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Crack self-healing in clay-cement concrete diaphragm of embankment dam

Самозалечивания трещин в глиноцементобетонной диафрагме грунтовой плотины

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Key words: embbankment dam; cement-clay concrete diaphragm; numerical simulation of filtration; self-healing crack; filtration strength; colmatage; healing layer; transient zones; suffosive strength

Ключевые слова: грунтовая плотина; глиноцементобетонная диафрагма; численное моделирование фильтрации; самозалечивание трещин; фильтрационная прочность; кольматаж; залечивающий слой; переходные зоны; суффозионная прочность

Abstract. The article presents the results of the analysis of seepage flow character in an embankment dams with impervious diaphragm made of clay-cement concrete, using the Gotsatlinskaya HPP as an example. The process of slits colmatage was considered in the clay-cement-concrete diaphragm (CCCD), that be caused in the zone of tensile forces or by seismic actions. Mathematical models build in two-dimensional and three-dimensional formulation to study the characteristics of flow in subvertical and subhorizontal cracks. By numerical simulation was received qualitative assessment of the dynamics of gradients of pressure for a non-defective impervious element, for an open crack in impervious element, for a washed-out crack in impervious element. The methods developed for design-experimental substantiation of the parameters of the transition zone (from riding and with the lower side of impervious element), parameters of transition zones for design that provide the process of cracks self-healing in the clay cement-concrete diaphragm. The granulometric composition shall, the capacity and number of layers of the reverse filter provided for the seepage strength of the system: upstream toe – upstream transitional layer – self-healing layer – CCCD – downstream transitional layer – downstream toe, selected according to the method.

Аннотация. В статье представлены результаты анализа характера фильтрационного потока в грунтовых плотинах с противофильтрационной диафрагмой, выполненной из глиноцементобетона, на примере плотины Гоцатлинской ГЭС. Рассмотрен процесс кольматирования щелевидных повреждений глиноцементобетонной диафрагмы (ГЦБД), возникновение которых возможно в зоне растягивающих усилий или вследствие сейсмических воздействий. Разработаны математические модели в двухмерной и в трехмерной постановке для исследования характеристик фильтрационного потока в субвертикальных и субгоризонтальных трещинах. Путем численного моделирования получена качественная оценка динамики значений градиентов напора для случаев: полностью исправного противофильтрационного элемента (ПФЭ), ПФЭ со сквозной трещиной, ПФЭ с замытой трещиной. Разработана методика расчетно-экспериментального обоснования параметров переходных зон (с верховой и с низовой стороны от ПФЭ), обеспечивающих самозалечивание трещин в ГЦБД. Подобранные согласно методике гранулометрический состав грунтов, мощность и количество слоев обратного фильтра, позволяют обеспечить фильтрационную прочность системы: верховая призма – верховой переходный слой – залечивающий слой – ГЦБД – низовой переходный слой – низовая призма.

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1. Introduction

The method of diaphragm wall is used to create impervious element in hydroengineering construction. Clay-cement-concrete (CCC) is the material for impervious element, which is performed by the method of diaphragm wall. Clay-cement-concrete is most often used, which under certain conditions in zones of tensile forces is prone to cracking. The design of the embankment dams (ED) can include elements that ensure the colmatage of the cracks formed in the clay-cement-concrete diaphragm (CCCD), that is, their self-healing. Self-healing of possible cracks in the CCCD is ensured by piling the transition zones from the sandy soil in the drilling zone of the bore-cutting wells. The reliability of the dam depends from the proper selection of the composition of the transition zones as a whole. Transition zones are designed to protect the dam from filtration deformations, mechanical suffusion and contact erosion, as well as to self-heal cracks in the event of their formation and to ensure reliable coupling of CCCD to the ground of resistant prisms of dams. A clear algorithm is not available for designing the structures of transitional zones of embankment dams with CCCD, so the development of the algorithm is relevant.

The purpose of this study is to develop an algorithm for the selection of transition zones of embankment dams with impervious element, made of clay-cement-concrete bearing drilling piles. To achieve this goal, it is necessary to solve the following tasks:

- To determine the character, qualitative and quantitative parameters of the filtration flow in the transition zones of both an undisturbed and disturbed impervious device.
- To determine the sequence of the calculation and experimental justification.

The process of ED local seepage strength recovery by a designated subsoil layer due to the so-called crack “healing” has been inadequately treated in the special-purpose literature [1-5]. According to the current standards of the Russian Federation [6] it is required to arrange special layers ensuring the colmatage of emerging cracks. However, previously published research results and standards provisions cover healing of curtain grouting (CG) made of clayey materials, the behavior of which differs significantly from that of clay-cement-concrete (CCC) in case of crack formation. Crack walls in clayey materials swell and close over time, while cracks in the CCC are not distorted. Crack walls in clayey materials with opening of over 1 mm are vulnerable with velocity of groundwater 1–3 cm/s [1]. The CCC scouring resistance depends on its formulation [7–11]. According to the results of the conducted laboratory research [12], walls of cracks in the CCC are normally resistant to scouring at the velocity of groundwater about 200 cm/s. As a result of scouring, clay particles may be entrained downstream from the cracks in clayey materials, thus causing colmatage of the transitional layers material from the downstream side. Formation of cracks in clay cores lying at a depth of 30-50 m from the embankment crest is virtually impossible, as this area is subject to high compressive stresses exceeding the cohesive soils adhesion [1]. While the location of cracks in the CCCD depends on the stress-strain state of the structure and working conditions [13–19], cracks may form at the depths exceeding those specified for clayey impervious elements. The said factors demonstrate different behavior of cracks in clayey materials and in the clay-cement-concrete, while demonstrating impossibility of direct application of all research data and current requirements for clayey impervious elements structures, as well as to impervious elements made of clay-cement-concrete. The clay-cement-concrete diaphragms made using the bored-secant piles technique have a number of apparent advantages over other techniques, such as: high processibillity, high level of industrialization of mixtures composition, supply and placing, high construction rate. However, they also have certain disadvantages caused both by its construction process and by the particular nature of its collaboration with the ED construction [20, 21]. The stress-strain state of the ED with CCCD may contribute to development of cracks in tension areas [13, 19] coinciding with the areas of the ED and CCCD combined deflection and longitudinal (downstream) displacements against abutments. Requirements to compensating measures are specified with consideration of the complex, multifactorial and time transgressive nature of crack formation process in the CCCD. A transition zone shall be arranged between the CCCD and the ED downstream toes to ensure seepage strength of the ED in case of potential crack formation in the CCCD. The upstream side of this transition zone shall have a special layer of soil adjacent to the CCCD which ensures the filling of cracks. It is the so-called “healing” layer.

In [5, 21, 22], the authors performed a numerical and laboratory-experimental simulation of the processes of self-healing of cracks in CCCD. The analysis of stress-stain state was carried out to clarify the most dangerous zones of development of cracks of the CCCD, by using numerical modeling [13]. Within the framework of this work, filtration modeling in two-dimensional and three-dimensional formulations has been performed to solve the tasks, and an analysis has been made of the characteristics of filtration flows for embankment dams up to 60 m in height with clay-cement-concrete diaphragms. New qualitative regularities are established of changes in the effective pressure gradients in various CCCD zones with a through and with a washed crack (for example, the embankment dam of the Gotsatlinskaya HPP).

A technique is proposed for calculating and experimental substantiation of the characteristics and parameters of the transition layers providing self-healing of cracks in the CCCD, on the basis of the analysis of the obtained results, which includes the following blocks:

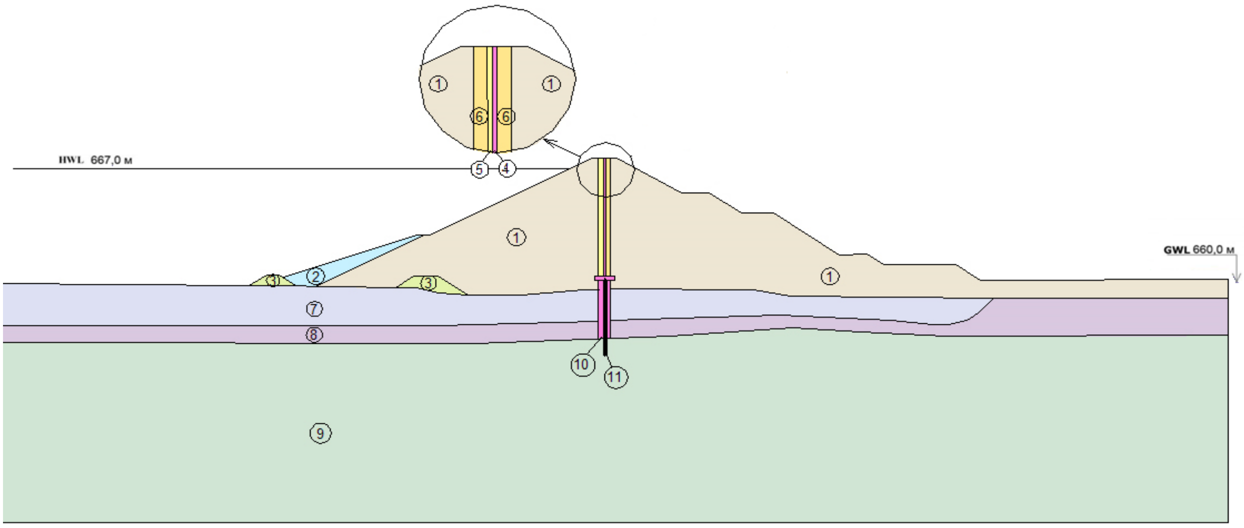
- Analysis of stress-stain state - to location, opening of potential crack in CCCD;
- Filtration modeling - to expected pressure gradients in transition zones and contact areas;
- Laboratory-experimental modeling - to confirm washing, clarify the nature of the wash, depending on the granulometric composition of the soil of the healing layer and the operating gradients;
- Selection of the optimal "soil mixture" and verification of its filtering-suffosive characteristics, the possibility of penetration into the crack, the possibility of penetration into the downstream transitional layer;
- Clarification of the necessary volume of the healing material.

Thus, the objectives of the research have been fulfilled.

2. Methods

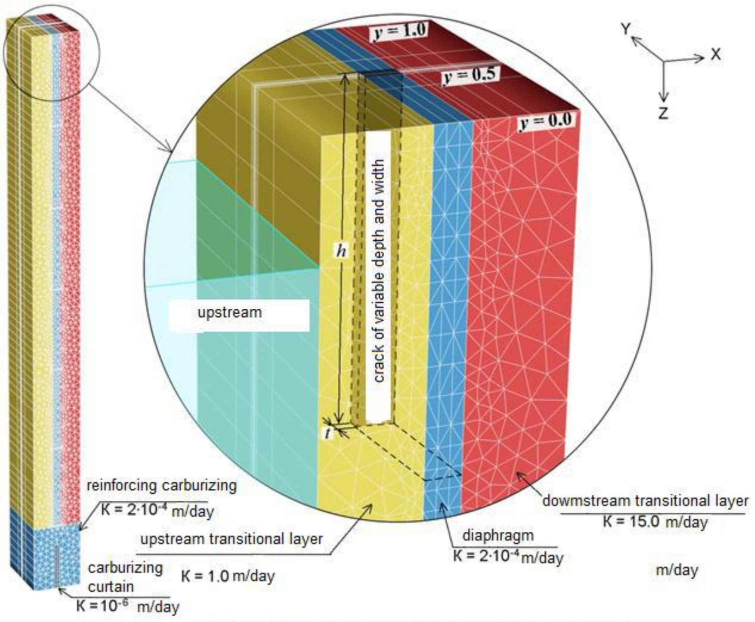
The crack healing process proceeds as follows: in case of formation and opening of cracks in the CCCD, the escape (towards the crack cavity) head gradients J, exceeding the critical head gradient values for this layer, of soil, appear at the contact with the healing layer. At the contact with the CCCD, due to temporary loss of its seepage strength, the healing layer soil material is entrained by the seepage flow into cracks formed in the CCC. Thus, the cracks are filled with the material of the self-healing layer, and the integrity of impervious elements is recovered.

The data on nature and structure of the ED with CCCD total seepage flow shall provide a more vivid representation of the self-healing procedure. The data were obtained during simulation of the steady-state seepage process for the channel damsite of Gotsatlinskaya HPP using Plax Flow (2D modeling) software unit (Fig. 1) and Feflow6.2 (3D modeling) software package [22] (Fig. 2).



1 – gravel of the dam body; 2 – sandy loam; 3 – rocky ground; 4 – clay-cement concrete diaphragm; 5 – upstream transitional layer; 6 – downstream transitional layer; 7 –gravel in the bases of constructions; 8 – fractured rock in the bases of constructions; 9 – rocky ground in the bases of constructions; 10 –cement grouting, 11 – cement-grout curtain.

Figure 1. Seepage model for the embankment dam of Gotsatlinskaya HPP for the option with impervious elements from the CCCD



Remarks: *The model is visually stretched several times on an axis at Y*

Figure 2. Three-dimensional model of a vertical crack in CCCD

3. Results and Discussion

The results of numerical modeling of filtration for the embankment dam with a clay-cement-concrete diaphragm, for example the embankment dam of the Gotsatlinskaya HPP, obtained by the authors earlier [22], are presented in Figures 3–5:

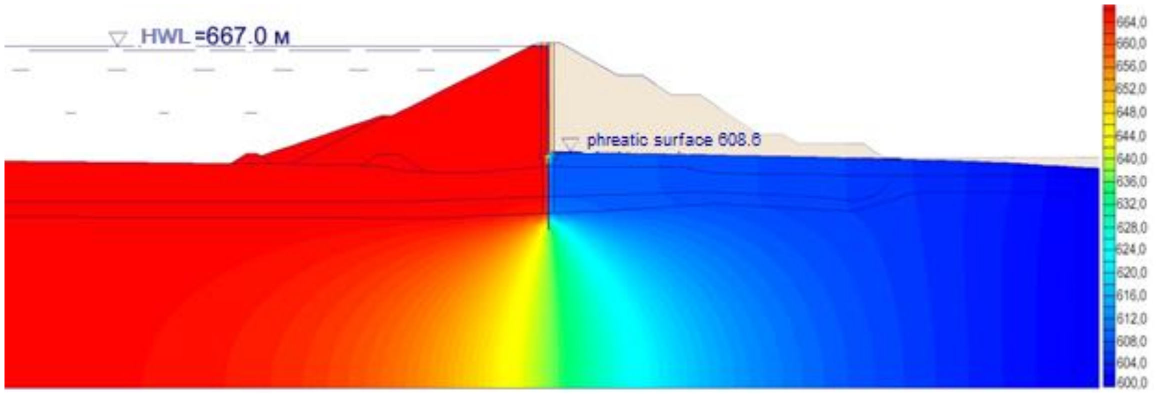


Figure 3. Phreatic surfaces and lines of total head in the body and the foundation of an embankment dam with impervious element from CCC with a working condition of the diaphragm

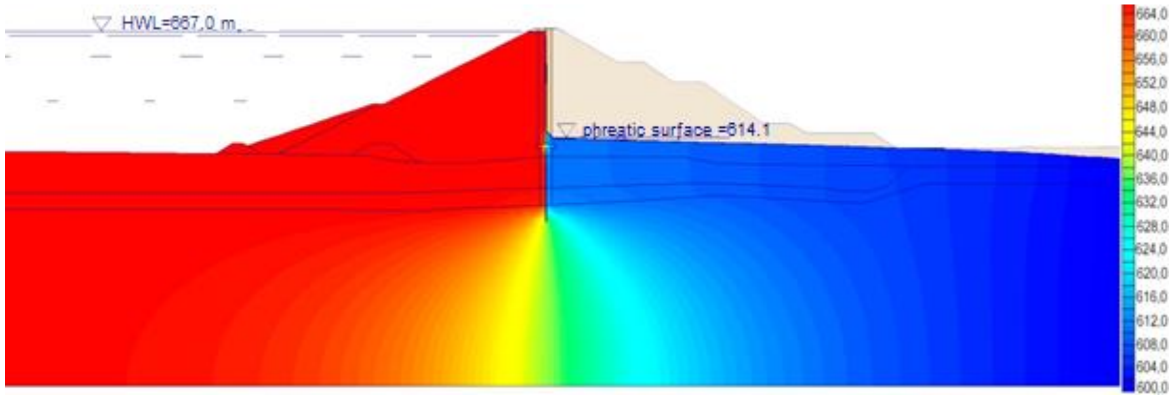


Figure 4. Phreatic surfaces and lines of total head in the body and foundation of an embankment dam with impervious element from CCC in the broken state of the diaphragm with a "healed" crack, opening 0.3 m

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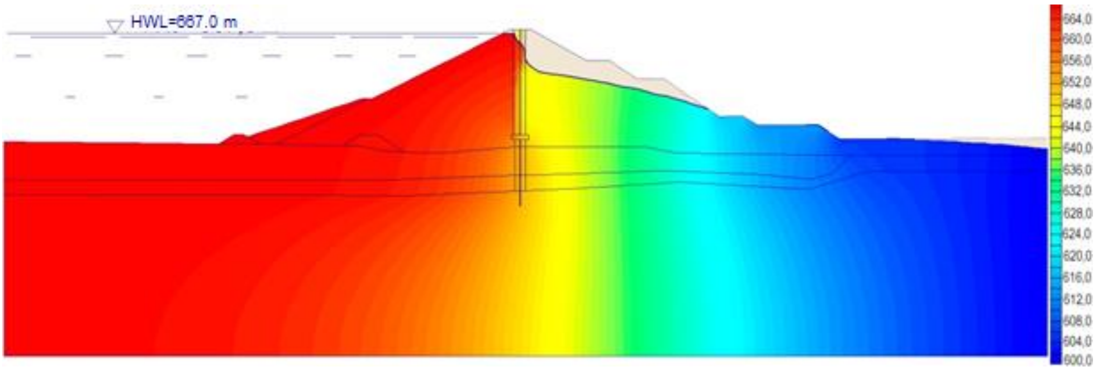


Figure 5. Phreatic surfaces and lines of total head in the body and foundation of an embankment dam with impervious element from CCC with complete diaphragm degradation

Results of the modeling follows for a clean vertical crack the maximum pressure gradients at the input J_{max} = 1850 and at the output J_{max} = 117 are predicted with its minimum opening δ = 5.0 mm, the gradients decrease with increasing crack opening; curves J (δ) in Figure 6 are trends of the form:

$$J = a \cdot \delta^b, -0.7 < b < -0.6$$

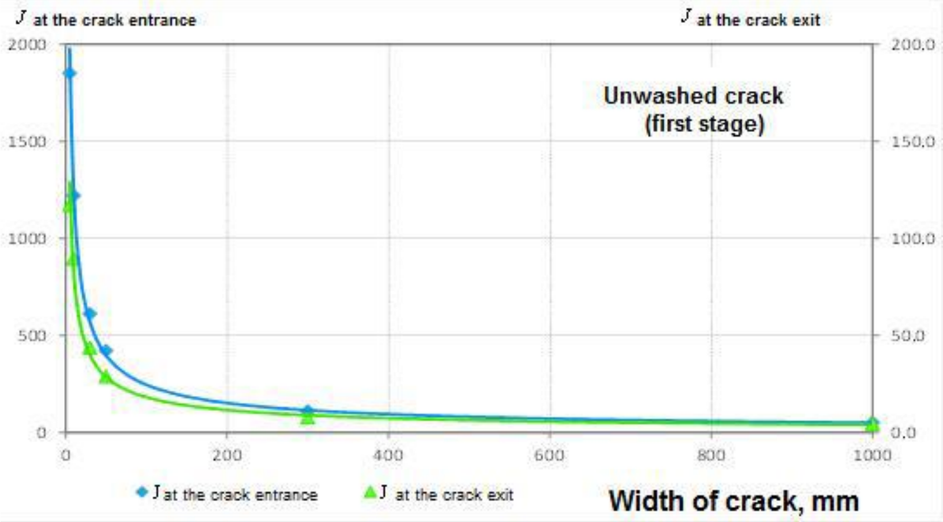


Figure 6. Dependence of pressure gradients on width an unwashed horizontal crack

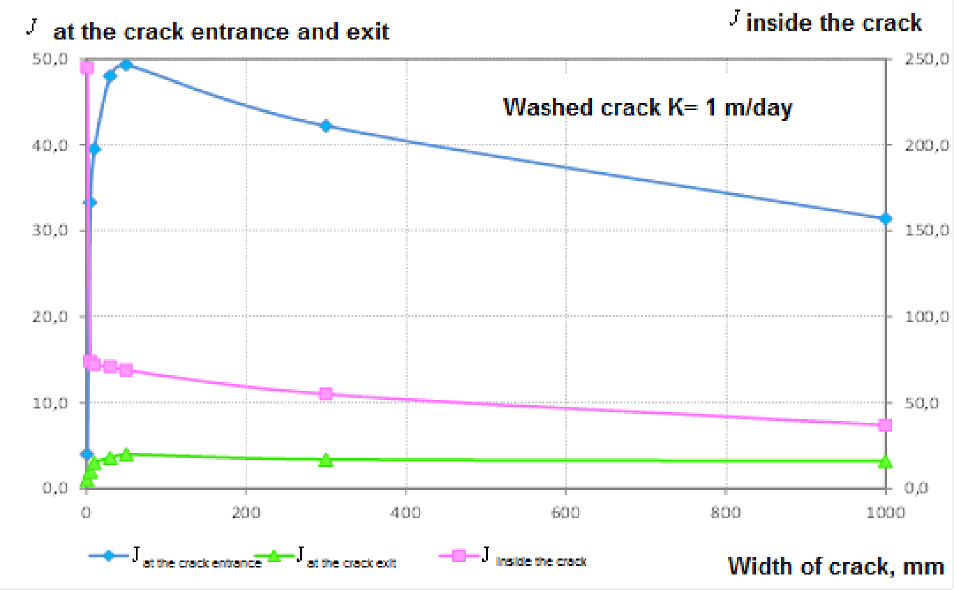


Figure 7. Dependence of pressure gradients on width washed horizontal crack

After self-healing of the horizontal crack (Fig. 7), gradients increase at the inlet and outlet with increasing its opening from 1 to 50 mm, reaching, at δ_0 = 50 mm, the maximum values of J_{max} = 49.0 and 4.0, respectively. With further expansion of the crack (δ > 50 mm), the gradients decrease; within the same crack, the maximum calculated gradient J_{max} = 245.0 is fixed at its minimum calculated width δ = 1.

Simulation results for the specified design of the ED with CCCD of Gotsatlinskaya HPP has allowed to establish common patterns of the seepage flow structure at the crack entrance, inside the crack and at the crack exit. At the crack entrance high head gradient values were recorded; inside the crack the head gradient values reduce significantly; at the crack exit the head gradient values are also considerable. Moreover, a wide difference has been observed between the head gradient values (by decades) for cracks that have and have not been washed out. This pattern has also been observed during laboratory-based experiments on physical models [5, 21]. Virtually all head losses occur at the CCCD (for the ED type with a core of dam).

In case of crack formation in the CCCD (with due account, differing coefficient of permeability of downstream toes and transition zone material), substantial head losses in the crack area occur largely in the transition zone material, being aggravated at the initial stage of crack opening by discontinuities within the seepage area.

Thus, at the initial stage of crack formation in the CCCD, all ED head applies to the upstream transitional layer while generating pressure gradients with the values conforming to the head distribution diagram, with the head losses in the transitional layer and at the crack entrance. If the seepage flow integrity is maintained, head losses occur in the crack itself, at the crack exit and in the downstream transition zone material (Fig. 8, Line 2).

At this stage, which shall be designated as Stage 1, or Dynamic Stage, it may also be assumed that after crack formation in the CCCD the downstream transitional layer is also affected by the head, after losses in the transitional layer and in the CCCD crack. The head generates pressure gradients with the values conforming to the head distribution diagram, and the exit gradient values at the contact with the downstream toe depending on the width of the downstream transitional layer.

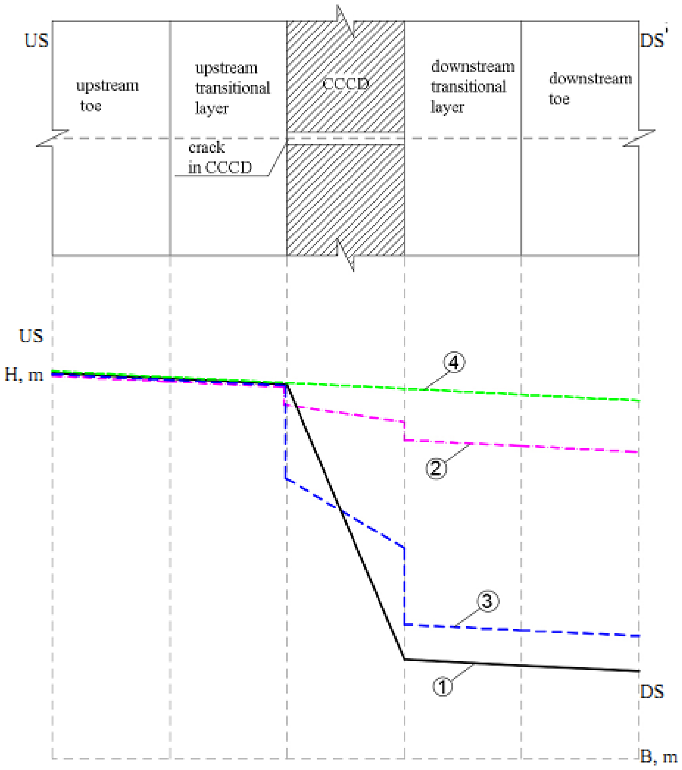
If the head gradients exceeding relevant critical values appear in the “seif-healing layer - crack” contact are, the healing layer material loses its seepage strength under the weight of seepage flow, and fills the crack cavity. At this moment, due to the emerging seepage resistance in a washed out crack, the entrance pressure gradients reduce, in some instances until complete stop of the colmatage process. Thus, a new seepage area with new head gradient distribution is formed (Fig. 8, Line 3).

If we continue the analysis of seepage flow structure in the ED with CCCD, while the seepage area integrity is recovered according to the self-healing procedure, we shall obtain a new head distribution diagram for the ED. By indicating this status with a healed crack as Stage 2 or Static Stage, it is noted that virtually the entire head applies to the embankment dam section consisting of the upstream transition zone material, crack filling material and downstream transition zone material.

In the design of the transition zone, consideration shall be given to these two stages different in the following:

the first “dynamic” stage defines the possibility of seepage strength loss by the transition zone healing layer, and filling of the opening crack with its material, while maintaining the healing layer residual integrity on the upstream side and the seepage strength of the “downstream transitional layer - downstream toe material” contact under the increased head gradients;

the second “static” stage defines seepage strength of the ED section in the area of well-formed crack filling material protected by the downstream transition zone material on the downstream side.



1 – the line for heads with a non-defective CG; 2 - the line for heads with an open crack; 3 - the line for heads with a washed-out crack; 4 - the line for heads in the structure without CG.

Figure 8. Head Patterns in the ED with CCCD

The general principles for design of transition zones in the ED with CCCD comply with the requirements to the transition zones and reverse filters of the embankment dam with impervious elements made of clayey materials, and are set out in [6, 23–27]. With due account for the nature of CCCD crack formation, and of the current head gradients at various sections of cracks and of the ED design in general, a number of special requirements to the design of the ED with CCCD and the CCCD “protection system”, which includes the healing layer and transition zones, may be formulated:

The healing layer material shall penetrate freely into the crack from the initial stage of its formation, i.e. penetrate into the finest cracks (1 mm and more), as it is these cracks that have the highest incoming head pressure gradients.

On the downstream side, the healing layer material filling the crack shall be sealed in the crack by a layer of reverse filter, i.e. the downstream transition zone material granulometric composition shall be selected so that the healing layer particles do not penetrate into the embankment dam downstream toe.

The healing layer thickness shall ensure filling up of the volume of formed cracks in the CCCD and prevent entrainment of the upstream transition zone material towards the crack to avoid crack clogging with coarse grain “coves”. The minimum healing layer thickness depends on its mechanized placing ability during the ED construction operations in the reverse filter area.

Reshaping of reverse filter layers on the upstream side shall not cause void formation and excessive deposits in the ridge area of the embankment dam.

According to the analysis of unique features of the “ED – CCCD” system operation: its stress-strain state, seepage flow structures at various stages of its life cycle, stated requirements to the healing material, a procedure for calculated justification of the design ensuring self-healing of cracks in CCCD was developed (Fig. 9).

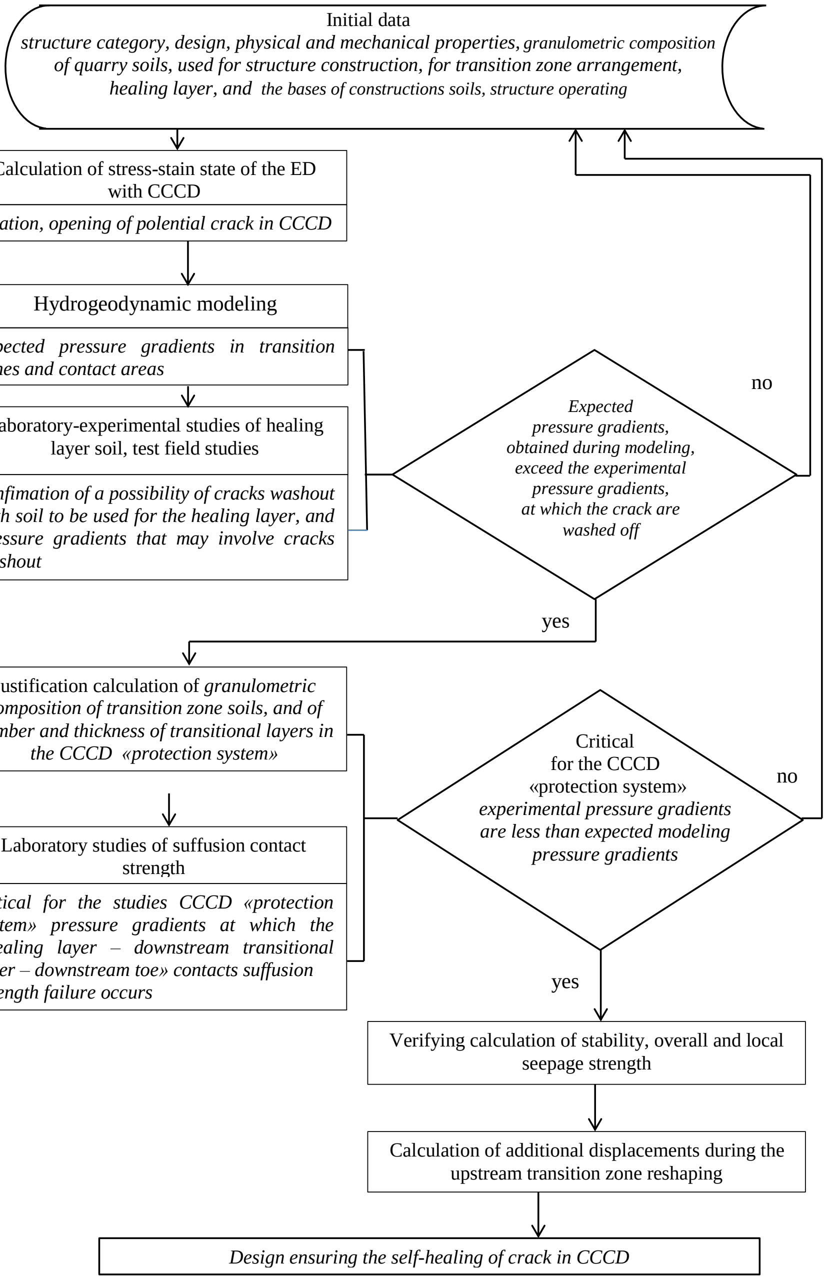


Figure 9. Block diagram of calculated justification of the design ensuring self-healing of cracks in the CCCD

4. Conclusions

The results was based of the simulation filtering in two-dimensional and three-dimensional analysis of fluid flow characteristics for embankment dams up to a height of 60 m with clay-cement-concrete diaphragms. Found that colmatage cracks in CCCD, the occurrence of which is possible in areas of tension or due to seismic effects, is almost complete (90 %) restoration of membrane properties of the diaphragm material specially selected to self-healing layer.

The proposed method of design-experimental substantiation of characteristics and parameters of transition layers. The method is a sequence of operations, determining methods of numerical simulation of pressure gradients in the transitional layers, and crack, rated selection of particle size distribution and the determination of the power transition layers of experimental verification of seepage-suffosion characteristics of selected materials and evaluate their bridging ability.

Presents the results of investigations contribute to the implementation in practice of hydrotechnical construction of new effective technologies of construction of the impervious elements from clay-cement-concrete in embankment dams.

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