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Causes of cracking in reinforced concrete faces of rockfill dams

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Abstract. There was conducted the analysis of the results of numerical modeling of 3D stress-strain state of rockfill dams with reinforced concrete face (CFRD). It was obtained that tensile and compressive strength may be affected in the reinforced concrete face.
Due to tensile strength failure the horizontal and inclined cracks appear in the face and due to compressive strength failure vertical cracks appear. From the point of view of tensile strength the most dangerous for the reinforced concrete face are not bending deformations but deformations of longitudinal extension arising from the dam body displacements. Therefore, stone in the dam body should have high shear strength, and stone distribution in the dam body by quality should be sufficiently uniform. It is recommended to construct high CFRD in several stages, because this creates longitudinal compressive force in the reinforced concrete face.
High compressive stresses in the concrete face are typical for ultra-high dams located in narrow alignments. They act in a direction from the side to the side. To minimize the danger of vertical cracks development the intersection joints should be sufficiently wide (at least 2 cm thick) and should be compacted by the material with low deformation modulus in order to have a possibility of compensating compressive stresses.

1. Introduction

One of the important tasks in present hydraulic engineering is working out safe structural designs of embankment dams for construction high-head dam projects. One of the most promising types of embankment dams at present is CFRD. Vast experience was gained abroad in construction and operation of the dams of this type, including high dams with height exceeding 200 m.

However, use of CFRD cannot be widely spread due to their insufficient safety. In the faces of many dams of this type after the first reservoir filling there were formed through cracks and repairs were required [1-5]. The examples may be dams Aguamilpa (187 m high, Mexico), Tianshengqiao 1 (178 m, China), Turimiquire (113 m, Venezuela), Mohale (145 m, Lesotho), Barra Grande (185 m, Brasil), Campos Novos (202 m, Brasil), Shuibuya (233 m, China) and many others. Location of cracks on reinforced concrete face was not similar in these dams. On some dams the cracks were horizontal or inclined; on the others they were vertical.

As the dam cannot operate with cracks in the concrete face it is necessary to reveal the causes of their formation in order to provide safe operation of dams of this type. To reveal the causes of crack formation in reinforced concrete face it is necessary to analyze its stress state.

2. Methodology of problem solving

Analysis of reinforced concrete face stress state is impossible based on the data of field measurements of stress because they are not available. The only possible way permitting assessment of the reinforced concrete face stress state is numerical modeling. At that, for calibration of numerical models it is possible to use data of field observations over the face and dam displacements.

Numerical solution of the reinforced concrete face SSS of rockfill dams presents certain difficulties. One of the reasons is in the fact that thin and rigid reinforced concrete face of a rockfill dam following the deformations of yielding rockfill is deformed in a complicated way which is difficult to simulate in numerical modeling. We showed that at SSS analysis by finite element method (FEM) for reinforced concrete face modeling it is necessary to use only high-order finite elements with square and cubic approximation of displacements. Otherwise the results of numerical modeling will be distorted and not accessible for analysis.

The other complexity in solving the problem of CFRD SSS is the necessity to consider sequence of the structure construction, non-linearity of rockfill behavior as well as non-linear effects of contact interaction between the dam body and the reinforced concrete face. The author worked out the methodology of such analysis as well as the computer program permitting its fulfillment [6]. Computations were carried out with consideration of sequence in dam construction and reservoir filling.

3. Results

There are scarce examples in solving the problem of CFRD SSS and the results are controversial. Some researchers and research associates [5] consider that the reinforced concrete face is in the state of biaxial compression, the others say about possibility of crack formation in it due to tensile stresses [7, 8]. Dispersed opinions is explained by the fact that the reinforced concrete face SSS may be variable because it is determined by multiple factors, such as stone deformation, dam height, construction sequence as well the shape and dimensions of the site where the dam was constructed. We conducted numerical studies on determination of these factors impact on the reinforced concrete face SSS.

We established that at reservoir filling the reinforced concrete face is subject not only to bending deformations but deformations of longitudinal extension [9]. They arise due to the rockfill dam displacement toward the downstream side (Fig.1) and are transferred to the reinforced concrete face via the face friction against soil.

The most considerable tensile forces appear in the reinforced concrete face lower part. Presence in the reinforced concrete face of longitudinal tensile forces is confirmed by the fact that at most of the constructed dams the perimeter joint opens for several centimeters [5].

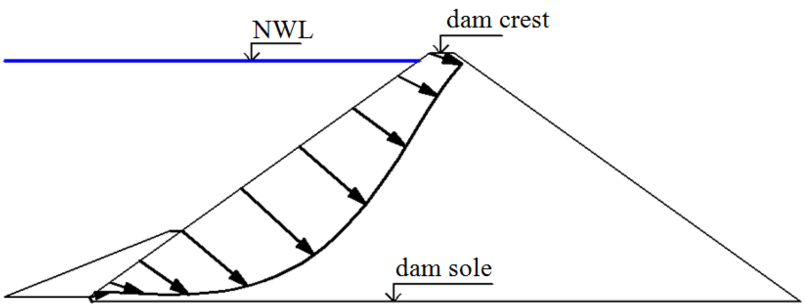

Figure 1. Scheme of reinforced concrete face deformations at taking hydrostatic pressure from the upstream side

Due to longitudinal tensile stresses and bend deformations for the reinforced concrete face downstream part it is typical to have tensile stresses in direction along the slope (Fig.2). Tensile stresses mainly appear on the face downstream part. In our opinion, it is tensile stresses that caused appearance of horizontal cracks in the reinforced concrete face at a number of dams.

In order to avoid horizontal cracks in the reinforced concrete face it is necessary to minimize deformations of rockfill by its proper compaction during dam construction. Analysis of data of field observations over construction settlements of rockfill dams shows that modern technologies permit achieving considerable decrease of rockfill deformation [10]. Secant modules of rockfill linear deformation may reach 400÷500 MPa. At insufficient compaction the rock mass deformation modulus may amount only to 30 MPa. Due to large data scattering of stone deformation modulus the dam construction settlements vary in a very wide interval: from 0.2% to 2% of the dam height [11].

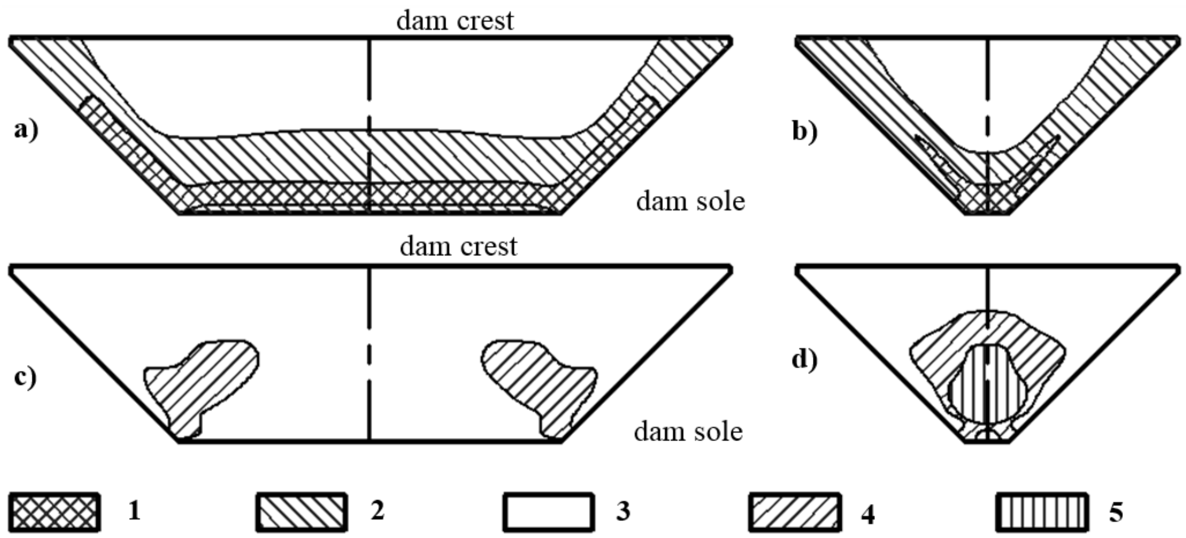

Figure 2. Scheme of reinforced concrete face stress state

a – maximum main stresses σ_1 on the face downstream part at a wide site, b – maximum main stresses σ_1 on the face downstream part in a narrow site, c – minimum main stresses σ_3 on the face upstream part in a wide site, d – minimum main stresses σ_3 on the face upstream part in a narrow site.

1 – high tensile stresses, 2 – low tensile stresses, 3 – low compressive stresses, 4 – increased compressive stresses, 5 – high compressive stresses

However, even at high values of rockfill deformation modulus in the reinforced concrete face the tensile stresses may appear. In order to achieve favorable reinforced concrete face SSS it is necessary to decrease the dam body horizontal displacements, which cause tensile longitudinal forces in the face. Therefore, apart from modulus of linear deformation, of great importance is Poisson's ratio and shear modulus.

With consideration of this, correct zoning of the stone is very important in the dam body. In modern CFRD as a rule the upper part of the dam is filled with sorted, thoroughly compacted stone, and from the downstream side by random rockfill [5]. The example may be Aguamilpa dam. Our calculations showed that if in the downstream dam shell the stone has low deformation modulus, its settlements will cause additional horizontal displacements of the dam body, and therefore, additional tensile forces in the reinforced concrete face. This is confirmed by operation experience of Aguamilpa dam. At this dam the subsidence of the downstream dam shell resulted in formation of horizontal cracks in the reinforced concrete face.

Accordingly, it is necessary to qualitatively compress the rockfill in the entire volume of the dam. To determine the magnitude of the rockfill deformation module that is required to be achieved to ensure the crack resistance of the concrete face, we can use the approximate formula obtained by us.

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The maximum value of the tensile longitudinal stress in the concrete face can be determined by the formula.

$$\sigma^{max} \approx 7.6 \cdot 10^6 \sqrt{\frac{P}{E}} \quad (1)$$

Here, E is the secant modulus of deformation of the rockfill (Pa),
P – the force of horizontal hydrostatic pressure on the dam from the side of the reservoir (N/m):

$$P = \gamma_0 \frac{H^2}{2} \quad (2)$$

where γ_0 is the specific weight of water (N/m^3),
H – water depth in the reservoir.

According to formula (1) for a 100 m high dam (H=95 m) at E = 200 MPa, the tension can exceed 3,5 MPa. This is the maximum voltage that can be removed by the device in the reinforced concrete reinforcement. Therefore, the stone outline must be compacted very carefully. In extra-high dams, the absence of cracks in concrete face is even more difficult to provide; it is difficult to compact the rockfill to E> 400 MPa. It is necessary to take additional measures to protect the concrete face from the formation of cracks.

Dam construction sequence and loading condition formation of reinforced concrete face SSS is of great importance. If the dam is constructed by stages it is possible to improve reinforced concrete face SSS. This happens due to the fact that at rockfill dam settlements under its dead weight the reinforced concrete face SSS is subject to compressive longitudinal force. Very high rockfill dams should be constructed by several stages.

The shape of the site where the dam is constructed does not change principally the pattern of stresses distribution in the reinforced concrete face [12]. If the dam is located in a narrow gorge its settlements and displacements may considerably decrease, however, this does not result in disappearance of tensile stresses in the face. The danger of crack formation in the face due to strength failure still exists. The tensile zone in reinforced concrete face appears along the whole contact of the face with rock foundation (Fig.2b). This may be the explanation of the fact that at a number of the dams (Xingo, Ita) inclined cracks appeared, which repeated the outlines of rock foundation. Arrangement in the reinforced concrete face of additional joint parallel to the perimeter one may be recommended.

In the direction from one side to the other the reinforced concrete face is in the compressed state (Fig.2c, d). This compression appears due to displacements of rockfill in the direction from the sides toward the river channel. The greatest level of compressive stresses is characteristic for the dams located at narrow sites (Fig.2d). The given result is also fixed in other SSS numerical studies of the dams with the reinforced concrete face [13].

However, danger of concrete compressive strength failure appears only in ultrahigh dams. Compressive strength failure in the face is accompanied by development of vertical cracks. This conclusion is confirmed by the fact that at a number of ultrahigh dams (Tianshengqiao 1, Mohale, Barra Grande, Campos Novos) vertical cracks appeared with characteristic outward bend of reinforcement with failure of its protection layer.

To avoid development of vertical cracks it is necessary to provide free deformations of the face in the direction from one side to the other. This may be achieved by cutting the reinforced concrete face into sections by vertical joints. However, for compensation of the face compression in the direction from one side to the other the vertical expansion joint should be sufficiently wide and flexible. The presently applied designs of intersection joints have small width (from 2 mm to 20 mm) and they are compacted by rather rigid materials (wood or PVC) [1, 5]. Due to this they cannot provide proper freedom of deformations of the face. According to our studies, in the ultrahigh dams the vertical joints should provide the possibility of the face slabs movements toward each other for 2÷4 cm.

It is necessary to stress that one should be careful with regulation of compression level in the direction from one side to the other. By the results of analysis the decrease of compression in the direction from one side to the other may worsen the reinforced concrete face SSS in direction along the slope: tensile stresses may be developed in it.

An additional factor that can contribute to the formation of cracks in the reinforced concrete face is the temperature effect. Especially dangerous is the cooling of the concrete face when the reservoir is filled, it leads to the formation of tensile stresses in the face. Our study [14] showed that due to the low modulus of deformation of the rock outline, the concrete face can shorten. Due to this, the tensile stresses in the concrete are reduced. With a rockfill deformation modulus of E = 60 MPa, cooling of the concrete at 20 °C causes in it a longitudinal tensile stress σ of about 0.6 MPa. At E = 240 MPa σ≈1.6 MPa, which is dangerous.

4. Conclusions

1. Rockfill faced rockfill dams are not sufficiently safe because their seepage-control element is subject to crack formation. Crack formation occurs due to considerable deformations which the dam acquires at reservoir filling. At that, cracks may appear due to both concrete compressive and tensile strength failure.
2. The cause of appearance of horizontal cracks in the reinforced concrete face is tensile stresses. Appearance of horizontal cracks in the reinforced concrete face is caused not only by bending deformations but also, as analysis shows, reinforced concrete face may be subject to the longitudinal tensile force. Longitudinal tensile forces in the face lower part may exceed concrete tensile strength. The face zone conjugated with rock foundation is mostly subject to crack formation.
3. In ultrahigh dams located at narrow sites there is a danger of the face compressive strength failure. It appears at great deformation of rockfill. Vertical cracks appear in the reinforced concrete face at compressive strength failure. To minimize the danger of vertical cracks development the intersection joints should be sufficiently wide (at least 2 cm thick) and should be compacted by the material with low deformation modulus in order to have a possibility of compensating compressive stresses.
4. To minimize the danger of cracks development in the reinforced concrete face it is necessary to achieve high degree of rockfill compaction. Rockfill deformation modulus of the dam upstream portion should be at least 250-300 MPa; at that, rockfill of the downstream dam portion should not differ by deformability from the upstream one by more than 3 times.
5. In order to decrease the danger of formation of longitudinal tensile forces in the reinforced concrete face it is recommended to fulfill dam construction gradually, by several stages. This will permit creation of compression longitudinal force in the face.
6. An additional factor that can contribute to the formation of concrete face cracks is its cooling when filling the reservoir.

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