Stress-Strain State of Rockfill Dam Concrete Face Due to Temperature Impact During Reservoir Impoundment

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Abstract. During the reservoir initial impoundment, a rockfill dam concrete face may be subject to intensive thermal effect. Thermal stresses may considerably change the concrete face stress-strain state (SSS) and induce crack formation in it. With the aid of numerical modeling, the author studied the concrete face thermal stresses and deformations for three alternatives of temperature distribution along the face thickness. It was shown that the character of temperature distribution plays an important role in formation of the face thermo-stressed state. At uniform cooling (or heating) due to rockfill low stiffness the face can partially compensate temperature deformations and thermal stresses. Thermal stresses makeup only 15-30% of the potential ones in constrained conditions. More dangerous is the case of non-uniform distribution of stresses: it causes the face bending deformations. Stresses from bending deformations actually are not compensated. Combination of linear and bending deformations causes high thermal stresses in the face, which may become the reason of crack formation in the face. To provide the face favorable thermo-stressed state without impact from bending deformation it is necessary to execute the impoundment of the reservoir during a long period. At designing rockfill dams with concrete faces, it is necessary to take into account the fact that the less is the face thickness the more is the value of thermal stresses caused by uniform cooling (heating). It is reasonable to revise the recommendations for assigning the face thickness.

1. Introduction
Concrete faced rockfill dams (CFRD) are widely used at construction of high-head projects, however, they have an essential disadvantage: the degree of their safety is not sufficiently high. Through cracks in the concrete face appeared at some CFRDs. The causes of this phenomenon are not reliably known, but it is evident that breach of the face integrity may be caused by several reasons.

Namely, crack formation may be related to thermal stresses, i.e. the stresses caused by thermal effect. It is known that in most cases the cracks were formed during the initial reservoir impoundment. The examples may be dams Campos Novos (202 m high) and Barra Grande (185 m), where breach of their integrity took place in 2005. [1]. At other dams the crack formation was also connected with the reservoir impoundment. For example, instantaneous formation of a vertical crack in the face of Mohale dam (Kingdom of Lesotho, height 145 m) occurred in February, 2006, during rapid reservoir impoundment [2]. Before that time the face had operated during several years without crack formation.
It may be supposed that at rapid reservoir impoundment the high thermal stresses appear, which contributes to loss of concrete strength. Due to temperature difference of water and the dam body the face may be subject to heating or cooling. If during the reservoir impoundment the face is cooled, the tensile thermal stresses will be developed, and if it is heated then compressive stresses.

However, this hypothesis requires confirmation, because the issue of thermal impact on the rockfill dam concrete face stress state has not been actually studied. Only in [3,4] there given the results of studies of Gongboxia dam SSS with consideration of a thermal effect. It is shown in these papers that in the zone of water level in winter the face are subject to maximum temperature variation, which causes high tensile stresses. The fact of forming a series of vertical cracks in the face of Gongboxia dam is attributed to this case [3,4].

However, these studies cover only the case of CFRD operation, when thermal effect bears local and short-term character. In the author’s opinion, the more dangerous is the case of the reservoir initial impoundment. The thermal effect in this case may be the most intensive and durable.

The author conducted studies on revealing the impact of the concrete face temperature variation on its stress-strain state.

2. Methods
The studies were conducted by numerical modeling with the aid of the finite-element method. There was considered a 100 m high CFRD whose concrete face has a uniform thickness. The Proceedings of International Congress on Large Dams [5] recommend for a 100 m high dam to assign the face thickness equaling to 0.5 m. In this study the three alternatives of the face thickness were considered: 0.5; 1 and 2 m.

The dam finite-element model used in the analyses includes solid finite elements and contact finite elements (Goodman elements). Contact finite elements modeled the possibility of slippage at the contact of the face with the supporting zone, as well as the possibility of opening of the perimeter joint. It was taken into account that in modern dams the face is placed on extruded curbsand is separated from them by a layer of bitumen emulsion to decrease friction. The tangent stiffness of the face contact with extruded curbs was taken equal 20 MPa/m. At creation of a finite-element model there were used the high-order finite elements with cubic degree of approximation of displacements inside the element.

The methodology of the concrete face stress-strain state (SSS) modeling was as follows. In the concrete face finite elements there were assigned potential internal forces appeared due to temperature variation. These are thermal stresses \( \Delta \sigma_t \) typical for constrained conditions without possible variation of the shape and volume. Additional forces in the finite-element model degrees of freedom were determined from internal forces. Then additional displacements of degrees of freedom were determined by solving the system of equations of the finite element method. They were used for calculation of deformations and stresses in the elements of the structure.

Internal forces from temperature variation were calculated from formula:
\[
\Delta \sigma_t = E \alpha_t \Delta t ,
\]
where \( E \) – linear deformation modulus of material;
\( \alpha_t \) – coefficient of material thermal expansion;
\( \Delta t \) – temperature variation.
If for concrete it was taken: \( E=29000 \) MPa, \( \alpha_t=10^{-5} \) C\(^{-1}\).

When calculating the internal thermal forces, the value \( \Delta t \) corresponds to a change in temperature compared to the moment of time at which the concrete hardened. Therefore, it is during the initial impoundment of the reservoir that the face undergoes a significant change in temperature. In this study, the most dangerous case of temperature effect was considered: the case of the face cooling. It manifests itself when the reservoir water is colder than that of the face concrete. The danger of the face cooling is the occurrence of shortening deformations and the possibility of appearing tensile stresses unfavorable for concrete.
In the calculations, it was conditionally assumed that the field of temperature variation does not change height-wise. Three schemes (alternatives) of thermal effect were considered.

The first scheme is uniform cooling of the face in thickness and height, when at all points of the structure the temperature changes by the same value $\Delta t$. This case is possible when the temperature regime of the dam has already been established after some time since the impoundment of the reservoir.

The second scheme is a hypothetical case of thermal effect, which is characterized by the absence of volume expansion and maximum temperature gradient. In this case, one half of the face (upstream part) is cooled, and the other (downstream part) is heated. The temperature difference between the faces is $\Delta t$. The temperature distribution across the face thickness was assumed to be linear. This case does not manifest itself in real conditions, but it should be considered to understand the face susceptibility to thermal effects.

The third scheme is a case of uneven cooling of the face when the temperature on the upstream side changes by $\Delta t$, and remains constant on the downstream side. It is a combination of cases 1 and 2. This case is close to that observed in the initial time interval after the reservoir impoundment.

Studies were carried out for several values of the linear deformation modulus of rockfill $E$, and the Poisson's ratio was taken equal to 0.2. The considered values of $E$ ($60 \div 480$ MPa) are in the range of values recorded during field measurements. This made it possible to study the effect of the stiffness of the dam body on thermal stresses. The presence of thermal effects in rockfill was not taken into account due to the small value of its linear deformation modulus.

3. Results and discussion
The calculations were carried out for the case of cooling the face by $\Delta t = 20^\circ C$. This case is quite real, for example, it corresponds to the case when the face concreted at a temperature of $+25^\circ C$, is cooled to water temperature of $+5^\circ C$. At $\Delta t = 20^\circ C$ the potential force due to temperature variation is 5.8 MPa. The tensile value of such a value is many times greater than the tensile strength of concrete, which indicates the danger of the temperature impact.

The calculation results showed that an uneven thermal effect has a more adverse effect on the SSS of the concrete face than a uniform one.

With uniform cooling the face generally experiences only linear deformations. Due to low friction between the face and the supporting zone, as well as rockfill deformability, freedom of the face linear deformations is provided. The face is shortened in the direction along the slope, due to which thermal stresses are significantly reduced as compared to potential ones. Tensile stresses reach their maximum in the middle of the face height (fig. 1).

![Figure 1. Distribution height-wise $Y$ of thermal stresses $\sigma$ in the face acting in the direction along the slope (face thickness 1 m, $E=480$ MPa). 1, 2, 3 – number of design scheme; single lines designate stresses on the upstream face, double lines designate stresses on the downstream face.](image-url)
It was found that the degree of thermal stress reduction depends on rockfill deformation modulus $E$ and the tangential stiffness of the contact between the face and the supporting zone. At $E = 60$ MPa the maximum tensile stress is 0.95 MPa, and $E = 480$ MPa - 1.95 MPa (fig. 2). As a percentage of the potential thermal force (5.6 MPa), thermal stresses are 15% and 30%, respectively. It can be seen that the higher is $E$, the higher are thermal stresses in the face. It can be concluded that in modern CFRD with high quality rockfill compaction, the concrete face is more susceptible to temperature changes.

However, tensile stresses do not exceed the tensile strength of concrete, which indicates favorable conditions for the concrete face operation in CFRD.

Figure 2. Variation of maximum values of tensile stresses in the face depending on rockfill deformation modulus.

Figure 3. Variation of maximum values of tensile stresses in the face depending on its thickness.

At non-uniform distribution of temperature (scheme 2), the face is subject to bending deformations. The upstream part of the face is subject to tension and the downstream part – to compression (fig.1). At that, the values of thermal stresses occurring in the face are close to possible thermal forces and do not depend on $E$ (fig.2). The maximum value of thermal stresses amounts to about 80% of thermal force value (2.8 MPa). If the temperature of the upstream face decreases by $20^\circ$C, the appeared tensile stress has the value 2.2 MPa (fig.2).

Non-uniform distribution of temperature in scheme 3 is even more dangerous because the face SSS caused by it is even more dangerous, because this face SSS combines the characteristics of schemes 1 and 2. The face upstream part is in tension, the downstream part is in compression. Tensile thermal stresses are higher than in schemes 1 and 2. At $E=60$ MPa the maximum value of tensile stress comprises 2.6 MPa, and at $E=480$ MPa – 3.05 MPa (fig.2), which is accordingly 45% and 53% of the thermal force value (5.8 MPa). These values exceed the concrete tensile strength, therefore, at the considered thermal effect the development of transverse cracks may be expected in the face.

The obtained results permit developing the following idea about the influence of temperature effects in the process of a reservoir impoundment on the SSS of a concrete face. In addition to the temperature difference, this effect is determined by two factors: the first factor is the filling rate of the reservoir; the second is the face thickness.

In addition to the temperature difference, this effect is determined by two factors: the first factor is the rate of the reservoir impoundment; the second is the face thickness.

If the reservoir fills quickly, cooling of the face will occur unevenly. Due to the uneven distribution of temperature over the thickness of the face, in the initial time interval the face will get additional bending deformations, which will lead to appearance of high thermal stresses. On the upstream face, tensile stresses can exceed the tensile strength of concrete. If the face experienced high compressive stresses due to the action of static forces, the growth of compressive stresses and the loss of compressive strength will be a danger. Thus, thermal stresses can contribute to formation of cracks in the face. A high filling rate of the reservoir (more than 2 m per day) took place on the Barra Grande dam, in the face of which cracking was observed.
Over time, the temperature field aligns in the face. At that, bending deformations of the face will give way to longitudinal deformations, and tensile stresses in the face will decrease.

If the reservoir is impounded for a long time, the temperature distribution in the face will be close to uniform distribution. In this case, the strength of concrete in most sections of the face will be provided. Unfavorable face SSS will be developed only in the zone of water level, because temperature distribution will be uneven. This is evidenced by the results of studies [3,4, 6].

It should be borne in mind that the value of thermal stresses depends on the thickness of the face. Analysis showed that in scheme 2 the face thickness does not matter, and in scheme 1 and 3 its influence is significant. The thicker is the face, the higher are thermal stresses in it due to uniform cooling (heating) (fig. 3). In a thin face, the probability of loss of concrete strength is significantly higher. In the case under consideration, with a face thickness of 0.5 m, the tensile strength of concrete will not be provided even with a uniform thermal effect.

The upper part of the Barra Grande Dam face was only 0.3 m thick, which could contribute to cracking. Apparently, approaches to the assigning the thickness of the concrete face should be revised.

4. Conclusions
The impact of thermal effects on the stress-strain state of a concrete facemay be comparable with the impact of static forces; they can become one of the reasons for formation of cracks in the face. The most powerful impact is the temperature effect that occurs when the reservoir is initially impounded. It can cause the appearance of high tensile stresses on the face or an increase in compressive stresses, which creates a risk of loss of concrete strength.

The degree of impact of temperature variations on the face SSS depends on the nature of the thermal effect. The greatest danger is the uneven distribution of temperature across the thickness of the face. Therefore, the probability of temperature cracks formation in the face depends on the reservoir impoundment rate. The most unfavorable SSS is formed in the initial period of time when the temperature field is characterized by uneven distribution over the thickness of the face. Over time, when leveling the temperature field, the risk of cracking decreases.

Also, the thickness of the face has a significant effect on the thermal stresses in the face. To provide crack resistance of the face it is advisable to revise the recommendations for assigning its thickness which should be increased.

5. References
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