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Strength of ultra-high rockfill dam concrete face

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Abstract. The problem of providing safety to ultra-high rockfill dams with concrete faces is urgent and unresolved. It is proved by the facts of face structural failure of several ultra-high dams. As a rule, these facts are attributed to the face non-uniform bending deformations or are explained by high compressive stresses in the face central part. With the aid of numerical modeling the author investigated the conditions of forming stress-strain state (SSS) of ultra-high rockfill dams with concrete faces. Analysis was made of internal forces appearing in a concrete face: longitudinal forces and bending moments. It was established that high tensile stresses are most dangerous for concrete face strength in ultra-high rockfill dams. They create a threat by formation of horizontal and inclined cracks oriented along the contact with the foundation. These tensile stresses are the result of not only concrete face transverse bending deformations but also the presence of longitudinal tensile forces and longitudinal bending deformations in it. It is possible to minimize the impact of these adverse effects by decreasing friction at the contact of the face with the dam, however, this does not provide favorable SSS of the concrete face. It is necessary to take special measures on concrete face SSS regulation. Namely, it was established that rockfill deformation modulus should make up at least 300÷400 MPa. Absence of precedent cases of crack formation in the faces of the existing ultra-high rockfill dams may be explained by relaxation of stresses due to creep of concrete.

1. Introduction

One of the urgent problems in modern hydraulic engineering is development of a theory and scientific validation of concrete faced rockfill dams (CFRD) structural designs.

The urgent character of this problem is related to a great number of existing dams of this type and hopeful prospects for their future use. By this time several dozens of high and ultra-high CFRDs have been built in the world [1]. There considered alternatives of constructing ultra-high CFRDs on the rivers of Central Asia and Siberia. In China there discussed the plans of constructing CFRDs about 300 m high [2-4].

In spite of the fact that CFRDs have been used for already more than a century, the necessity in scientific validation of their structural designs is still urgent. Till present CFRD structures are being designed and built in compliance with the rules obtained experimentally. The principles of selecting CFRD structural solutions are given in Proceedings of International Commission on Large Dams (ICOLD)[1].

The durable experience permitted considerable refinement of CFRD structural designs and construction sequence, however, technical and technological solutions applied by present do not guarantee their safety. The scientific literature describes several dozens of cases of CFRD seepage-control element integrity failure [3, 5–11]. These failures were demonstrated by formation of large through cracks in concrete faces (CF). Their locations were not similar, which evidences that there is not only one but several causes of crack formation. In CF of some dams the vertical cracks were formed [6, 7], in others there were horizontal cracks [8] or inclined cracks [9].

[1] ICOLD. Concrete Faced Rockfill dam: Concepts for design and construction, International Commission on Large Dams. 2010. Bulletin 141

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The magnitude of CF failures evidences that they were caused by unfavorable stress-strain state (SSS). Therefore, a great number of scientific publications of different authors are devoted to analysis and investigations of CFRD SSS. The examples may be demonstrated by papers [1,12–23]. However, they do not create an integrated theory of CFRD operation, and sometimes they contradict each other.

There still existing a concept that CFRD seepage-control element works mainly in bending appearing at rockfill deformations under the action of hydrostatic pressure. At the same time, there are statements in literature that at that, the face is subject to compression in both directions, then crack formation in it cannot be explained. Formation of vertical cracks in CF is attributed to cleavage of the face surface layer in the compressed zone.

To solve the scientific problem in scientific validation of ultra-high CFRD structural designs the author with the aid of numerical modeling fulfilled a number of investigations of their SSS. They permitted determining the conditions of CF SSS formation, reveal the main peculiarities and assess its strength.

2. Methods

SSS studies were conducted by the author with the aid of the finite element method. Analyses were carried out on the example of a 200 m high abstract dam (Fig. 1). The face thickness was assumed to be constant and was equal to 2 m. The structure of the dam body was assumed to be uniform by deformation properties. At analyses the sequence of SSS formation was taken into account: several stages of the dam construction and the reservoir impoundment were considered.

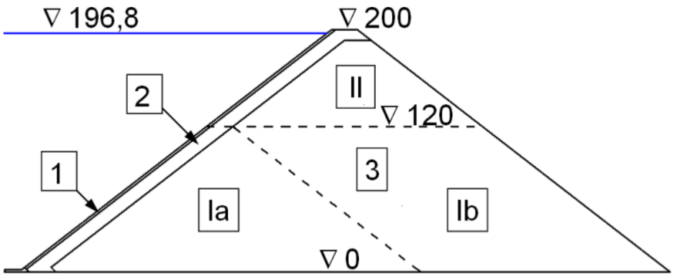

Figure 1. Structural diagram of an ultra-high rockfill dam with a concrete face
1 – concrete face – the first stage in scheme 3; II – the second stage in scheme 2; Ib, II – the dam second stage in scheme 3.

The specific feature of the research methodology for modeling of a CF thin-walled structure was use of solid finite elements with a cubic degree of approximation of high-order displacements. Thanks to use of high-order elements, calculations allowed us to obtain a continuous function of the stress distribution in a rigid thin-walled structure in all directions.

Due to use of solid finite elements, rather than plate or shell finite elements, all components of the stress tensor in CF were determined. This provides the ability to perform a more complete analysis of its stress state. Using the components of the tensor, the internal forces in the sections of the CF structure were calculated: longitudinal forces and bending moments.

When developing the finite element models of the structure, it was possible to exhibit non-linear effects at the contacts between structures, the rigidity of whose materials varies greatly. This is a possibility of tearing off and slipping. When modeling the slippage effect, the Coulomb model was used. For this, contact finite elements (Goodman elements) were used. These elements were provided between the face and rockfill, between rockfill and the rock foundation, and also simulated the behavior of the perimeter joint.

The analyses were carried out for various alternatives of rockfill deformability, using the model of linear deformation of soil. To assign the values characterizing rockfill deformability the data of field measurements of CFRD deformations was processed. It showed that depending on the quality of rockfill compaction the value of rockfill linear deformation modulus E varies within a wide range: from 30 MPa to 500 MPa [24]. SSS calculations were carried out for four values of E: 60, 120, 240 and 480 MPa. The Poisson's ratio of rockfill was taken equal to 0.2.

3. Results and Discussion

Analysis of the results of numerical modeling revealed the main characteristic features of the CF SSS of rockfill dams. It turned out to be more complicated than in approximate, speculative representations. This is due to the complicated nature of the dam body deformations and the interaction between the CF and the dam body.

It was revealed that not only cross bending but also other forms of deformation are characteristic of the face SSS. They appear even in the simplest loading scheme (scheme 1), when the reservoir is impounded only after the completion of the dam construction.

The cross bending of the face is not the prevailing form of its deformations; taking into account other forms of the face deformations leads to a considerable change of stresses in it.

Cross bending of the face is caused by the non-uniform height-wise distribution of deflections of the face (movements in the direction across the slope). As a rule, the bend of the face towards the downstream side prevails, but it may also occur in the opposite direction. This is illustrated in Fig.2.

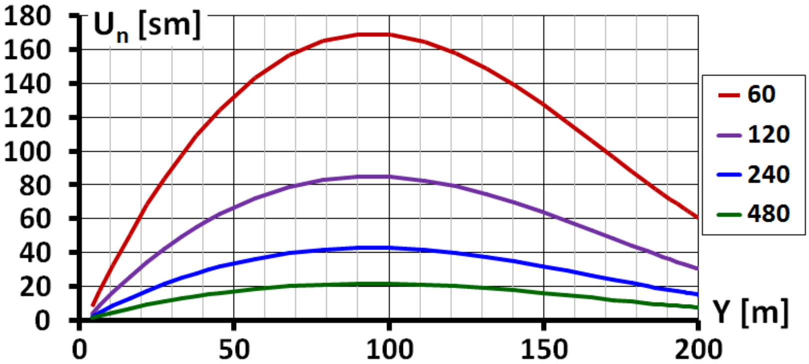

Figure 2. Distribution of deflections (movements in the direction across the slope) of the concrete face height-wise Y. Figures designate values of rockfill linear deformation modulus E.

With a simple construction sequence (scheme 1), the bending of the face towards the downstream side is characteristic of its part which is below the water level. The greatest intensity of bending deformations is observed at the very bottom of the face (Fig. 3). In the zone of water level, the face bends towards the upstream side. As the reservoir is impounded the shape of the deflection curve changes, and the upward bend zone toward the upstream side moves upward as a "wave" (Fig. 3).

Presence of the face bend in the upstream direction is confirmed by field measurements at the existing dams. The outward bend of the face is accompanied by formation of thin horizontal cracks in it. Mori1 indicates that such cracks have openings of about a few tenths of a millimeter, but they close after rising water levels in the reservoir.

At complicated construction sequence, the nature of cross bending deformations is significantly more complicated. The characteristic effect is the presence of the face upward bend in the upstream direction observed on the crest of each stage of the dam (Fig. 4). The presence of this effect was found at SSS numerical modeling of the Tianshengqiao-I dam in China, as well as during field measurements [14]. Separation of the face from the dam body is also possible. The presence of this separation is a typical feature indicating the danger of cracking in the face.

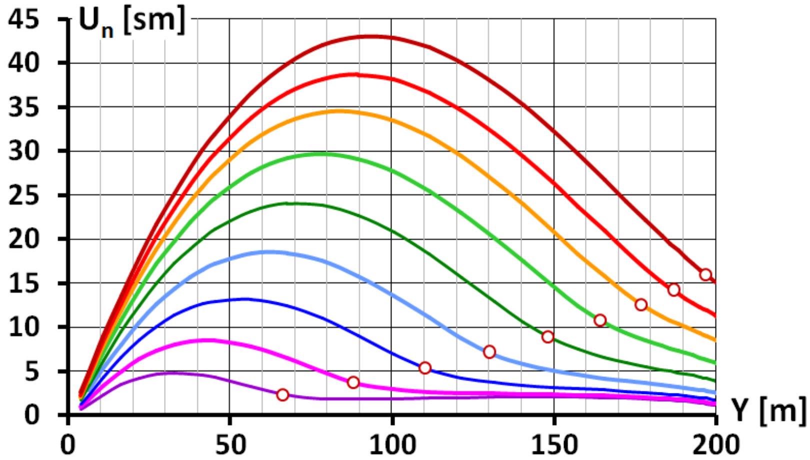

Figure 3. Variation of concrete face deflections with growth of the upstream water level (at E=120 MPa).Circles designate the upstream level corresponding to the curve of deflections.

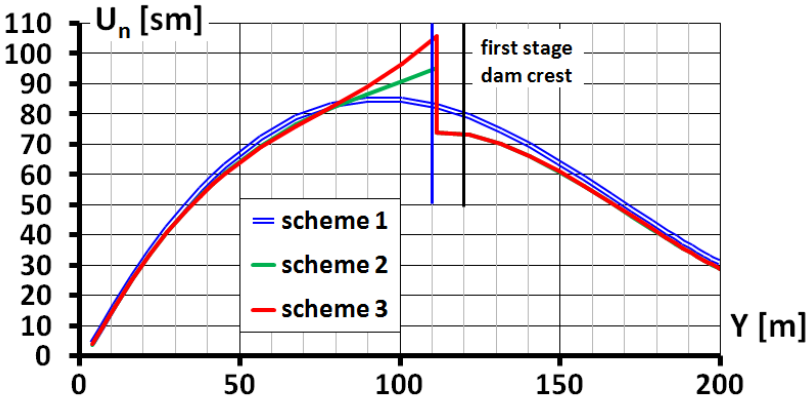

Figure 4. Variation of distribution pattern height-wise the face deflections depending on the sequence of the dam construction and the reservoir impoundment at E=120 MPa). Scheme 1 – reservoir impoundment after full completion of the dam construction; schemes 2, 3 – 2nd stage dam construction and the reservoir impoundment.

Fig.4 shows the example of variation of the 200 m high dam face deflections. Three schemes of sequence of dam construction and reservoir impoundment were considered. In Scheme 1, the reservoir is filled only after full completion of the dam construction. In schemes 2 and 3, the construction of the dam and the reservoir impoundment are carried out in two stages. The height of the first stage is 120 m, and the level of the upstream level is 110 m. In scheme 2, the profile of the first stage of the dam has a very wide crest, and in scheme 3 – 10 m (Fig. 1).

From Fig. 4 it is seen that construction of the 2nd stage dam reduces deflection of the face in the lower part of the 1st stage dam and in the 2nd stage dam. However, on the crest of the 1st stage dam the deflections sharply increase. In this zone, the face bends towards the upstream side, and these deformations are very significant in magnitude. Formation of tensile stresses in the face may be expected. It is confirmed by formation of cracks in the upper part of the face of the first stages at dams Tianshengqiao-I [14], Shuibuya and Buxi [8].

It should be noted that when the dam is erected by stages, the danger of cracking is characteristic not only of the 1st stage face, but also of the 2nd stage face. In Fig. 4, an increase in deformations of the 2nd stage face cross bending in the zone adjacent to the dam of the first stage is noticeable.

To minimize additional bending deformations, it is necessary that the crest of the first stage dam should be very wide: in scheme 3 the bend is less than in scheme 2 (Fig. 4). This confirms the statement of Marques and Pinto that the asymmetric profile of the first stage contributes to formation of tensile stresses in the face [25]. However, even when using the symmetric profile of the first stage (Scheme 3), the danger of cracking in the CF remains.

However, not only cross bending deformations pose a danger to the integrity of the face. The author's studies showed that in addition to cross bending deformations, the face experiences longitudinal deformations, i.e. linear deformations in the direction along the slope. They arise due to the presence of tangential stresses τ on the contact between the face and the dam.

The assumption of the significant role of shear stresses in the formation of the face SSS was made by Marques and Pinto even in 2005 [25]. They expressed the opinion that during deformations of the dam body, tangential stresses may occur at the contact of the face and the dam, causing deformation of the longitudinal extension of the face. Marques and Pinto proposed a method for determining frictional forces at the contact of the dam face. They pointed out that the tensile strength of concrete may be provided if the stresses did not exceed 3 MPa, and made a supposition that with conventional reinforcement the formation of rupture cracks in the CFRD face was inevitable.

However, the method of determining friction forces proposed by Marques and Pinto, involves reaching by them their limit values, which in real conditions usually does not occur. The exact values of the friction forces may only be determined by numerical modeling. Using numerical modeling, the effect of formation of tensile longitudinal forces in CF was confirmed by the author in 2006 [13] and Arici in 2011 [12].

Let us Consider the conditions for formation of friction forces at the CF contact with the dam body using the simplest dam construction scheme as an example (Scheme 1). Before impoundment of the reservoir the tangential stresses τ are caused only by forces from the dead weight of the face. They are directed from top to bottom and increase evenly from the crest to the foot. In this case, the contact perceives only part of the face dead weight, and the rest is transmitted through the perimeter joint to the foundation.

After filling the reservoir the tangential stresses τ at the contact change. This change is associated with high horizontal displacements of the dam under the effect of hydrostatic pressure on the upstream face. As a rule, the deformation properties of rockfill are such that the displacements and settlement of the dam are comparable in magnitude. Due to large displacements, the face separates from the foundation: the perimeter joint opens, separating them from each other. The joint opening is confirmed by the data of field measurements at most of CFRDs given in the proceedings of ICOLD. It also indicates the presence of the face movements in the direction along the slope and appearance of linear longitudinal deformations in the face.

Separation of the face from the foundation leads to the fact that the dead weight of the face is entirely perceived by the tangential stresses τ at the contact between the face and the under-face supporting zone and τ grows. But when filling the reservoir, not only growth occurs, but also the redistribution of tangential stresses lengthwise the contact. This redistribution is caused by the uneven deformations of the dam body. As the rigidity of the CF and rockfill varies greatly, the CF cannot be deformed jointly with the dam body; at the contact between them the face and the dam move relative to each other. The consequence of this movement is additional friction forces at the contact, due to which the tangential stresses τ are redistributed lengthwise the contact.

Designs of CFRD provide for arrangement of a special under-face zone to smooth out the unevenness of the face deformations. However, as our studies have shown, this zone does not play a significant role due to its small thickness.

A more important role is played by friction characteristics (shear parameters) at the contact between the CF and the under-face supporting zone. In modern dams (since 1999), the surface of the upstream slope is formed in the form of curb blocks made of low-cement concrete [26]. Moreover, to reduce friction, the contact between the CF and the curb blocks is covered with a bitumen emulsion.

SSS analysis was conducted for two alternatives of CFRD structure. In alternative 1 it was assumed that the under-face zone is made of crushed stone and the curb blocks are not arranged. The tangential stiffness of the contact was taken equal to 200 MPa / m. In alternative 2, the presence of both curbs and an antifriction layer was taken into account. The modulus of deformation of the material of the curb blocks was taken equal to 5 GPa. The tangential stiffness of a contact coated with a bitumen emulsion was approximately assumed to be 20 MPa/m.

Calculations show that the taken measures cannot completely eliminate friction on the contact. Regardless of the tangential stiffness of the contact, the distribution pattern of the tangential stresses τ on the contact does not change basically.

Figure 5 shows the distribution of τ obtained by calculation for alternative 2. It may be seen that in the lowest part of the contact the tangential stresses get the opposite direction (from the crest to the foot), and on the rest of the contact they increase in magnitude (Fig. 5). The indicated effect is not fundamentally new. It also manifests itself at the contact of the foundation of structures with a deformable soil foundation.

This effect of "negative friction" is important in formation of CF SSS; it causes longitudinal extension in the face which affects the strength of the face.

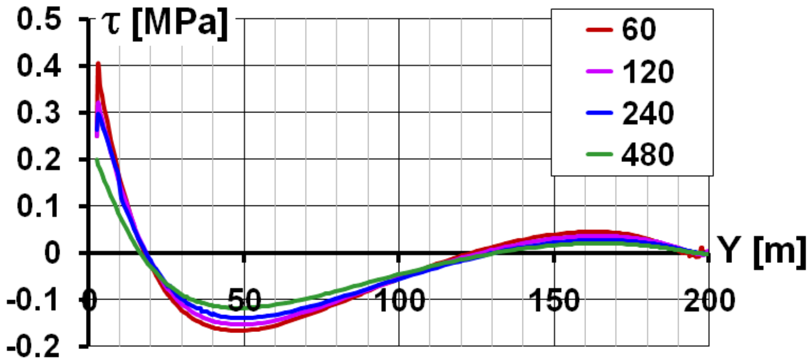

Figure 5. Tangential stresses on the contact of the face with the under-face zone (if bitumen emulsion layer is provided).
Figures designate values of rockfill linear deformation modulus.

Figure 6 shows the obtained by calculations pattern of distribution of the longitudinal forces N in the CF for a simple construction scheme (Scheme 1). In the lower quarter of the height the face is subject to tensile force (extension deformations), and in the upper quarter it compresses (contraction deformations). It should be noted that the values of tensile and compressive longitudinal forces are quite significant.

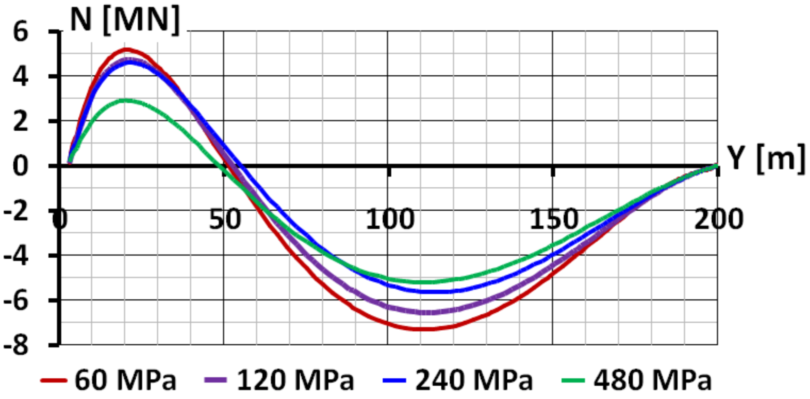

Figure 6. Longitudinal forces in CF (if bitumen emulsion layer is provided). Figures designate values of rockfill linear deformation modulus.

Thus, the author found that the CF SSS is characterized by the presence of not only bending moments M, but also longitudinal forces N. This has an extremely adverse effect on the strength of the CF. The combined action of bending moments and tensile longitudinal forces leads to the appearance of high tensile stresses in the faces of ultra-high CFRDs.

This is illustrated in Figs. 7 and 8, which show the distribution of the longitudinal stresses along the CF height, i.e. stresses acting in the direction along the upstream slope. They clearly show that the lower CF part of an ultra-high dam will experience very high tensile stresses, many times greater than the tensile strength of concrete.

The value of tensile stresses depends on many factors, among which the main impact is exerted by rockfill deformability (E), the shear characteristics of the contact, and also the deformation modulus of concrete E_b.

Fig. 7 corresponds to alternative 1, when the friction reduction at the contact is not performed, and E_b = 29 GPa. In this case, even with the most thorough compaction of rockfill tensile stresses are many times higher than the tensile strength of concrete (1.8 MPa). This is due to the fact that tensile stresses only from longitudinal forces (excluding bending) exceed 2 MPa. This indicates an extremely low level of safety of ultra-high CFRDs, as well as the need for measures to reduce friction at the contact between the CF and the dam body.

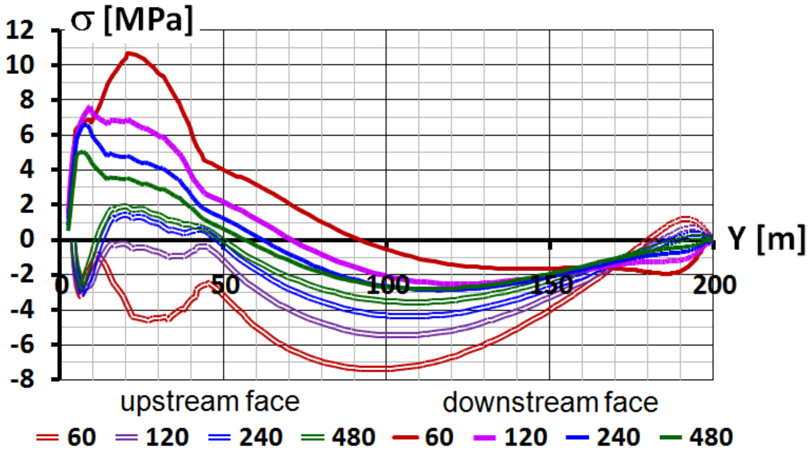

Figure 7. Distribution of longitudinal stresses on the upstream and downstream faces of the dam face (at the face contact with the under-face zone made of soil; simple scheme of dam construction and loading).

Figure 8 shows the calculation results for alternative 2 and E_b = 29 GPa. However, even in this case, in all options, the standard tensile strength of the CF is not provided.

Comparison of the results of SSS calculations in two alternatives (Figs. 7 and 8) permits revealing the role of friction in formation of the CF SSS. For analysis by the values of longitudinal stresses in the face, bending moments M were determined. Curves of the distribution of bending moments are shown in Figs. 9 and 10.

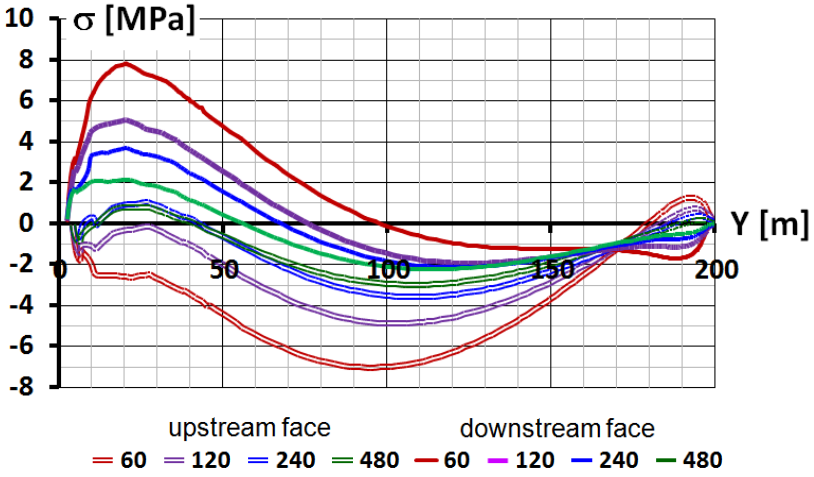

Figure 8. Distribution of longitudinal stresses on the upstream and downstream faces of the dam face (at decrease of friction at the contact of the face with concrete under-face zone; simple scheme of dam construction and loading).

Comparison of the bending moments in alternatives 1 and 2 allowed the author to identify another effect characteristic of CF SSS. This is the effect of the face longitudinal bending. It consists in the appearance of an additional bending moment in the face. In Fig. 9 (alternative 1), a sharp jump in bending moments in the lowest part of the CF is clearly visible, while alternative 2 does not have it (Fig. 10).

The effect of longitudinal bending is characteristic only of the edge sections of the face. It arises due to the peculiarity of their stress state, which consists in the deviation of the lines of action of the main stresses from the longitudinal direction (direction along the slope). Therefore, in the horizontal section of the face, the longitudinal force does not coincide in magnitude with the friction force. This inequality causes an additional moment from the longitudinal bend.

Longitudinal bending has a significant and adverse effect on the SSS of the face in alternative 1; it increases the bending moment directed towards the downstream side. Accordingly, it contributes to formation of transverse cracks in the face. Reduction of tangential stresses on the contact permits avoiding longitudinal bending.

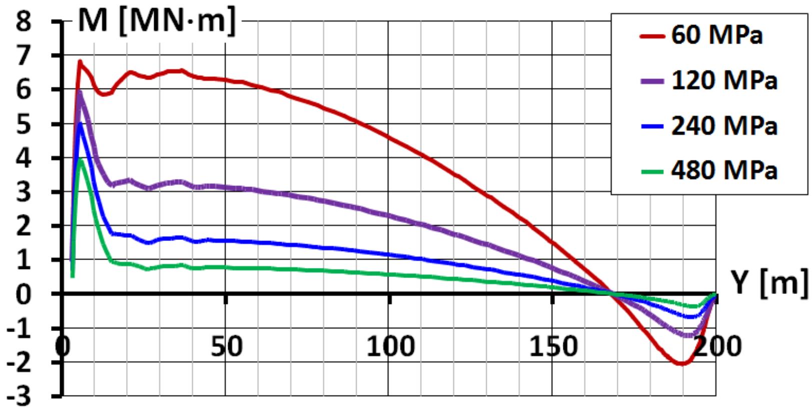

Figure 9. Distribution of bending moments height-wise the face (at the face contact with the under-face zone made of soil; simple scheme of dam construction and loading).

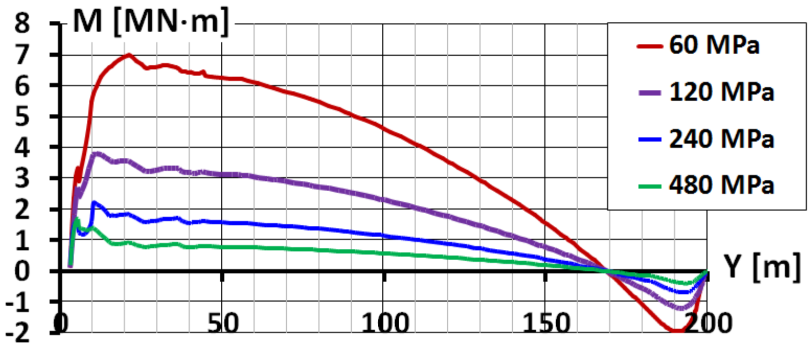

Figure 10. Distribution of bending moments height-wise the face (at decreasing friction at the face contact with concrete under-face zone; simple scheme of dam construction and loading).

Thus, decrease of friction at the CF contact with the dam has a favorable effect on the CF SSS: it reduces the longitudinal tensile force and the moment of longitudinal bending. In ultra-high dams this is a necessary measure.

However, it does not permit providing the necessary level of the CF safety. Even in alternative 2, at E < 350 MPa, tensile stresses exceed 3 MPa and formation of transverse cracks in the face may be expected. Calculations of the SSS in the 3D formulation [21] show that the orientation of these cracks will repeat the position of the foundation outline. On the channel sections the cracks will be located horizontally, and on the side sections they will be inclined.

High (almost one hundred percent) probability of formation contradicts the practice of construction and operation of ultra-high dams. Not all ultra-high CFRDs showed cracking. Several explanations can be given for this.

First of all, it is the influence of spatial conditions. Ultra-high dams are erected, as a rule, in narrow rock gorges. The impact of the rock sides leads to decrease of both displacements and settlements of the dam. In this case decrease of horizontal displacements occurs more intensively than that of settlements. This has a favorable effect on CF SSS. Compared to flat conditions, both compressive and tensile forces acting in the CF in the direction along the slope are reduced.

However, studies of the spatial CFRD SSS [21] show that the effect of spatial conditions is not critical in terms of providing the tensile strength of concrete.

Therefore, the more credible assumption is that not one, but several factors act, creating a difference between the calculated conditions for CFRD SSS formation from the real ones.

Firstly, the improvement in the CF SSS may be related to time dependent relaxation of stresses in the face concrete. According to Russian standards, due to creep the deformation modulus of concrete E_b may be reduced by 20 ÷ 60%.

Analyses of CFRD SSS with a value of E_b = 12 GPa made it possible to evaluate the effect of this phenomenon on the CF strength. Figure 11 shows the longitudinal stress distribution for alternative 2.

Analyses showed that a 60% decrease in E_b reduces stresses in the CF by about 30 %. Due to this, in alternative 2, at E> 400 MPa, the standard value of concrete tensile strength (1.8 MPa) is provided (Fig. 12).

This result allows us to recommend the construction of ultra-high CFRDs to be long and gradual, so that concrete can adapt to rockfill deformations and stresses in it are reduced due to relaxation processes. This recommendation is confirmed by the operating experience of the Mohale dam [7], in which loss of the CF integrity occurred during repeated, but very fast impoundment of the reservoir.

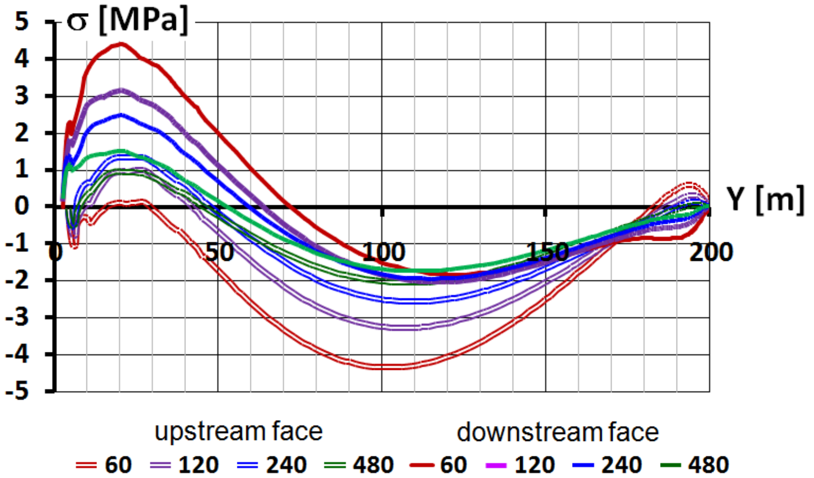

Figure 11. Distribution of longitudinal stresses on the upstream and downstream faces of the dam face (at decreasing friction of the face contact with concrete under-face zone).

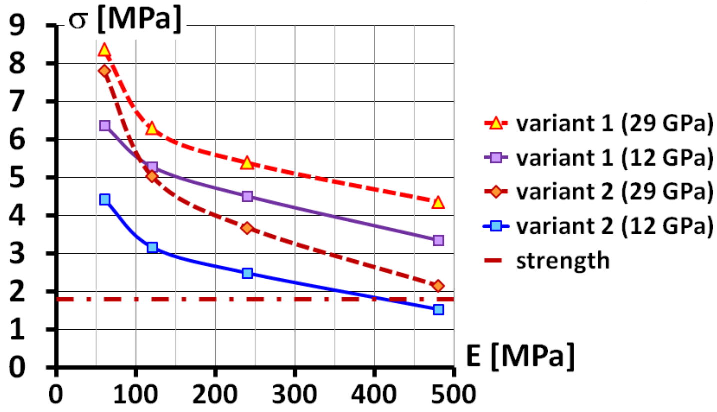

Figure 12. Relationship between maximum values of tensile stresses in the face and rockfill linear deformation modulus E, linear deformation modulus of concrete and friction at the contact. Variants 1, 2 are variants of the contact shear characteristics. Figures in brackets designate the value of concrete linear deformation modulus.

Secondly, it can be expected that in regions with a warm climate, the tangential stiffness of the bitumen emulsion layer will be lower than 20 MPa / m, which reduces friction and longitudinal forces.

Taking into account the influence of other factors (spatial conditions, face reinforcement, staged construction), it is recommended to compact rockfill in ultra-high dams until the values of rockfill deformation modulus E> 300 MPa are reached.

Another characteristic feature of the CF SSS of ultra-high dams, which determines their strength, is known from the scientific and technical literature. It consists in the presence of high compressive stresses in the face in the direction along the dam section (from one side to the other side). It is confirmed by the facts of formation vertical cracks in the CF at a number of ultra-high dams [6, 7]; and also it is revealed as a result of numerical studies of the CF spatial SSS by different authors [1, 15, 20].

The reason for formation of high compressive stresses in the CF is not attributed to bending deformations, but the presence of longitudinal compressive force in the direction from one side to the other side. This force arises from the uneven distribution of dam settlements along the alignment. The river channel section of the dam with the highest dam height settles more than the side sections of the dam, which leads to horizontal displacements of the dam in the direction from the sides to the channel. It is due to them that compressive longitudinal forces appear in the face.

The author's calculations [21] showed that the higher is the dam and the narrower is the site, the more intensive are the horizontal compressive forces in it. In ultra-high dams located in narrow sites, compressive stresses can be comparable with the compressive strength of concrete (about 15 MPa). This explains the observed cases of formation of vertical joints at the existing dams.

The non-uniform distribution of dam settlements and displacements along the alignment is associated with one more feature of the CFRD SSS. It can be described as a bend of the face in its plane. The river channel sections of the face receive longitudinal displacements larger in size than the side ones. The plane bending of the face is expressed rather weakly and is almost completely compensated by vertical intersectional joints. It does not pose a serious danger to the strength of CF.

4. Conclusion

The research results revealed the most vulnerable places in the CF structure and possible causes of their integrity failure associated with its unfavorable SSS. Briefly relevant conclusions can be formulated as follows:

1. Failures of the CF integrity should be associated not only with loss of concrete compressive strength, but also with loss of tensile strength;

2. The reason for appearing vertical cracks in the face of an ultra-high dam is high compressive longitudinal forces in the direction from one side to the other side. The formation of such cracks is possible only in the central part of the face;

3. When the dam is constructed by stages, it is very likely that failure of the CF tensile strength may be related to the local effect of an increase in bending deformations in the stage boundary zone;

4. The most dangerous from the point of view of crack formation is the interface zone of the face with rock foundation. In this zone, the face experiences not only the bending moment of the cross bending, but

also the tensile longitudinal force (in the direction along the slope) and the bending moment of the longitudinal bending. This leads to appearance of tensile stresses on the face, which threaten with formation of horizontal and inclined cracks.

According to the results of calculations, the formation of high tensile stresses in the face is almost inevitable and it is very difficult to provide tensile strength of concrete in the face of an ultra-high dam.

Therefore, the urgent task of research is selection and justification of measures to provide tensile and compressive strength of the concrete face. The main of these measures is to reduce rockfill deformability due to the high degree of its compaction. Based on the calculation results, it may be recommended to achieve rockfill linear deformation modulus E of at least 300 MPa.

Bearing this in mind when choosing measures, it should be taken into consideration that, with rockfill low deformability, the main danger to CF strength is posed not by bending deformations, but by longitudinal extension deformations. This is illustrated by the curves in Fig. 13, which show change in the maximum values of bending moments M and tensile longitudinal forces N depending on various factors. On them it is seen that an increase in rockfill modulus E decreases M_{max} to a greater extent (Fig. 13b) than N_{max} (Fig. 13a).

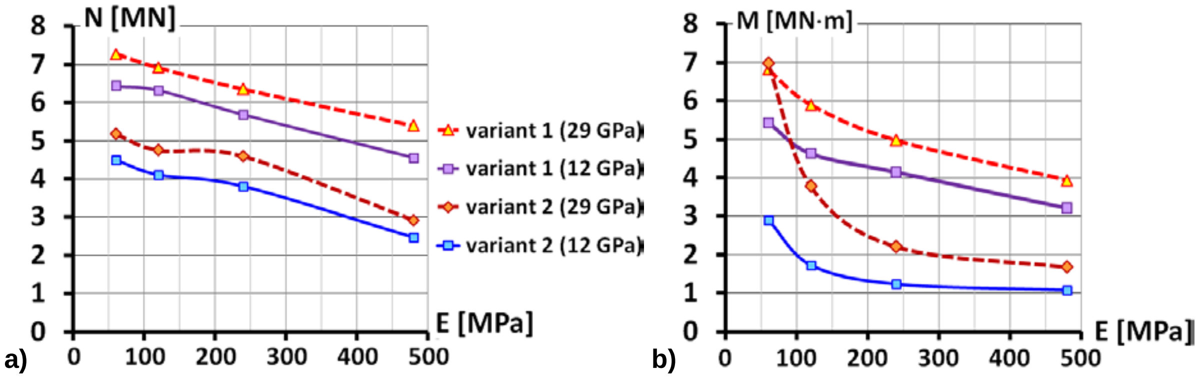

Figure 13. Relationship between maximum values of longitudinal forces (a) and bending moment (b) and rockfill linear deformation modulus E, concrete linear deformation modulus and friction on the contact.

Therefore, measures to provide the CF strength should first of all be aimed at reducing the longitudinal forces in the face and at reducing the part of the stresses caused by these longitudinal forces. One of such measures is reduction of friction at the contact between the face and the dam body. It allows not only reducing the value of tensile and compressive longitudinal forces in the face, but also protection of the face against deformations of longitudinal bending.

Both of the above measures are necessary, but not sufficient to provide strength of concrete in the face of an ultra-high dam. A full complex of measures is required.

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