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Tendencies in developing structural designs of non-soil seepage-control structures of embankment dams

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Abstract. Introduction. The urgent scientific and practical problem in hydraulic engineering is refinement of structural designs of embankment dams with seepage-control elements (SCE) made of artificial materials. They should conform with the requirements of effectiveness and safety. Different authors make proposals on refinement of structural designs of embankment dams with SCE to be made of materials based on cement and on widening the sphere of their application. Materials and methods. Analyses were made of the spheres of application in hydraulic engineering of the materials based on cement: concrete, clay-cement concrete, soil-cement concrete, soil-cement mixes. With this consideration the analysis was made of SCE structure alternatives. Their classification permitted revealing the main tendencies in development of embankment dam structural designs. Results. The sphere of possible application of SCE different types depends on the dam height. For low-head and medium-head dams the most applicable design solution refers to dams with diaphragms made of clay-cement concrete bore piles. It was already tested in practice. For high-head and ultra-high-head dams the effective and safe solution has not been found yet. Four conceptual ways may be considered, but all of the men visage using structures made of cement-containing materials. The first way is refinement of a concrete face rockfill dam structural design. It may be realized by doubling the seepage control facility with use of geo-synthetic materials. The second way is elaboration of a principally new massive seepage-control structure to be made of material based on cement. The third way is use of combined dams, where the dam safety is enhanced by replacement of a part of an embankment dam by concrete. The fourth way is combination of different types of SCE each of which is arranged at different by height dam sections. Conclusions. Materials based on cement propose wide possibilities for refinement of embankment dam structural designs. Nevertheless, the main tendency in development of high-head embankment dam structural designs is application of SCE complicated structures with use of materials based on cement. By their structure they may be either double (multi-layered) or compound (SCE combination).

1. Introduction

The urgent problem of hydraulic engineering is refinement of structural designs of embankment dams. Structural designs used at present are varied: they differ by type (earthfill, rock-earthfill, rockfill), by structure (core, face, curtain, diaphragm) and by material of a seepage-control element. However, all of them have limitations either in the field of application or do not guarantee the proper level of safety.

Therefore, refinement of embankment dam structural designs envisages solution of at least one of the following tasks:

1. Enhancing effectiveness of dam construction: decreasing the cost, decreasing man-months and construction period;
2. Enhancing reliability and safety of the dam structural design;
3. Widening the field of embankment dam application for higher heads.

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At present the only type of dams which may be used actually for any head and conditions is rock- earthfill dam with central core made of clay soil. The highest dam of such type is 300 m high dam of Nurek HPP in Tajikistan.

However, rock-earthfill dams have limitations by application related to the possibility of placing clay soils into the seepage-control core. In severe climatic conditions it is difficult to provide proper quality of clay soil placement which results in decreasing the dam safety level. This is testified by operation experience of the highest in Russia rock-earthfill dam of Kolyma HPP built in Magadan Oblast [1]. As a result of insufficient quality of soil placement, the dam is subject to considerable deformations, and there are zones of increased permeability in the core. Danger of affecting the seepage strength of the soil core is also a characteristic feature for other rock-earthfill dams. The case of complete failure in 1976 of 93 m high Teton rock-earthfill dam (USA) is well known [2]. In literature there described cases of hydraulic fracturing of Balderhead dam cores (England) [3, 4], of Kureika dam [5–7].

Therefore, the urgent problem is search for alternatives of embankment dam structural designs [8]. A number of publications is devoted to this issue. Analysis of these papers shows that the most perspective is use of seepage-control elements (SCE) of non-soil materials in embankment dam structures. This is explained by the quality of artificial materials production and provision of the required level of their strength and water permeability.

A that, the important role is played by the materials based on cement. Based on cement a wide spectrum of different materials may be created and various methodologies may be applied for their production.

This article presents the analysis of proposals on refinement of the existing and elaboration of new structural designs of embankment dams with use of materials based on cement in order to estimate the perspectives of these materials' application.

2. Materials and methods

Analysis of the considered issue is carried out in two stages. At the first stage there was made a review of used materials based on cement in hydraulic engineering. The considered materials are those where cement plays the role of a binding agent. At the second stage there were analyzed the ways of further refinement of embankment dam structural designs as well as the advantages and disadvantages of structures proposed by different authors.

3. Results

3.1. Review of information about the materials developed based on cement

Materials created on the base of cement differ in composition and / or manufacturing technology. They may be classified as follows.

1. First of all, it is traditional concrete and reinforced concrete. However, it should be noted that for the increased level of SCE safety, special solutions can be applied to the design of concrete structures. In particular, instead of traditional concrete reinforcing with steel bars, it is possible to use distributed reinforcement. In particular, the face of the Shuibuya dam was reinforced with geosynthetic fibers to increase tensile strength [9]. It is also proposed to use self-healing concrete.

2. In hydraulic engineering and road construction, so-called roller compacted concrete is widely used. In hydraulic engineering, it has been used since the middle of the 20th century. It is a particularly hard concrete mix with a low cement content and a high content of coarse aggregate. Unlike conventional concrete, it is placed by layers and compacted not by internal vibrators, but by vibration rollers.

3. Further development of roller compacted concrete technology is the “hard fill” technology, which found its application in the 21st century. [10–13]. As a result of its application, a new type of dam was created – the “hard fill”. The profile of such dams is trapezoidal, like that of embankment dams, but with steeper slopes (about 0.8). Abroad, a hard soil-cement mix of cement, sand and gravel is called CSG, and in Russia it is called soil-cement concrete. The technology for producing soil-cement-concrete can be various. The already produced CSG mix is placed in the dam and compacted by rollers. It includes not more than 80 kg/m^3 of cement, and sand and gravel in equal proportions. It is also possible to obtain soil cement concrete by pouring coarse soil with cement mortar, the so-called divided technology.

Technologies of roller compacted concrete and “hard fill” are convenient for construction of massive structures, but roller compacted concrete and soil-cement concrete are quite permeable, therefore, they require additional seepage-control structure. For example, the upstream face of CSG dams is covered with a protective layer of concrete.

4. Clay-cement concrete or plastic concrete is used exclusively to create seepage-control structures. It is concrete with the addition of local clay materials. Bentonite clay or similar local clay soils are used as such

additives [14]. Additives are designed to reduce the stiffness of cement stone. The ratio of cement and bentonite in clay-cement concrete mix may be different. For example, clay cement concrete used for construction of Karkhe dam seepage-control wall (Iran) contains 200-220 kg of cement and 30-40 kg of bentonite in 1 m^3 [15], while clay cement concrete of the Kureika dam wall contains 125-156 kg of Portland cement and 120-140 kg of bentonite.

Depending on the ratio in the content of cement and clay, it is possible to obtain clay-cement concrete with the necessary deformability and strength. The modulus of deformation of clay-cement concrete may vary widely: it may be less than 100 MPa or may exceed 1000 MPa [15]. Clay-cement concrete has plastic properties, due to which it can have the ability to self-heal cracks [16], so it is advisable to use it for installation of seepage-control walls. To increase the strength of clay-cement concrete, it is proposed to introduce distributed reinforcement, fiber in its composition in the form of metal wires or in the form of polymer fibers [17, 18].

A separate class of cement-containing materials is composed of various soil-cement mixes. They are soils, binded in one way or another with cement. Depending on the technology of consolidation, several types of soil-cement mixes are distinguished.

5. *Soil cement* is produced by mixing soil with cement directly at the site of placement. It was first used in the USA for protection of the slope against the effects of waves.

Soil-cement mixes can be formed during the development of soil. Recently, such methods of creating seepage-control walls in soils as the mixing method and the jet grouting method have appeared[1]. In these methods, cement and soil are mixed in place, during the execution of the wall. The base soil is not removed, but is part of the cement-soil material. Depending on the content of cement, water and air, the properties of soil-cement mixes can vary greatly.

6. *Soil cemented by injection* of cement-based grouts is produced by injecting the grout into the pores of coarse-grained soil at a pressure of 0.5-6 MPa [19, 20], and after hardening of which a cemented stone is formed.

The material of curtains and walls produced by injection, mixing, and jet grouting is unpredictable in properties, because its composition is determined by the composition of the original soil massif.

Even a brief review shows that the range of cement-based materials used in hydraulic engineering is very wide.

Perspectives of using in embankment dams of new structures of seepage-control elements made of cement-containing materials.

Use of the above cement-containing materials, as well as the technology of their application, allows creating new design solutions for embankment dams.

A peculiarity of scientific and technical progress in hydraulic engineering is that fundamentally new solutions are rarely implemented; more often development is carried out by improving or borrowing already existing technologies. In construction of embankment dams, the main trend is the transfer of technology, that is, the adaptation of those structures and technologies that have previously proven themselves in any field and have proven their effectiveness, reliability, to solve new problems.

Expanding the scope of application of this or that material, technology is limited by technical capabilities and gained experience. Therefore, the ways of developing designs of low-, medium- and high-head technologies differ.

Perspectives of using seepage-control elements made of cement-containing materials in embankment dams of low and medium heights.

Development of structures of low-head and medium-hed embankment dams is aimed at increasing the efficiency of construction, as the problem of providing reliability and safety can be solved by traditional methods. It is proposed to use SCE of cement-containing materials (including concrete) as an alternative to the traditional soil SCE (cores and faces of clay soils).

This is proved by the experience of repairing several rock-earthfill dams, where cracks appeared in seepage-control cores. An example is Balderhead Dam in England [3, 4]. Its repair was carried out in 1968, first by grouting to fill the cracks, and then by creating a trench method of a seepage-control wall made of soil concrete with a thickness of 0.65 m and a depth of up to 45 m [21]. There are other examples of creating new seepage-control diaphragms in the bodies of repaired dams using the trench method, for example, at Navajo dam (USA, 1987) [21].

[1] Broid I.I. Jet geotechnology. – M.: ACB, 2004. – 448 p.; Development of Dam Engineering in the United States. Pergamon Press. Edited by E.B. Kollgaard and W.L. Chadwick, 1988. 1072 p.

Another technology for creating a new seepage-control wall is the technology of bored piles. An example is the dam at the Kureika hydroelectric station, in one of the sections of which in 1992 failure occurred with loss of core tightness [5–7]. The dam repair was proposed to be implemented by creating a new SCE of bored piles [5–7]. It was completed in 1998–1999 and after that the dam continues to operate successfully.

According to the experts of VNIIG named after B.E. Vedeneev, making a diaphragm of bored piles is a promising way to create SCE in low-head embankment dams. This was shown by recent experience in building the dam of the Nizhnyaya-Bureya hydroelectric plant [22, 23]. VNIIG named after B.E. Vedeneeva developed typical designs of dams with diaphragms made of clay-cement concrete for future use[2].

It should be noted that this idea has already been realized abroad. Already in the 1970s –1980s, the diaphragms of a number of embankment dams were made using the "slurry trench cutoff wall" method [24]. For example, at 6.5 meters high Wadi Hawashinah dam (Oman), a 0.6 m thick diaphragm was constructed using a trench method [25]. In the 1970s, 31 m high Formiz dam was built in Germany, the SCE of which was the core of silty sands, and a wall was built in its center [26]. The wall with a thickness of 0.6 m was erected with use of the trench method by 4 m high layers. The material softer than concrete was used as the diaphragm material, i.e. clay-cement concrete.

For medium-head dams, Russian authors propose a new type of dam SCE – a bored pile diaphragm erected by layers [17, 27]. A number of papers published recently have been devoted to the issues of possible use and development of such structures [28–30]. The complexity of using this design is vulnerability of connection of the diaphragm layers [31].

Abroad, there is an experience in creating deep (in one layer) seepage-control diaphragm walls for repair of rock-earthfill dams. These walls are made by the trench method. In 1985–1986 in this way, the Fontenel Dam was repaired in the USA: a 0.65 m thick and 55 m deep concrete wall was constructed in sandy-loamy soil [21, 32, 33]. At the Mud Montain Dam (USA), the depth of the wall, made in a similar way, was 120 m [34]. The wall thickness was 0.85÷1 m [21].

There is experience in application to create a temporary diaphragm wall in the cofferdam and body of the Xianlongdi dam in China [22]. Its total depth (in the dam and foundation) was 52 m. The diameter of the borehole columns was 1.2 m.

In all these cases, SCE arranged by various underground methods in the body of a filled dam, showed their reliability during several years of operation. Thus, the use of diaphragm walls makes it possible to create safe structures of embankment dams.

Perspectives of using seepage-control elements made of cement-containing materials in high-head embankment dams.

For high and ultra-high dams, the problem of SCE safety is the main one, and the issues of construction efficiency are fading into the background. These dams require special design and technological solutions.

Currently, for high-head dams, only one SCE made of artificial materials is used: this is a concrete face. At present, the highest concrete face rockfill dam (CFRD) is Shuibuya Dam in China. Its height is 233 m. Chinese designers suggest using CFRD with even at a height of 300 m [9, 35, 36]. However, as practice shows, the safety of CFRD is not guaranteed. At a number of such dams, the faces were damaged and needed repairs. Dams Campos Novos, Aguamilpa, Tianshengqiao 1, Mohale, Barra Grande [35, 37, 38] may be presented as examples. For the possibility of using SCE of non-soil materials, it is necessary to solve the problem of providing the necessary level of its safety. As experience and research show, of all types of non-soil materials, only cement-based materials are suitable for construction of ultra-high dams.

Two fundamentally different ways of solving the safety problem of high-head dams with non-soil SCE can be distinguished:

- the first way is to improve the applied design of CFRD;
- the second way is development of a fundamentally new dam design.

The first way, enhancing safety of the applied design of CFRD can be realized by duplication of one SCE (concrete face) with another, i.e. by using a multilayer construction. A similar approach is used in the design of sludge collector dams, ash and slag dumps and toxic liquid storage facilities where an increased level of seepage-control protection is required. For example, in them, asphalt concrete and geosynthetic faces are simultaneously performed, between which drainage is arranged to collect and drain filtered water.

Several alternatives for construction of a multilayer SCE structure may be considered. The first alternative is a combination of concrete and geosynthetic faces. This method has proven itself at construction

[2] Company-specific standard STP 310.02.HT-2017. Recommendations for designing, analysis and construction of a seepage-control element made of clay-cement concrete bored piles / edited by Miltzin V.L., Orishuk R.N., Solsky S.V.: JSC «VNIIG named after B.E.Vedeneev», JSC «Lenhydroproject». 2017. 118 p.

of Bovilla dams [39] and repair of concrete face of dams Turimiquire [40], Salt Springs [41] and New Exchequer [42]. Its disadvantage is the possibility of damage to the open geomembrane due to mechanical and thermal effects, as well as by solar radiation.

The second alternative is a combination of concrete and soil-cement concrete face. This idea is promoted by a number of Russian authors – L.N. Rasskazov [43], Yu.P. Lyapichev [44], A.S. Bestuzheva [45]. The idea is not only to increase safety of SCE due to appearance of a second line of seepage-control protection, but also to provide the maintainability of SCE, which is achieved by repairing a soil-cement concrete zone by injecting grouts. The concept of creating a massive SCE of cement-containing materials is debatable, because according to the results of our research [46], this does not increase, but reduces the concrete face efficiency.

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The second way to improve the design of high-head embankment dams, i.e. elaboration of new designs of ultra-high dams, is even more problematic. A number of publications are devoted to this issue. Several dam designs may be proposed and considered. For example, L.I. Kudoyarov proposed to use steel faces for construction of ultra-high dams [47], however, this alternative of the dam is very costly and difficult for repairs.

More realistic alternatives are also available. As a rule, their idea is based on use of materials based on cement. All the proposed alternatives may be classified as three different concepts.

Concept No. 1 is based on use of a massive SCE made of one of the materials based on cement in the dam design. An injection curtain or a concrete mass (core) may present such a SCE.

Alternative 1 – an *injection core* (curtain) made by binding a gravel-pebble soil with a cement-containing mix (Fig. 1). The advantage of this option is that it has already been put into practice in one form or another. For example, the grout curtain is at the bottom of a series of SCE high embankment dams. These are Atbashinsk [48], Yumaguza [49] dams, dams of Kambarata hydroelectric power plant-2 [50] and Mainskaya hydroelectric power plant [20].

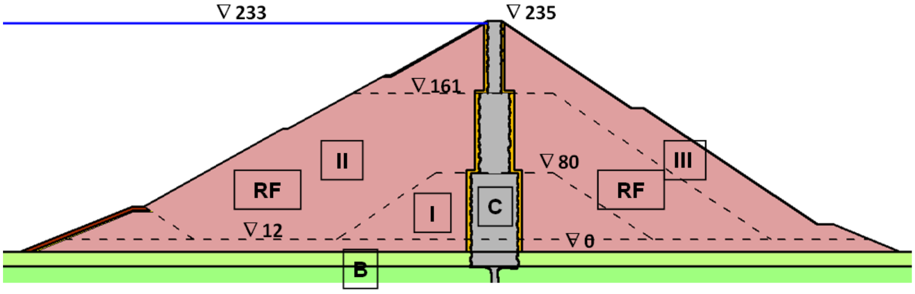

Figure1. Design of rockfill dam with a seepage-control elements grout curtain.
C – grout curtain, RF – rock fill, B – bedrock base, I, II, III – construction project phases.

There are cases of grout curtain in the body of an embankment dam for repair purposes. An example is Orto-Tokoi Dam (Kyrgyzstan), 52 m high, in which clay-cement grout was injected to reduce seepage through the dam body.

Successful experience gained in operating the above dams shows that the grout curtain may be used as the main SCE of an embankment dam. Grout curtains (cores) have several advantages over other types of SCE. Firstly, due to arrangement of a curtain (injection) after completion of the dam construction, SCE will be free from deformations of rockfill of the construction period, which improves its SSS. Secondly, in the event of breaking water tightness, the injection core can be repaired by re-injecting the developed cracks.

However, injection cores have a major drawback: in order to ensure seepage strength, the grout curtain in coarse soil should have a greater thickness, which leads to an increase in the cost of the dam.

Option 2 – a massive concrete core made of roller compacted concrete. One such proposal was put forward by V.F. Korchevsky and V.V. Orekhov [51, 52]. To give the concrete core greater flexibility, it is proposed to cut it height-wise with horizontal joints into separate blocks (Fig. 2), and for greater safety, arrange an asphalt concrete face from the upstream side.

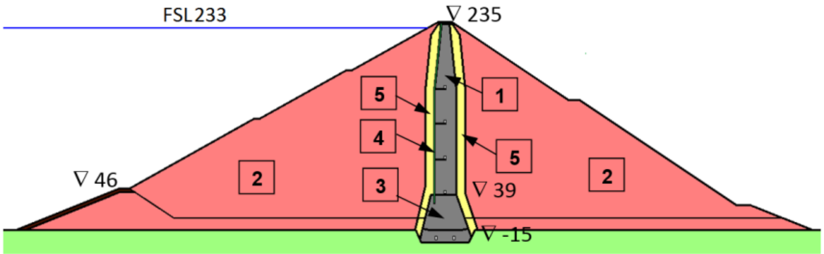

Figure 2. Scheme of arrangement of concrete face rockfill dam 1 – concrete face made of roller compacted concrete, 2 – rockfill shells, 3 – concrete face foundation made of vibrated concrete, 4 – asphalt concrete face, 5 – transition zones.

It was proposed in VNIIG to arrange in the dam body a concrete face enclosing an asphalt concrete diaphragm.

We conducted studies on reliability of the mentioned alternatives [8, 53]. They showed the insufficient level of their reliability. Besides, using massive concrete structures is not feasible because it requires a large volume of both rock excavations and earth moving and concrete work, which is economically unfavorable.

Thus, the concept of elaboration of embankment dam structures based on using massive stiff SCE in most cases is inconsistent. However, analysis of the proposed alternatives permits revealing an important tendency in selection of structural designs of ultra-high embankment dams. It is striving to apply two doubling SCE in one structure.

Concept No.2 is use of combined dams. The dam is called combined when it integrates a concrete dam and an embankment dam. The idea of combined dams is in the fact that in the lower part of an embankment dam a more safe and serviceable concrete structure should be used.

A number of combined dams have already been constructed in the world. They integrate a concrete structure and CFRD. Some of the them are the result of increasing the height of a concrete dam. The example may be 150 m high New Exchequer dam rehabilitated in USA in 1968 [42]. Besides, there known the dams which from the very start were constructed as combined dams. These are 192 m high Sogamoso dam in Columbia [44], 162 m high Yacambu dam in Venezuela.

Other alternatives of combined dam construction may be considered. The example may be 164 m high Quxue dam [54], where a concrete structure is combined with an asphalt concrete diaphragm and Bovilla dam with the face made of geomembrane [39].

Using combined dams seems to be advantageous, however, it also does not guarantee achievement of proper safety level. This is explained by the fact that a concrete and an embankment parts of a dam work actually independently from one another, which may lead to development of decompaction zones at the contact between them. This conclusion is confirmed by technical problems with water tightness at the interface of a concrete face with a concrete structure, which took place during operation of New Exchequer dam [42].

Concept No.3 in development of new structures of ultra-high embankment dams is use of combined non-soil SCE consisting of CSEs of two different types.

Dams with combined non-soil SCE are not principally new; they have been used for a long time in hydraulic engineering. Combination of non-soil SCE appears in case if the dam is rested on a thick layer of soil foundation. In this case in the foundation there arranged a vertical SCE in the form of SCW or a grout curtain which then is continued in the lower part of the dam. Using dams of such design permits increasing effectiveness of their construction. Using in the lower part such SCE as grout curtain, seepage-control wall permits dam construction without performing pit excavation, i.e. without the pit dewatering.

The examples of dams with combined SCE with grout curtain may be At-Bashinsk dam (79 m high, 1970) and the dam of Kambarata HPP-2 (50 m high, 2010) in Kyrgyzstan. At-Bashinsk dam SCE consists of a polyethylene diaphragm (in the upper part) and a grout curtain (in the lower part) [48]. The dam of Kambarata HPP-2 in Kyrgyzstan where SCE consists of a PVC face (in the upper part) and a grout curtain (in the lower part) [50].

The examples of dams with combined SCE with use of a seepage-control wall may be Hengshan dam in China [55] and Arkun dam in Turkey [56, 57]. The first is 70.2 m high, the second is 140 m high. In both cases SCE in the upper part is arranged in a form of a concrete face.

Taking into account this experience at construction of an ultra-high dam it is feasible in the upper part to use SCE as well proven concrete face and in the lower part to use a vertical SCE in the form of a grout curtain or a seepage-control wall. VNIIG specialists proposed to use the design of an ultra-high rockfill dam with combined SCE consisting of a concrete face and a grout curtain [58]. However, till present these dam designs have no analogs; scientific validation is required for their construction.

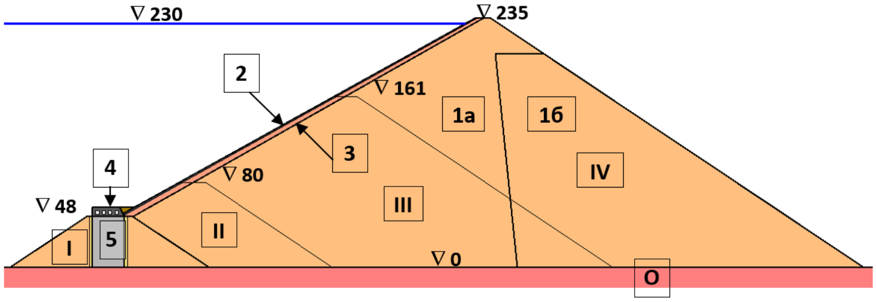

Figure 3. Dam design with combination of seepage-control elements: a concrete face and a grout curtain. 1a, 1b – rockfill, 2 – concrete face, 3 – under-face zone, 4 – concrete gallery, 5 – grout curtain, I, II, III, IV – dam construction stages.

The same may be said about all the proposed new structural solutions of ultra-high rockfill dam with SCE: their possible use will appear in case of thorough scientific validation.

4. Conclusions

1. Due to development of technologies the materials based on cement acquire new properties and become cheaper. All these permits saying about possible widening of application field of these materials based on cement in dam construction. Namely, for low-head and medium-head dams the effective structural solution is arrangement of clay-cement concrete diaphragms.

2. The urgent scientific problem is refinement of structural designs of high embankment dams with use of seepage-control structures made of non-soil materials. Different concepts and alternatives for elaboration of new types of ultra-high dam structures with structures made of materials based on cement are put forward. However, their scientific validation is required for introducing new dam designs.

3. The main tendency in refinement of seepage-control structures of embankment dams is use of complicated structures. The effective ways of enhancing safety of embankment dams is use of doubling each other seepage-control structures as well as use of combined structures. In these structures the important role is played by the materials based on cement.

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