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# Stress-strain state of CFRD with a decrease in friction at the face-sidewall contact

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**Keywords:** dams, curbs, shear stress, friction, finite element method, interfaces (materials), strain, concrete faced rockfill dam (CFRD)

**Abstract.** Friction forces arise at the contact between a concrete face and a rockfill dam body at deformations caused by hydrostatic pressure. They cause tensile and compressive longitudinal forces in the face which decrease the safety factor. In modern CFRD, a layer of emulsified asphalt is placed at the contact between the face and the sidewall made of low cement concrete to decrease the friction. Tests carried out in China permit determining shear characteristics of such a contact. They revealed the effect of increasing tangential stiffness with growth of compressive pressure. At high pressures the contact stiffness may reach 200÷500 MPa/m. The author refined the relationship describing the effect of increasing tangential stiffness and determined its parameters. Availability of the data on tangential stiffness and strength of the contact permitted the author to make a more precise model of the concrete face stress-strain state by the finite element method. The results of analyses showed that measures on decreasing the contact friction do not reach the required effect: considerable tensile longitudinal forces appear in the face. The contact tangential stiffness should be more decreased. Tentatively it may be recommended that in a 100m high dam to provide the face tensile strength the contact tangential stiffness should not exceed 50 MPa/m. However, for more justified conclusion it is necessary to carry out additional experimental studies of shear characteristics of the contact between face and the sidewall; and they should be conducted for conditions of very low shear rates typical for real dams.

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## 1. *Introduction*

The urgent and debating issue in hydraulic engineering is refining the theory of concrete faced rockfill dams (CFRD). The dams of such a type are unique structures: in them a thin-wall and continuous structure of a concrete face perceiving hydrostatic pressure is subject to high deformations which are typical for earth fill. The concrete face (CF) thickness, as a rule does not exceed 1 % of the dam height and 0.5 % of the face length. Deflections of the face at high CFRD make up 0.1÷0.5 % of the dam height, i.e. they are comparable by value with the face thickness.

Debating is the theoretical concept of the concrete face stress-strain state (SSS) specific features. Traditionally it is considered that the face concrete mainly works in bending (in two planes) for perceiving pressive from its own weight.

However, one more specific feature of CF SSS was revealed bases on field measurements and with the aid of numerical modeling. For CF it is typical to have compressive stresses in direction from one bank to the other. The presence of these stresses is evidenced by formation of characteristic vertical cracks in faces of some ultra-high CFRD. The examples are dams Tianshengqiao-1 (China, dam height H = 178 m, the year of emergency situation is 1999), Barra Grande (Brazil, H = 185 m, 2005), Campos Novos (Brazil, H = 202 m, 2005), Mohale (Lesotho, H = 145 m, 2006) [1–6]. By the results of field measurements, in Mohale dam face at the moment before crack formation the horizontal relative linear deformation amounted to 0.00065 [3]. The deformation of such a value corresponds to compressive stress amounting to about 20÷25 MPa, which is higher than concrete compressive strength.

The issue on the causes of appearing high compressive stresses in the face is debatable. It may be affirmed that the main cause is friction forces between the face and the body of the dam which appear at displacements of the dam body from the sides towards the valley floor. With the aid of numerical modeling it was obtained that the risk of appearing high compressive forces is characteristic for ultra-high dams in a narrow site [7].

It is evident that friction forces may act not only in horizontal direction but also in the direction along the slope. In this case they may present danger for the face strength. The hypothesis about considerable role of contact friction in formation of CF SSS was put forward in 2005 in paper [2] of P. Marques Filho and N. Pinto. They proposed that contact friction forces may cause high tensile stresses in the face in the direction along the slope. By their approximate calculations the tensile stresses in the face may reach 9 MPa. Such stresses are much higher than concrete tensile strength and may cause appearance of transversal cracks in the face.

Numerical modeling may give more precise evaluation of friction forces role in CF SSS formation. According to the studies conducted by Y. Arici (2011), formation of transversal cracks due to high tensile stresses may be expected in the lower part of high CFRD face in the direction along the slope [8]. The similar result was obtained by the author of this article in 2006 with the aid of numerical modeling [9]. It was shown that for CF SSS the characteristic feature is action of tensile longitudinal forces. Thus, there was confirmed the hypothesis about possible appearance of tensile longitudinal forces in CF due to contact friction. Consequently, CF works not only to perceive bending and transversal forces but also longitudinal forces.

In 2000 A. Marulanda and N. Pinto proposed special measures for decreasing friction between CF and the dam body. Their concept obtained the name “Bond Break”[1]. These measures were required because of changes in CFRD construction methodology. At construction of Ita dam (1999) there was used a new method of creating a plane surface for subsequent concreting of the face [10]. The method of Ita envisages to form the dam upstream slope using blocks made of low cement concrete. In technical literature such construction is called “extruded curb” or “extrusion-sidewall” (SW). The Ita method afterwards was used at construction of two dams and became a commonly-accepted method.

However, presence of stiff construction under CF increases friction, therefore, additional measures were required. Concept “Bond Break” envisages separation of CF from SW by an intermediate layer to decrease friction [11]. The role of this layer is played either by asphalt emulsion (about 2 mm thick) or a geomembrane. By recommendation of International Commission on Large Dams (ICOLD)[2] the antifriction measures were applied at the dams constructed in the XXI$^{th}$ century, but they were used at construction of Ita dam.

It should be noted that concept “Bond Break” has earlier analogs. Already in the first half of the XX$^{th}$ century the engineer Girand proposed the structure of a flexible laminated face where concrete slabs were separated from each other by bitumen layers. Such structural design was used in Chile at 85 m high Cogoti dam constructed in 1938. In 1943 the dam successfully withstood the earthquake with acceleration 0.2 g [12]. However, there were also flawed examples of using laminated concrete faces.

Therefore, it is important to evaluate the effectiveness of measures for decrease of friction. Studies of CFRD SSS conducted by the author [13, 14] with the aid of numerical modeling showed that the role of friction forces at the contact between the face and the dam body is high. Tangent stresses at the contact as a rule do not reach the limit values, nevertheless they may cause considerable tensile stresses in the face, especially in the face of an ultra- high dam.

However, the mentioned results of CFRD SSS numerical modeling may be doubtful. Many ultra-high CFRD are operating normally without loss of tensile strength and crack formation in the face. This may be explained by favorable effect of other factors (effect of spatial conditions of operation in a narrow river valley, relaxation of stresses in concrete, other reasons), but it also may be connected with overestimated in analysis characteristics of contact friction. In the studies of CFRD SSS carried out by the author the contact tangential stiffness was assumed to be equal to 50÷200 MPa/m.

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[1] Marulanda, A., Pinto, N.L. de S. Recent Experience on Design, Construction, and Performance of CFRD Dams. J. Barry Cooke Volume, Concrete Face Rockfill Dams, ICOLD, 20th Congress, Beijing, China, September, 2000.

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

Therefore, the author fulfilled this study on revealing the effect of characteristics of contact friction between CF and SW.

## 2. Methods

The study of effect on CF SSS of tangential stiffness $K_t$ value of the contact between CF and SW was conducted with the aid of numerical modeling. The idea of the study includes:

- use at analysis of experimental data on determining $K_t$;
- making calculations for a wide range of $K_t$ values.

For this purpose, the author analyzed experimental data on shear characteristics of the contact between the face and the dam body.

***Data of experimental studies of the contact shear characteristics.***

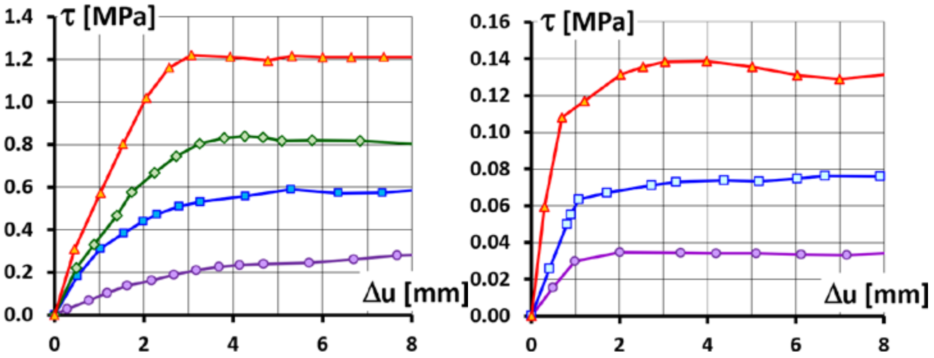
Experimental tests of shear characteristics of contacts with concrete structures were carried out by different authors [15–20]. However, most of these studies were devoted to contacts of concrete structures with soils.

For the aims of our studies the most valuable is experimental data [19, 20], which was obtained in China at designing Shuibuya dam (2008), the highest CFRD in the world (H = 233 m). These tests were conducted with the aid of special equipment which permits conducting shear tests of coarse sample of constructions (25×25 cm) at downward pressure up to 2 MPa. The studies were conducted for several alternatives of contact surface along which a shear of a concrete slab occurs. Concrete slab shear tests were conducted against crushed stone as well as against the surface of low cement concrete provided there was an antifriction layer. For an antifriction layer there was used a 1 mm thick layer of emulsified asphalt, 0.2 mm thick polyethylene membrane and asphalt felt. The tests were conducted at several values of downward pressure (0.5; 1; 1.5; 2 MPa) at a rate of relative displacements about 0.1 mm per minute.

The results of tests fulfilled by W. Hou et al. [19, 20] are shown in Fig. 1 they are presented in a form of relationship between tangent stresses $\tau$ and relative displacement $\Delta u$ of two contacting surfaces. By the results of the experiments there were determined the parameters of contacts shear strength and tangential stiffness.

It was established that the contact of concrete with crushed stone has the highest shear strength: the angle of internal friction $\varphi$ makes up 41°. The contact shear strength with arrangement of interlayers of emulsified asphalt and polyethylene membrane is approximately one forth as less as the contact with crushed stone: $\varphi$ = 30°÷32°. The lowest shear strength has the contact with a layer of asphalt felt: $\varphi$ = 4°. Its shear strength is approximately 10 times as less as of the contact with crushed stone.

Of great interest are the results of contact stiffness studies. It was established experimentally that the contact of concrete with crushed stone has the highest tangential stiffness. Tangential stiffness $K_t$ of the contact with layers of emulsified asphalt and a polyethylene membrane is nearly similar. Arrangement of an antifriction layer between CF and SW approximately by 5÷7 times decreases tangential stiffness $K_t$. Even lower is tangential stiffness of the contact with a layer of asphalt felt: it is approximately 20 as less as that of the contact with crushed stone.



**a) concrete contact with emulsified asphalt** **b) concrete contact with asphalt felt**

σ: ◆ **0.5 MPa** ■ **1 MPa** ◆ **1.5 MPa** ▲ **2 MPa**

**Figure 1. Results of interface shear experiments (W. Hou et al.).**

It is noted that at approaching the limit state (slippage along the contact) the tangential stiffness decreases. At reaching the limit value by tangential stiffness the shear at the contact has unlimited increase.

The important result of tests was revealing the effect of relationship between tangential stiffness $K_t$ of the contact and downward pressure $\sigma$ (Fig. 1). For example, for the contact a layer of emulsified asphalt at $\sigma$ = 0.5 MPa $K_t$ does not exceed 100 MPa/m, and at $\sigma$ = 2 MPa it reaches 600 MPa/m. As it is seen, at increase of $\sigma$ the tangential stiffness increases intensively.

For the purpose of our study, we apply the range of stresses $\sigma$ from 0 to 1 MPa. From the results of experiments it is evident that at $\sigma$ = 1 MPa for the contact of concrete with crushed stone the tangential stiffness $K_t$ ≈ 850 MPa/m, at arrangement of the layer of emulsified asphalt it is equal approximately 180÷250 MPa/m, and at arrangement of the layer of asphalt felt $K_t$ ≈ 60 MPa/m.

For description of non-linear relationship between $K_t$ and $\sigma$ W.Hou et al. [20] proposed to use power dependence in the form of:

$$K_t = K_0 p_a \left( \frac{\sigma}{p_a} \right)^n ,$$

where $K_0$ is dimensionless modulus, $p_a$ is atmospheric pressure, $n$ is power index.

Similar relationship was used at numerical modeling of CFRD SSS by some authors [21, 22].

However, use of such a relationship means that at the absence of downward pressure ($\sigma$ = 0) the contact has zero tangential stiffness, which contradicts the physical principles of the contact operation.

Therefore, the author proposed to use more full relationship with two components:

$$K_t = p_a \left[ K_0 + K_\Delta \left( \frac{\sigma}{p_a} \right)^n \right],$$

where $K_0$ and $K_\Delta$ are dimensionless moduli.

The model parameters were obtained by the author from condition of maximum approximation of design relationship to the results of experiments. They are given in Table 1.

***Table 1. Model parameters of shear along the contact.***

| Code of design alternative | Type of contact | $K_0$ | $K_\Delta$ | $n$ | $\varphi$ |
|---|---|---|---|---|---|
| | filling material | 4670 | 13.3 | 2.47 | 39° |
| alternative “A” | emulsified asphalt | 41 | 58.4 | 1.48 | 31° |
| alternative “F” | asphalt felt | 850 | 1.44 | 2.74 | 30° |

The analysis shows that in the value of tangential stiffness of the contact between concrete with crushed stone and with a layer of asphalt felt the most part is presented by its constant part not depending on pressure $\sigma$.

The obtained relationships and their parameters were used at numerical modeling of the dam concrete face SSS. The alternative with a layer of emulsified asphalt was designated as alternative “A”, and the alternative with a layer of asphalt felt as alternative “F”. At SSS analysis of alternative “A” the modulus $K_\Delta$ was assumed equal to 72, i.e. it is somewhat increased as compared to experimental data for their better approximation in the range of $\sigma$ from 0 to 1 MPa. It may be expected that at increase of emulsified asphalt layer to 2 mm the contact tangential stiffness will become 2 times as less, however, in this study the SSS analyses were conducted for the values obtained experimentally (for 1 mm thickness).

For comparison the SSS analyses were also conducted for the model with constant tangential stiffness $K_t$ Three options of value $K_t$ were considered: 5, 50, 300 MPa/m. They are designated as “a”, “b”, “c” respectively. The considered interval of tangential stiffness values includes stiffness of contacts with layers of emulsified asphalt and asphalt felt at $\sigma$ = 1 MPa. The maximum value of the considered interval

$K_t$ is somewhat higher than the value of the largest contact stiffness of alternative “A”, and the minimum value is somewhat less than stiffness in alternative “F”. In contrast to alternatives “A” and “F” in options with constant stiffness (“a”, “b”, “c”) the contact was assumed to be absolutely strong at shear.

### *Principles of numerical modeling of concrete faced rockfill dam stress-strain state*

Study of the contact tangential stiffness effect on CF SSS was conducted on the examples of an abstract dam (CFRD) 100 m high (Fig. 2). The dam has slopes were 1:1.4. The concrete face was of variable thickness: from 0.3 m at the top to 0.8 m in the lower part.

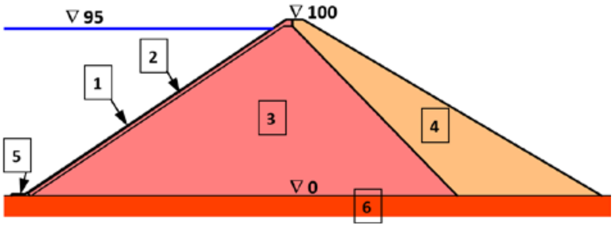


**Figure 2. Scheme of the design of a concrete faced rockfill dam**
**1 – concrete face; 2 – filter zone; 3 – dam upper body; 4 – dam downstream body;**
**5 – plinth; 6 – dam foundation.**

The dam body has a heterogenous structure. It was assumed that its upper part is less deformable than the lower part. The dam rock foundation was assumed to be absolutely stiff and was not included in the computational domain.

SSS analyses were conducted in 2D formulation for the dam cross section. A finite element model was developed and consisted of 500 finite elements of continuous medium and 40 contact finite elements. The sidewall structure was modeled in the form of a slab similar to [23]. Contact finite elements modeled contact interaction between CF with the dam and in the perimeter joint. There were used finite elements of high order with cubic approximation of displacements which provides high accuracy in distribution of stresses in a stiff thin-wall face. The total number of the model degrees of freedom comprised 4356.

Analyses were conducted taking into account the sequence of the dam construction and the reservoir impoundment: 28 design stages were considered. First 16 stages modeled the layered dam filling; one more stage modeled creation of the face. Then there were simulated gradual reservoir impoundment throughout 11 stages. At such a simple scheme the dam dead weight does not affect CF SSS: it is determined only by rockfill deformations under the action of hydrostatic pressure.

For description of the dam material deformation at SSS analyses a linear model was used where two parameters were applied: modulus of linear deformation $E$ and Poisson’s number $\nu$. For the face concrete the following values were assumed: $E_b$ = 29 GPa, $\nu_b$ = 0.2. For the extruded curb concrete based on the test results given in [24], $E_b$ = 5 GPa.

SSS analyses were conducted for three alternatives of rockfill deformation. In alternative No. 1 modulus of linear deformation of the dam upstream part was taken equal $E$ = 120 MPa, in alternative No. 2 $E$ = 240 MPa, in alternative No. 3 $E$ = 480 MPa. Rockfill modulus of deformation in the dam downstream part was assumed to be 2 times as less as that in the upstream part. Poisson’s number in all the alternatives was assumed to be 0.2.

All in all, 15 design variants were considered. Their parameters are given in Table 1.

## *3. Results and Discussion*

Analysis of CFRD SSS was conducted for the time moment of the reservoir impoundment up to $\nabla$ 95 m. The results of CFRD SSS analysis are given in Fig. 2–4. They show distribution of displacements in the face height-wise $Y$. Extreme values of SSS parameters in all the alternatives are given in Table 2.

By the results or analyses the face is subject to bending deformations (Fig. 2). Maximum deflection $U_n$ is observed at $\nabla$ 45 m. Its value is determined by rockfill deformation. At rockfill modulus of deformation $E$ = 120 MPa the face maximum deflection makes up 19.2 cm, i.e. 0.19 % of the dam height, at $E$ = 240 MPa $U_n$ = 9.6 cm, and at $E$ = 480 MPa $U_n$ = 5.3 cm.

The largest bending deformations occur at the lowest part of the face (below $\nabla$ 6 m).

***Table 2. Parameters of design alternatives.***

| Code of design alternative | A.1 | A.2 | A.3 | F.1 | F.2 | F.2 | a.1 | a.2 | a.3 | b.1 | b.2 | b.3 | c.1 | c.2 | c.3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alternative or value of $K_t$ [MPa/m] | A | A | A | F | F | F | 300 | 300 | 300 | 50 | 50 | 50 | 5 | 5 | 5 |
| $E$ [MPa] | 120 | 240 | 480 | 120 | 240 | 480 | 120 | 240 | 480 | 120 | 240 | 480 | 120 | 240 | 480 |
| $\Delta U_{t,max}$ [mm] | 2.3 | 1.7 | 0.8 | 6.1 | 4.0 | 1.1 | 7.2 | 4.6 | 1.0 | 4.1 | 3.3 | 1.5 | 1.0 | 1.0 | 0.5 |
| $\Delta U_{t,min}$ [mm] | -3.7 | -3.2 | -2.4 | -2.7 | -2.3 | -1.7 | -7.2 | -6.0 | -4.5 | -1.4 | -1.2 | -0.9 | -0.3 | -0.2 | -0.2 |
| $\sigma_E$,max [MPa] | 5.3 | 3.6 | 2.2 | 3.5 | 2.3 | 1.8 | 3.1 | 1.9 | 1.3 | 4.8 | 3.1 | 2.0 | 6.5 | 4.6 | 2.6 |
| $\sigma_E$,min [MPa] | -3.2 | -2.2 | -1.3 | -2.7 | -2.0 | -1.5 | -2.6 | -1.6 | -1.1 | -3.1 | -2.2 | -1.7 | -3.6 | -2.4 | -1.8 |

Designations:

$\Delta U_t$ is face displacement relative sidewall, $\sigma_E$ is longitudinal stress in the face (in direction along the slope).

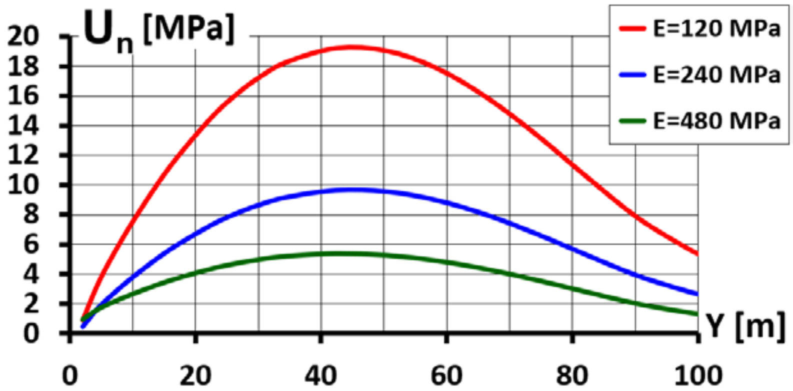


**Figure 2. Height distribution of face deflections.**

However, the dam body deformations occur not only in the direction perpendicular to the upstream slope (deflections), but along it also. Longitudinal displacements occur due to the fact that the dam horizontal displacements toward the downstream side are greater by value than its settlements. The result of longitudinal displacements of the face is opening of the perimeter joint between the CF and the plinth.

Presence of longitudinal displacements plays an important role for the concrete face SSS formation: they create friction forces between the face and the dam body. In the face these friction forces induce linear deformations (elongation-shortening) and longitudinal forces. Due to presence of antifriction layer between CF and SW the friction forces are partially compensated in the contact between them. This is reached due to relative displacements $\Delta U_t$ in the contact, i.e. displacements of the face (CF) relative to SW. they are shown in Fig. 3 and take into account displacements not only at perception of hydrostatic pressure but also under the action of face dead weight.

By the results of analyses the distribution of $\Delta U_t$ height-wise Y has a complicated pattern (Fig. 3). By value they may be both positive and negative. Positive displacements $\Delta U_t$ correspond to the case, when the face displaces upward along the slope relative to the sidewall (or SW displaces downward along the slope relative to the CF), and negative displacements take place at movement downward along the slope.

In most alternatives (alternative “F”, options “a”, “b”, “c” with constant value of $K_t$) three sections are distinguished in distribution of relative displacements $\Delta U_t$ height-wise Y. In the lowest part of the contact (below ∇ 10m) the zone of the greatest by value positive displacements $\Delta U_t$ is observed. In alternative 1.F the maximum value of $\Delta U_t$ makes up 6 mm (Fig. 3), i.e. the difference between displacements of the face and SW is great. At the section $\nabla$ 10m ÷ $\nabla$ 60m relative displacements $\Delta U_t$ are negative, and higher than $\nabla$ 60 m they are again positive.

In alternative "A" (emulsified asphalt) there are only 2 characteristic sections for distribution of $\Delta U_t$ The face lower part (below $\nabla$ 50÷60 m) displaces downward along the slope, and the upper part displaces upward (Fig. 3). Thus, the face «expands» in direction along the slope striving to compensate longitudinal deformations transferred to it.

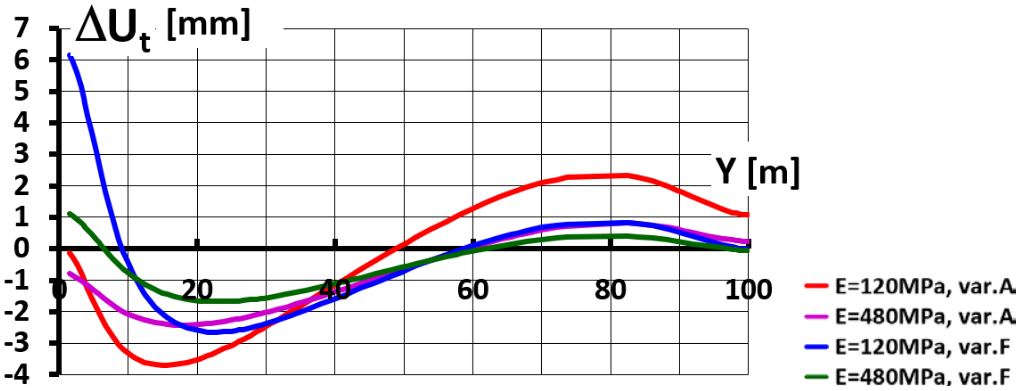


**Figure 3. Height distribution of face offsets relative to sidewall.**

Distribution of displacements $\Delta U_t$ conditions the direction of tangent stresses $\tau$ between the face and SW. Relative to CF and CW the tangent stresses are applied in opposite directions. Positive $\tau$ correspond to the case when they are directed relative to CF from the top downward along the slope. The sign of tangent $\tau$ corresponds to the sign of $\Delta U_t$ Positive $\tau$ are observed at the section below $\nabla$ 20 m, and higher on the most part of the contact length they are negative.

Such distribution of tangent stresses causes appearance of compressive and tensile forces in the face. In the lower section (below $\nabla$ 30 m) the face is subject to tensile longitudinal forces and in the upper section it is subject to compressive forces. The evidence of this is distribution height-wise the face of medium (with respect to the face thickness) values of longitudinal stresses $\sigma_E$, shown in Fig. 4. At high contact stiffness the tensile $\sigma_E$ exceeds the concrete tensile strength.

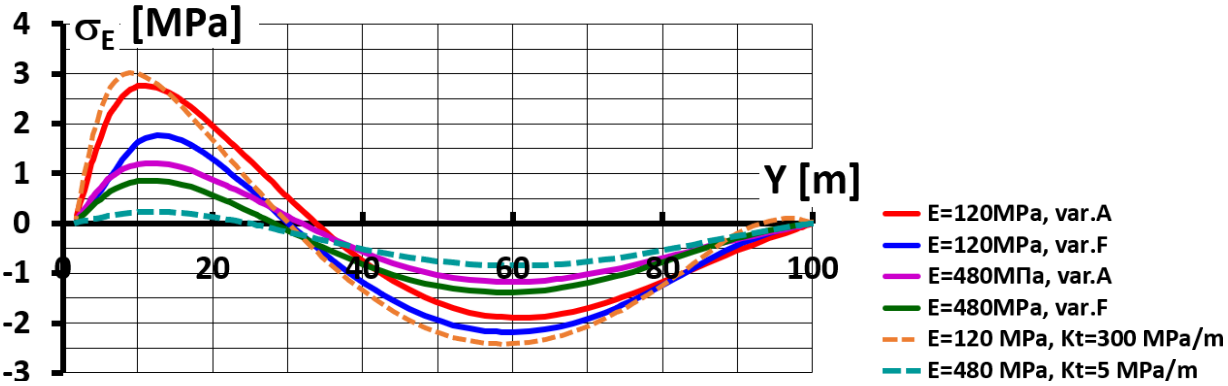


**Figure 4. Height-wise distribution of mean values of longitudinal stresses in the face.**

The analysis shows that induced by friction longitudinal forces play the decisive role in formation of longitudinal stresses $\sigma_E$ in the face (Fig. 5). Non-uniform distribution of stresses $\sigma_E$ between the upstream and downstream edges of the face caused by bending demonstrates considerably less effect. The exclusion is the lowest section of the face where bending deformations are greatly developed.

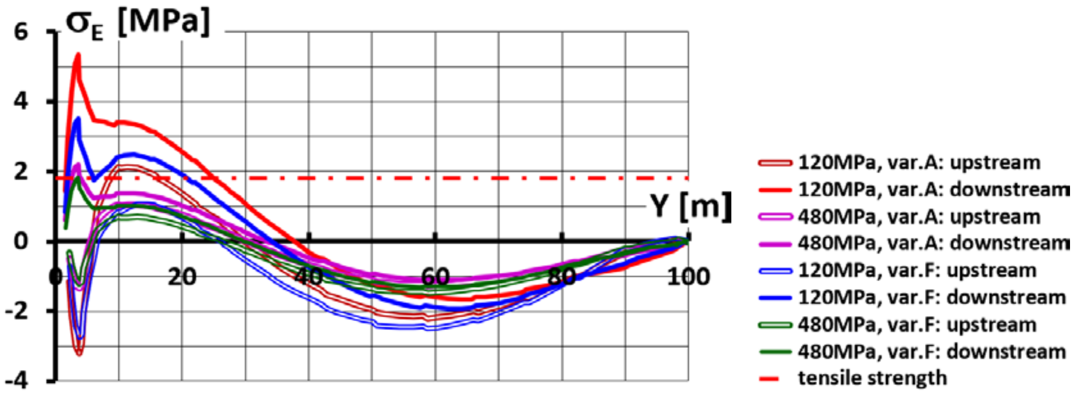


**Figure 5. Distribution of longitudinal stresses on the upstream and downstream edges of the face.**

The pattern of concrete face SSS described above is characteristic for all the considered alternatives not depending on the value of rockfill modulus of deformation $E$ and tangential stiffness $K_t$ of the contact between CF and SW. However, $E$ and $K_t$ determine quantitative size of deformations and stresses. Their impact may be evaluated from Fig. 6, showing maximum and minimum parameters of CF SSS. It permits evaluation of effectiveness of antifriction measures in regulation of CF SSS.

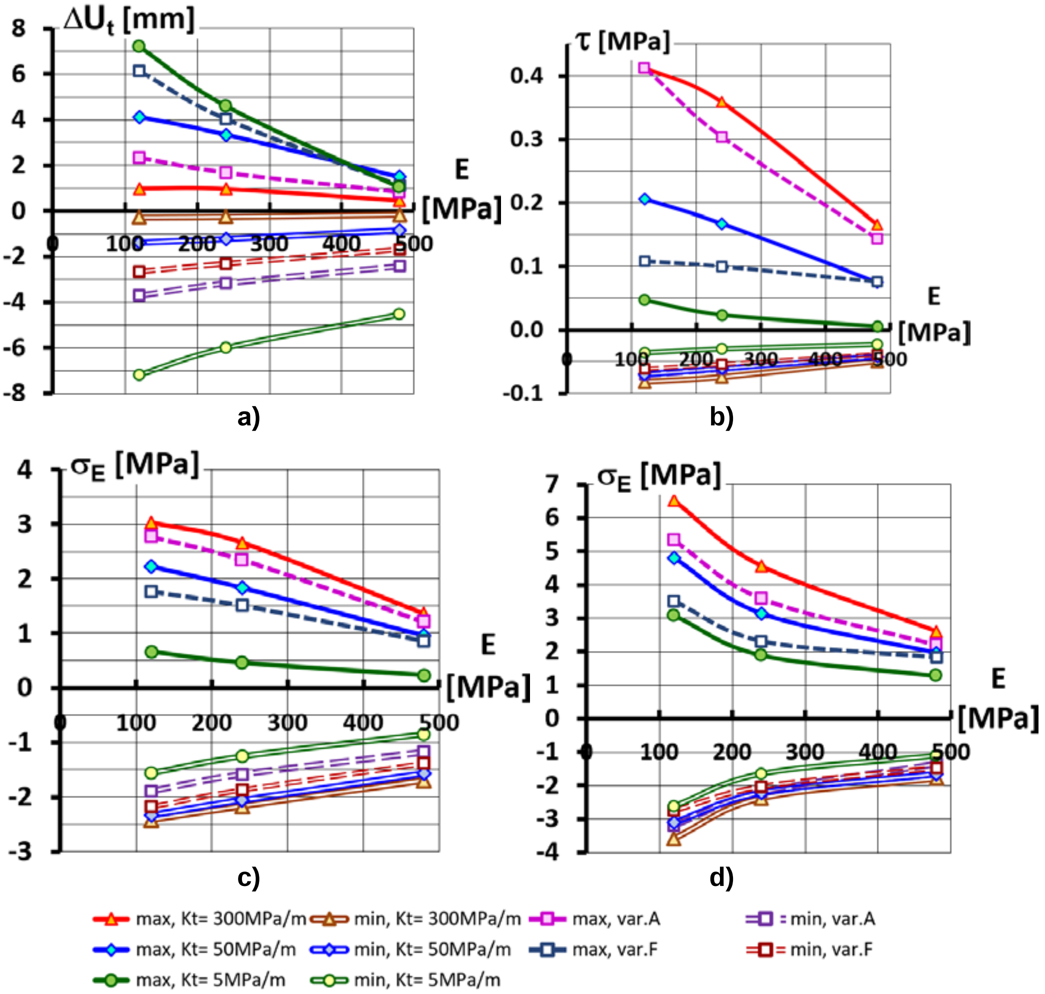
Fig. 6a permits evaluation of $E$ and $K_t$ effect on relative displacements $\Delta U_t$ between the face and the sidewall. It is evident that the lower is stiffness $K_t$ , the higher is $\Delta U_t$ Therefore, in the options of alternative “F” (a layer of asphalt felt) displacements $\Delta U_t$ are greater than those in the options of alternative “A” (a layer of emulsified asphalt). At using a layer of asphalt felt the maximum value of displacements $\Delta U_t$ is approximately 1.5÷3 as much as at using a layer of emulsified asphalt. Rockfill deformation $E$ has great effect on the value of $\Delta U_t$ . At high values of $\mathrm{E}$ the effect of $K_t$ on $\Delta U_t$ decreases.

It may be noticed that by values $\Delta U_t$ the options of alternative “F” (a layer of asphalt felt) are closer to options of series “c” ( $K_t$ = 50 MPa/m), and the options of alternative “A” (a layer of emulsified asphalt) to the options of series “a” ( $K_t$ = 300 MPa/m).

Maximum values of tangent stresses $\tau$ at the contact CF-SW considerably depend on tangential stiffness $K_t$ . At stiff contact ( $K_t$ = 300 MPa/m, alternative “A”) they reach 0.2÷0.4 MPa, and at the most flexible one ( $K_t$ = 50 MPa/m) they do not exceed 0.05 MPa (Fig. 6b). It is necessary to note that for the moment of the reservoir impoundment completion in all the alternatives the tangent stresses do not exceed the contact shear strength: shear strength is maintained at the whole length of the contact. However, in alternative No. 1.F at the intermediate stages of the reservoir impoundment the failure of shear strength of the contact lower part was recorded.

By maximum values of tangent stresses (Fig. 6b) the options of alternative “A” (a layer of emulsified asphalt) are close to options of series “a” ( $K_t$ = 300 MPa/m), and options of alternative “F” (a layer of asphalt felt) are in the intermediate position between options of series “c” ( $K_t$ = 5 MPa/m) and “b” ( $K_t$ = 50 MPa/m).

From Fig. 6b it may be noticed that decrease of tangential stiffness $K_t$ by an order (10 times) the tangent stresses are only approximately 4 times as less.



a)

b)

c)

d)

**Figure 6. Variation of maximum and minimum values of concrete face SSS parameters depending on rockfill modulus of deformation $E$**
**a – CF displacements relative to SW; b – longitudinal stresses.**

By maximum values of longitudinal tensile forces (Fig. 6c) the options of alternative “A” (a layer of emulsified asphalt) are closer to options of series “a” ($K_t$ = 300 MPa/m), and options of alternative “F” (a layer of asphalt felt) to options of series “b” ($K_t$ = 50 MPa/m), but are somewhat “behind”. Thus, account of the contact tangential stiffness $K_t$ variation led to decrease of tensile forces in the face, however, this improvement is not very significant.

To more extent the account of the contact tangential stiffness $K_t$ variability effected the values of maximum tensile longitudinal stresses $\sigma_E$ (Fig. 6d). In many options the tensile stresses decreased approximately by 1 MPa. Nevertheless, this change is not sufficient for guaranteed provision of the face concrete tensile strength.

The results obtained in this study contribute to the study of the SSS formation of a concrete face, taking into account the application of the "extrusion-sidewall" technology. This issue is controversial, there are different opinions about the role of SW in the formation of SSS of the concrete face of the rock fill dam. For example, in works [25–26], based on numerical simulations, it is argued that the SW device improves the strength of CF. However, the article [27] states that the influence of SW on SSS of the concrete face is small, except for its end sections. Similar results were obtained by the author of this article in [14]. It was found that the presence of an antifriction layer between CF and SW plays a more significant role. The important role of this layer in the formation of SSS CF is also noted in [28]. G. Zhang and J.-M. Zhang in publication [29] it was shown that the arrangement of the asphalt layer between CF and SW significantly changes the stress state of the screen. This is consistent with the results of the study presented in this article. The magnitude of stresses in the screen depends on the magnitude of the tangential stiffness of the CF and SW contact, this is demonstrated by the results of the study carried out in this article. In addition, it can be noted that the presence of an antifriction layer is important for the formation of a face (CF) under temperature influences. This is stated in [30].

# 4. Conclusion

1. Tangential stiffness of the contact between the concrete face (CF) with the sidewall (SW) made of thin-cement concrete, where it is envisaged to arrange a layer of asphalt emulsion of 1 mm thickness, by the results of experiments, may reach considerable values 200÷500 MPa/m. Such value of tangential stiffness does not provide decrease of friction forces on this contact to be sufficient to prevent appearance of tensile stresses in the face. At increase of emulsion thickness to 2 mm it may be expected that tangential stiffness will decrease but still will be considerable.

2. The important effect is increase of the contact tangential stiffness depending on downward pressure. Therefore, in ultra-high dams at the contact between the face with the dam the greater friction forces are acting and they present greater danger. The author proposed empirical relationship between tangential stiffness and a downward pressure; and it is also a possibility to take into account the presence of stiffness even at the absence of downward pressure.

3. Consideration at numerical modeling of stress-strain state of the fact that at small downward pressure the tangential stiffness is decreased, permits obtaining more favorable stress state of the face than at using constant value of stiffness. However, this change is not determining: it does not change the earlier made conclusions about specific features of CFRD SSS.

4. SSS analyses fulfilled for a wide range of tangential stiffness values of the contact between CF and SW and with consideration of its variable value, permits affirming that for CF SSS the presence of tensile longitudinal forces is a specific feature. It is confirmed by the fact that in all CFRD the perimeter joint between the face and the foundation is open. It was revealed that decrease of tangential stiffness by an order decreases longitudinal tensile forces in the face by 2-3 times. Therefore, to improve the face stress-strain state it is necessary to decrease considerably the tangential stiffness. It may be recommended that tangential stiffness of the contact should not exceed 50 MPa/m.

5. For more precise quantitative predictions of CFRD SSS it is required to carry out additional studies of shear characteristics of the contact between CF and SW, having antifriction layers. Necessary studies should include determination of the contact characteristics at very low shear rates. It may be expected that in these conditions the forces of internal friction in emulsified asphalt will be low, accordingly tangential stiffness will be considerably lower than that which was used in analyses. On the other hand, it should be expected that in real conditions the surface of the contact between CF and SW may have large roughness and irregularities, which results in increase of tangential stiffness. It also requires additional studies.

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