: SergeevSA@mgsu.ru

Сергеев Станислав Алексеевич, кандидат технических наук, доцент кафедры «Гидравлики и гидротехнического строительства», научный сотрудник Научно-образовательного центра «Геотехника» Национального исследовательского Московского государственного строительного университета (НИУ МГСУ) 129337, г. Москва, Ярославское ш., д. 26, тел. +7 (495)-287-49-14 доб.14-19 e-mail: SergeevSA@mgsu.ru

Stupivtsev Andrey Vladimirovich, postgraduate student of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, phone +7 (495) -287-49-14 ext. 14-19, e-mail: StupivtsevAV@gmail.com

Ступивцев Андрей Владимирович, аспирант кафедры «Гидравлики и гидротехнического строительства» Национального исследовательского Московского государственного строительного университета (НИУ МГСУ) 129337, г. Москва, Ярославское ш., д. 26, тел. +7 (495)-287-49-14 доб.14-19 e-mail: StupivtsevAV@gmail.com

Bokov Ilia Alexeyevich, student of the Institute of Hydrotechnical and Power Engineering (IGES) of the National Research Moscow State University of Civil Engineering (NRU MGSU), 129337, Russia, Moscow, Yaroslavskoe shosse, 26, phone +7 (495) -287-49-14 ext. 14-19, e-mail: ibokov111111@gmail.com

Боков Илья Алексеевич, студент Института гидротехнического и энергетического строительства (ИГЭС) Национального исследовательского Московского государственного строительного университета (НИУ МГСУ), 129337, г. Москва, Ярославское ш., д. 26, тел. +7 (495)-287-49-14 доб.14-19. e-mail: ibokov111111@gmail.com