Theory of stress-strain state of concrete faced rockfill dams

Mikhail Sainov
Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, Russia
E-mail: mp_sainov@mail.ru

Abstract. In spite of the fact that concrete faced rockfill dams began to be used long ago; their designing is based on empirical approaches and there is still no common theoretical concept about peculiarities of their operation. With the aid of numerical modeling the author studied conditions of forming stress-strain state (SSS) of a concrete face with consideration of impact of various factors. The used methodology of analysis took into account operation of the face not as that of the plate but as a 3D structure interacting with the dam body in a complicated way. This permitted obtaining new knowledge about the face operation. It was revealed that friction forces at the contact of the face with the dam body play the main role in SSS formation. Due to friction the concrete face perceives not only deformations of cross bending but also longitudinal forces and deformations of longitudinal bending. The most dangerous is the face lower section where the face is subject to tensile longitudinal force and longitudinal bending, which may result in appearance of transversal cracks in the face. Considerable compressive forces perceive the face in the direction from the bank to the bank. The new theoretical concept about the concrete face SSS dictates reconsideration of approaches to designing of concrete face rockfill dams. For decrease of tensile longitudinal force, the pattern of rockfill zoning in the dam body should not allow considerable difference in deformation of the dam zones; also it is necessary to decrease friction on the contact of the face with the under-face zone. “Soft” vertical joints should be arranged to decrease compression in the face in the direction from one side to the other side.

1. Introduction
Concrete (or reinforced concrete) faced rockfill dams (CFRD) have been used in hydraulic engineering already from the XIX-th century. Since then structural designs have been changed as well as methodologies of these dams’ construction [1]. On the one hand, these changes permitted enhancing economic effectiveness in using dams of this type and on the other hand, they made it possible to increase their height considerably. By present time several dozens of ultra-high CFRDs have been constructed [2]; and the highest of them is 233 m high Shuibuaya dam in China [3].

CFRDs of the present type were first used in 1970-s; and one of the first such dams is Cetana dam in Australia (110 m high, 1973). Since then CFRD structural designs and methodologies of construction have been improved even more. The theory of CFRD designing is presented in Proceedings of International Congress of International Commission on Large Dams (ICOLD) [4,5]. The following features are peculiar for modern CFRD structural designs:

- Rockfill is placed in the dam body by relatively thin layers with subsequent compaction by vibratory rollers, which permits obtaining very high quality of compaction. At that, attention is focused on compaction of the upper part of the shell, while in its lower part a more heterogeneous and loose rockfill may be placed;
Concrete face is made continuous height-wise and is relatively thin (about 1% of the dam height). The face is cut only by vertical intersection joints, which are arranged with thin inserts and water stops;

The dam body upstream slope, on which concrete face is placed, is formed by curbs made of low cement concrete [6]. In compliance with «Bond break» concept a bitumen emulsion layer is placed to decrease friction between the face and the concrete bedding [7];

The under-face zone is made of coarse debris whose grain size distribution is selected from condition that there is no piping at the contact with other soils;

Concrete face reinforcement is single-raw for perceiving temperature-humidity deformations.

The indicated principles of CFRD designing are based on large accumulated experience of designing, construction and operation of such dams, i.e. on empirical approach.

Nevertheless, there are evidences of breaking integrity of concrete faces [8-10]. Examples include Dam: Campos Novos, Barra Grande, Mohale, Shuibuya, Aguamilpa, Turimiquire. The formation of cracks in the screens of these dams occurred in different ways; accordingly, various theories are expressed about the causes of the loss of concrete strength. For example, in [11] it was suggested that the formation of cracks in the face of the Shuibuya dam is associated with the temperature effect on the face under conditions of limiting the movement of the face along the slope. In international recommendations [5], the formation of structural cracks in the face is associated with uneven face movements.

Nevertheless, the reasons for the formation of through structural cracks in the concrete face are not reliably known. Which require reconsideration of theoretical concepts about CFRD operation.

In spite of a great number of CFRD SSS studies [12], performed mainly by numerical modeling, simplified theoretical concepts prevail with respect to operation of such dams. It is considered that the face works mainly in bending. However, this does not explain the presence of high compressive stresses in direction from one side to the other side, which is recorded by field studies at a number of dams [3].

Recently there appeared papers where another concept of conditions for formation of CFRD SSS is set forth, namely, in [3,13]. Already in 2005 Marques and Pinto in paper [9] expressed their supposition that the face stress state along the slope may be characterized by not only by bending deformations, but also by longitudinal tensile forces.

In this article there presented the concept about working conditions of rockfill dam concrete face, which was formulated by the author based on the results of multiple studies conducted by numerical modeling.

2. Methods

Studies of CFRD SSS was conducted by the author by the finite element method. Review of the results of investigations performed by the other authors showed that at present the numerical modeling is the only available method of studying the concrete face SSS which provides the required accuracy and adequacy of the results [11].

However, the results of numerical modeling to a large extent depend on the quality of the used methodology. The author used the methodology where for modeling of the concrete face operation the use was made of finite elements of continuum of solid type with high (square or cubic) degree of approximation of displacements. On the one hand, this permits sufficiently differentiable representation of the complicated character of the face bending deformations, and on the other hand, analyzing not only bending deformations, but presence of linear deformations (and longitudinal forces) as well. Longitudinal forces and bending moments in the face were analyzed.

The author met one more important condition of correct modeling of CFRD SSS: consideration of friction between the face and the dam body, as well as possibility of appearing non-linear effects at the contact of the concrete face with other structural elements (namely, possible opening of the perimeter joint and slippage on the contact). To model the nonlinear behavior of the contacts, finite elements of the Goodman type were used.

2
Analysis was conducted both in 2D and 3D formulations. The calculation was carried out on the load from its own weight, from hydrostatic pressure (fig.1) and from temperature effects.

3. Results and Discussion
The results of CFRD SSS studies conducted by the author are given in [13-16] and in other papers. They permitted revealing the following main features of concrete face SSS formation in a rockfill dam body:

1. At joint operation with a rockfill dam body the concrete face is subject to deformations of a complicated character. At that, the effect of the face cross bending deformations (fig.2a) is not always of fundamental importance. The face is subject to linear deformations of extension-reduction in its plane as well as to deformations of longitudinal bending (fig.2b). Besides, the face is subject to bending deformations in its plane, however, these deformations are actually fully compensated by vertical intersection joints.

2. Friction at the contact with the dam body plays a major role in formation of the concrete face SSS (fig.2c). It is friction that causes linear deformations of the face plane as well as its longitudinal bending. Longitudinal bending is a consequence of eccentricity of longitudinal forces application. It has local propagation and is revealed only at the edges of the face slab.

Figure 1. This is a figure illustrating the shear stress pattern at the contact between the concrete face and the dam body
\( \gamma_0 \) – specific gravity of water; WL – water level; DC – dam crest; \( \tau \) – shear stress

Figure 2. This is a figure illustrating the formation of the stress-strain state of a concrete screen.
\( a \) – diagram of the displacements \( U \) of the concrete face in the direction perpendicular to the slope; \( b \) – plot of bending moments \( M \); \( c \) – plot of shear stresses \( \tau \) at the contact between the face and the dam body; \( d \) – plot of longitudinal forces \( N \) in a concrete face, that is, forces acting in the direction along the slope; \( l \) – bending moments caused by the effect of longitudinal bending.
3. Both compressive and tensile longitudinal forces (N) may appear in a concrete face (fig.2d). Compressive longitudinal forces act in the face in direction from one side to the other side; they are also characteristic for the face upper part, where they act in direction along the slope. Tensile longitudinal forces appear in direction along the slope in the face lower part (fig.2d). Similar effect was obtained in investigations of Arici [17]. They are the consequence of deformations of dam soil lateral expansion at perceiving hydrostatic forces. Under the lower edge of the face the tangent stresses may act in direction from the top downward.

4. The zone of the face conjugation with rock foundation is most dangerous with respect to cracking. In this zone the face is subject to the greatest cross bending deformations, as well as to tensile longitudinal forces and longitudinal bending deformations. It threatens with loss of concrete compressive strength and formation of transversal joints. To prevent local increase of bending deformations the under-face zone should be made of curbs for the full height, but avoiding their resting on rock foundation and contour slab.

5. Measures on decreasing friction at the contact of the face with the dam body provided in structural designs of modern dams have favorable effect on the concrete face SSS. Due to friction decrease the tensile longitudinal forces transferred to the face reduce as well as deformations of its longitudinal bending. However, the extent of these measures effectiveness as well as their impact should be studied additionally.

6. In spite of the existing cases where vertical joints appear in faces of a number of ultra-high dams [8,10] due to loss of compressive strength in concrete; appearance of compressive stresses in the face in direction from one side to the other side is not a threat which may not be eliminated. First of all, high compressive stresses in the face comparable by value to compressive strength appear not often. They may appear only in ultra-high dams and only at considerable rockfill deformation. Secondly, high compressive stresses may be compensated by deformations of vertical intersection joints. However, it should be taken into account that, in order to provide possibility for joints to fulfill their important function they should be sufficiently wide (more than 10 mm) and should be filled with flexible material. Compressibility of the filling material is much more important than frequency of the face cutting into sections. Deformation modulus of the joint filling material should be sufficiently low in order to provide nearly full convergence of joint even at small efforts.

7. Unfavorable effects in concrete face SSS may be created by staged dam construction. It was also shown by other authors [18]. Staged dam construction may lead to local growth of cross bending deformations at the top of the dam construction stage, as well as to longitudinal bending deformations. However, staged construction may also have a favorable effect on the concrete face SSS: it leads to appearance of additional compressive longitudinal force in it. Besides, sequential dam construction and reservoir impoundment will provide possibility to rockfill for gradual adaptation in perceiving hydrostatic pressure.

8. The decisive role in concrete face SSS formation is played by rockfill deformation properties, especially at perceiving shear forces. However, increase of rockfill deformation modulus to a greater extent affects the values of bending moments due to cross bending than the value of longitudinal forces.

9. The important factor determining the concrete face SSS is the character of rockfill deformation properties distribution in the volume of the dam shell. Considerable increase of rockfill deformation in the shell downstream part (as compared to the upstream part) causes additional horizontal displacements of the dam body toward the downstream side, and consequently, additional tensile longitudinal force in the face. This is the reason why the dams with non-uniform structure (for example, Aguamilpa dam) are less safe than dams with deformation distribution close to uniform one (for example, El Canon dam). Therefore, requirements for reduction of non-uniformity of the dam shell structure should be set forth to rockfill zoning in the dam body. In modern chinese dams the

---

1 Similar effect is observed in foundations of high structures on a compressible base, which perceive a considerable weight of the structure.
rockfill in the lower part and at the crest is compacted more thoroughly than in the remaining volume of the downstream shell.

10. High degree of rockfill compaction in the bodies of modern ultra-high dams permits obtaining considerable decrease of concrete face bending deformations, however, does not protect against formation in the face of tensile longitudinal forces. Only at narrow sites it is possible to expect decrease of tensile longitudinal forces due to decrease of dam displacements toward the downstream side. May be with this respect the approaches to assigning the concrete face thickness should be reconsidered. At present the face thickness is recommended to be not large, which allows decrease of tensile stresses from perceiving bending deformations. However, this increases stresses from perceiving longitudinal forces. In conditions, when the face bending deformations are weakly expressed, the face thickness, optimal from the point of view of providing its safety, may considerably differ from those given in recommendations in the international practice.

11. Rockfill low deformation in modern dams results in increase of the concrete face sensibility to temperature variation. At reservoir impoundment the face temperature may be considerably decreased which results in appearance additional tensile longitudinal force in it. Deformations of the rockfill outline compensate for a large proportion of tensile stresses, however, the higher the rigidity of the rockfill outline, the greater the influence of temperature on the strength of the face. Therefore it is necessary to decrease friction on the contact of the face with the under-face zone.

12. Concrete deformation properties have a marked effect on the concrete face SSS. It is known that in the course of time the relaxation of stresses due to creep takes place in concrete structures. This effect permits decrease of stress values in the face concrete. The author showed that decrease of concrete deformation modulus by 60 % reduces stresses in the face concrete approximately by 30 %. To improve the face SSS the reservoir should be impounded gradually.

4. Conclusions

1. Numerical modeling of concrete face rockfill dams SSS permits obtaining a new theoretical concept about peculiarities and conditions of the concrete face SSS formation. The essence of it is in the fact that the face works not only for cross bending but also for perception of longitudinal forces and longitudinal bending. Danger is presented by appearance of tensile longitudinal forces in the face. It should be taken into account at designing concrete face rockfill dams. At their structural analysis it is necessary to take into account that values of bending moments and longitudinal forces are determined by multiple factors such as heterogeneous structure and deformation of the dam shell, characteristics of friction between the face and the dam, sequence of dam construction.

2. Variation of the theoretical concept leads to reconsideration of approaches to engineering of concrete face rockfill dams. Namely, it is necessary to reconsider approaches to rockfill zoning in the dam body and to assigning the face thickness. Besides, this creates the basis for selecting methods of SSS regulation, which permit providing strength and crack resistance of this seepage-control element.

3. Numerical modeling shows that the risk of crack formation in ultra-high dams is very high, however, cracks appear not always. Evidently, this is attributed to the fact that the face SSS changes in the course of time due to relaxation of stresses in concrete and at the contact with the dam as well as due to rockfill creep deformations. These issues require additional investigation.

References

[1] Sainov M and Yurieva E. Structures of concrete faced rockfill dams in historical retrospective. 2018. Construction of Unique Buildings and Structures. 9(72). 46-60.
[2] Song W, Sun Y, Li L, Wang Y. Reason analysis and treatment for the 1st phase slab cracking of Shuibuya CFRD. 2008. Journal of Hydroelectric Engineering. 3(27). 33–37.
[3] Wen L, Chai J, Xu Z, Qin Y, Li Y, Junrui C. A statistical review of the behaviour of concrete face rockfill dams based on case histories. 2018. Géotechnique. 68(9). 749–71.
[4] ICOLD. Rockfill Dams with Concrete Facing, International Commision on Large Dams. 1989. Bulletin 70.
[5] ICOLD. Concrete Face Rockfill dam: Concepts for design and construction, International
Commision on Large Dams. 2010. Bulletin 141.

[6] Materon B, Resende F. Construction Innovations for the Itapebi CFRD. 2001. The International Journal on Hydropower and Dams. 8(5). 66–70.

[7] 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. Proc. 20th Congress ICOLD, Beijing, China, September, 2000.

[8] Ma H Q, Cao K M. Key technical problems of extra-high concrete faced rock-fill dam. 2007. Science in China. Series E: Technological Sciences. 50(1). 20–33.

[9] Marques Filho P, De Pinto N L S. CFRD dam characteristics learned from experience. 2005. The International Journal on Hydropower & Dams. 12(1). 72–76.

[10] Freitas M S J. Concepts on CFRDs Leakage Control – Cases and Current Experiences. 2009. ISSMGE Bulletin. 3(4). 11–18.

[11] Zhou W, Hua J-J, Chang X-L, Cao Y-H. Cause analysis of cracking of concrete slab for high CFRD based on concrete crushing-type side wall technology. 2008. Yantu Lixue/Rock and Soil Mechanics. 29. 2037–42.

[12] Soroka V B, Sainov M P, Korolev D V. Concrete-faced rockfill dams: experience in study of stress strain state. 2019. Vestnik MGSU. 2. 207–24.

[13] Sainov M P. Causes of cracking in reinforced concrete faces of rockfill dams. 2018. Proc. IOP Conf. Series: Materials Science and Engineering. 365. 052004.

[14] Sainov M P. Vliyanie formy stvora na napryazhennoe sostoyanie zhelezobetonnogo ekrana kamennno-nasyynoy plotiny. 2016. Magazine of Civil Engineering. 3. 16–39.

[15] Sainov M P, Borzov M S. Role of vertical joints in regulation of stress-strain state of concrete faced rockfill dam. 2018. The Eurasian Scientific Journal. 2(10).

[16] Sainov M P, Egorov I M, Pak K V. Impact of rockfill dam structure heterogeneity on reinforced concrete face stress-strain state. 2019. Stroitel'noe nauka i obrazovanie. 9(2).

[17] Arici Y. Investigation of the cracking of CFRD face plates. 2011. Computers and Geotechnics. 38. 905–16.

[18] Zhang B, Wang J G, Shi R. Time-dependent deformation in high concrete-faced rockfill dam and separation between concrete face slab and cushion layer. 2004. Computers and Geotechnics. 31. 559–73.