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Numerical analysis of the causes of face slab cracks in Gongboxia rockfill dam

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ABSTRACT

There are face slab cracks on the Gongboxia concrete face rockfill dam (CFRD), which is located on the Yellow River in China. They generally occur as vertical cracks at the top of the panel near the water level. The region where Gongboxia CFRD is located is subjected to low temperatures during the winter months and high temperatures during the summer months. Also, this region experiences large temperature fluctuations during the day and night. In this study, the causes of crack formation in the face slabs of the dam are numerically analyzed from the perspective of structural- and temperature-induced stresses. The results show that temperature-induced stress is the main reason for the slab cracks on the Gongboxia CFRD; the structure-induced stresses lead to more cracks in the steep dam section than in the riverbed dam section, and the occurrence of vertical cracks are likely caused by slight variations in the water level.

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1. Introduction

Over the past few decades, the concrete face rockfill dam (CFRD) has been constructed widely all over the world. It is used because of its low cost and rapid construction. Concrete slab is one of the most important impervious structures of the CFRD. Once penetrating cracks develop, water will flow through them. Fine particles will be washed away with the water, making the dam unsafe. Consequently, crack prevention in the concrete faces of the dam is one of the most important subjects in the design and construction of CFRD.

Face slab cracks have occurred in many earlier CFRD due to various reasons. Lesu Dam in Romania, which is about 60 m in height, suffered from rockfill rheology during its operating period, resulting in face slab cracks in its right abutment (Fu and Feng, 1993). Xibeikou Dam, which is the first CFRD in China, suffered cracks during its construction period. Many cracks occurred on its concrete front panel in the first winter after the end of concrete placement. These cracks were generally horizontal and widely spread in the concrete front panel. According to the analysis conducted by Jiaxuan Mai and Lixun Sun, temperatureinduced stress and shrinkage stress are the major causes of the cracks in Xibeikou Dam (Mai and Sun, 1999). Many cracks also occurred during the construction and operating period of the Shuibuya Dam, the highest CFRD in the world (233 m height). They occurred in the lower and middle parts of the panel, and most of them were horizontal cracks. Shrinkage stress, temperature-induced stress and the settlement of

* Corresponding author. Tel.: + 86 2583786727. *E-mail address:* 723188713@qq.com (S. Liu). of the cracks (Luo et al., 2011). Many cracks have also occurred in the face slab of Gongboxia CFRD during its storage and operating period. These were vertical gradies that

the foundation of the dam are the main reasons for the development

during its storage and operating period. These were vertical cracks that usually developed at the top of the face slab near the water level whereas, in other similar projects, face slab cracks occurred in the lower and middle portions of the panel and the cracks were of the horizontal type. The face slab cracks in the Gongboxia CFRD are therefore unusual. Many scholars have already conducted research on the causes of face slab cracks (Neves, 1991; Wang, 2000; Cao et al., 2001; Zhang and Peng, 2001; Zhang et al., 2001; Sun, 2004; Yu and Wang, 2004; Wang and Liu, 2005) (Navlor et al., 1988). In this paper, after first analyzing the monitoring deformation data of the Gongboxia CFRD, we then used back analysis to determine the Merchant viscoelastic rheological model parameters of the rockfill. After that, the stress and deflection of the face slab during the operating period was obtained using these rheological parameters. By comparing the simulated results with monitoring data, the reliability of these parameters was verified. Based on observational temperature data from the local region, the temperature-induced stress of the face slab during the operating period was calculated. Combining rheological stress with temperature-induced stress, the causes of the cracks in the Gongboxia CFRD were then analyzed. Results may provide useful data for solving similar geotechnical problems.

2. Engineering overview

Gongboxia hydropower station is located on the Yellow River in Qinghai Province in China. It is a large-scale comprehensive hydro









Fig. 1. Distribution of water level settlement gauges at the typical transect (0 + 130 m).

project responsible for electric power generation, flood control, irrigation and water supply. The key works of the Gongboxia hydropower station consist of the concrete face rockfill dam, the water diverting system for hydropower generation on the right bank and the overflow spillway on the left bank. The station started its dam filling on August 1, 2002, and its first generating unit was put into production on August 8, 2004.

The reservoir's normal water level, design flood lever, check flood lever and dead water level are 2005.00 m, 2005.00 m, 2008.28 m and 2002.00 m, respectively. It is a daily regulation reservoir. The total storage capacity is 0.62 billion m³.

The maximum dam height is 132.2 m. The main materials in constructing compacted rockfill dams are the main rockfill materials (3BI, 3BII) and downstream rockfill materials (3C), as shown in Fig. 1. There are 26 water level settlement gauges put in the whole dam to monitor its settlement. Fig. 1 shows the distribution of several water level settlement gauges at the typical transect (0 + 130 m).

3BI, main rockfill materials; 3BII, main rockfill materials (sand gravel); 3C, downstream rockfill materials.

A full crack checking of Gongboxia Dam's face slab was done in June, 2011 (Huang et al., 2011). It was found that there were 157 cracks in the 36 face slabs, with 135 of these cracks occurring near the water level. According to the results of cross-crack drilling, the crack openings were wide at the surface but narrower at depth. The depths of the cracks were from 11 cm to 25 cm. None of the cracks penetrated the face slabs. Fig. 2 shows a sketch of the cracks on the surface of face slab above an elevation of 2002 m. The identifier number shown in Fig. 2 corresponds to the panel number. The width of every face slab is 12 m.

The cracks in Gongboxia Dam's face slab gradually developed during the operating period. There are several formation rules about these cracks, which are shown as follows: First, most of the cracks occurred near the water level. Second, more cracks occurred on the two banks than on the riverbed. Third, more cracks occurred in the winter months than in the summer. Fourth, within one face slab, the first crack generally occurs in the middle and then the cracks spreads to the two sides. Fifth, most of the face slab cracks are vertical. In this paper, we will use a numerical simulation to explain these special phenomena occurring at the Gongboxia CFRD.

3. Analysis on structure-induced stress of Gongboxia Dam's face slab

3.1. Observational dam deformation behavior

The dam filling started from August 1, 2002, and finished on October 22, 2003. Fig. 3 shows the measured values of the settlement gauging points 9, 10 and 12 at the typical transect (cf. Fig. 1). It can be seen as follows: (1) As the rockfill dam rises, the settlement of these gauging points increases during the construction period (before October 22, 2003), leading to a steep slope. (2) The value of the settlement in the downstream side (gauging point 12) is larger than those in the upstream side. That is because the elasticity modulus and the compacting requirement of the secondary rockfill area in the downstream side are lower than those of the main rockfill area in the upstream side. (3) After impounding, the measured values of these settlement gauging points increase over time, revealing a clear rockfill rheological phenomenon. It should be mentioned that the values of the settlement decrease from filling completion to impounding. This is because some of the measuring instruments were broken during this period. Once fixed, these instruments returned to normal use. Fig. 4 shows settlement at gauging points 8-12 and 21-23 from August 22, 2004 to March 23, 2010. The maximum value of these points is 218 mm, which occurs at point 23 (corresponding dam height, 132.2 m).

3.2. Back analysis for rockfill parameters

In geotechnical engineering, the measured value of displacement is often used to obtain material parameters based on back analysis.

<u>▼2005m</u> <u>▼2002m</u>		2#	11# 	10# , _	9#	8# f)	7#	6#	5# }, ı	4#	3# 2#	1#
<u>▼2005m</u> ▼2002m	24#	23#	22#	21#	20#	19#	18# }{}	17#	16# 1	15#	14# 1	13#
\bigtriangledown 2005m \checkmark 2002m	36#	35#	34#	33#	32#	31#	30#	29#	28#	27#	26#	25#

Fig. 2. Sketch of the cracks on the surface of face slab above an elevation of 2002 m.

Fig. 3. Measured values of the settlement gauging points 9, 10 and 12 at the typical transect.

The thinking goes as follows: first transform back analysis into an optimization procedure, combine the numerical method with the optimization theory, then find a minimum difference between the measured value and numerical value by changing the material parameters. In this paper, a simulated annealing method is used to carry out the material parameters.

The objective function in simulated annealing method is shown as follows:

$$F(X) = \sum_{t=1}^{T_n} \sum_{i=1}^{N_d} \left(U_i^t - U_i^{t^*} \right)^2 \tag{1}$$

where T_n is the number of time steps; N_d is the number of observation points; U_i^t and $U_i^{t^2}$ are the simulated and measured displacement in the gauging point *i* at the time *t*, respectively; and *X* is the parameter for back analysis.

The Merchant viscoelastic model is used in the rheological calculation (Garlanger, 1972; Borja and Kavazanjian, 1985). The volumetric strain rate \hat{s}_{V} and the shearing strain rate $\hat{\gamma}$ are expressed as:

$$\dot{\varepsilon}_{V} = \alpha \left(\varepsilon_{Vf} - \varepsilon_{Vt} \right), \ \dot{\gamma} = \alpha \left(\gamma_{f} - \gamma_{t} \right)$$
(2)

where ε_{Vt} and γ_t are the volumetric strain and shearing strain at the time *t*, respectively, while ε_{Vf} and γ_f are the final volumetric strain and final shearing strain, respectively. ε_{Vt} and γ_t can be expressed as:

$$\Delta \varepsilon_{\rm V} = \sum \dot{\varsigma}_{\rm V}(t) \Delta t, \ \Delta \gamma = \sum \dot{\gamma}(t) \Delta t \tag{3}$$

 ε_{Vf} and γ_f can be expressed as:

$$\begin{cases} \varepsilon_{Vf} = b(\sigma_3/p_a)^{m_1} + c(q/p_a)^{m_2} \\ \gamma_f = d(S_1/(1-S_1))^{m_3} \end{cases}$$
(4)

where σ_3 is the minimum principal stress; p_a is the atmospheric pressure; S_1 is the stress level; q is the deviatoric stress; α , b, c, d, m_1 , m_2 and m_3 are the parameters in the Merchant viscoelastic model.

Fig. 5 shows the three-dimensional finite element mesh of Gongboxia CFRD. The number of elements and nodes is 37,024 and 39,474, respectively. Goodman elements are used for joint elements between the face slabs and cushion materials (Goodman et al., 1968).

The Duncan-Chang (E-B) model is used for rockfill materials (Duncan and Chang, 1970). The parameters of this model are determined by lab tests and are shown in Table 1. Dam filling construction, face slab concrete pouring and water impounding are all simulated in line with these parameters. Fig. 6 shows the simulated settlement value and the measured settlement value of the gauging points 8–12 (cf. Fig. 1) at the end of the construction. It reveals that simulated results closely mirror the measured results, in turn demonstrating that the parameters in the Duncan-Chang model are reasonable.

Due to problems with some measuring instruments from filling completion to impounding, the measured data of this period is not reliable. Consequently, the measured data of 8 gauging points in the present paper (points 8–12 and 21–23 at the typical transect) were selected after the end of impounding (from August 22, 2004 to August 22, 2011) and are used for the back analysis. Table 2 shows the results of 8 parameters in the Merchant viscoelastic model.

Fig. 7 shows the increment of simulated and measured rheological value of the gauging points 8–12 from August 22, 2004 to August 22, 2011. It can be seen that simulated results are similar to the measured results. Fig. 8 shows the processes of the simulated and measured settlements at gauging point 9. The simulated and measured settlements also match well. Predicted settlement is also shown in Fig. 8. It can be seen that the tendency of settlement forming will slow down after 2016. That is to say, the rheological deformation of the rockfill will slow down after 2016.

3.3. Calculation on the deflections and stresses of the face slab

The simulated deflections and axial stresses of the face slab in 2004 and 2016 are shown in Figs. 9 and 10, respectively. It can be seen from these figures that deflection has a tendency to spread to both sides of the bank. The maximum amount of deflection occurs at 1/3 dam height,



Fig. 4. Settlement of the gauging points after impounding (mm).





Fig. 5. Three-dimensional finite element mesh and selected points.

ranging from 18.0 cm (2004) to 24.3 cm (2016). The pressure stress (+) mainly occurs on the riverbed, while tensile stress (-) occurs on both sides of the bank. The maximum pressure stress is 8.4 MPa during impounding, increasing to 9.0 MPa by 2016. Generally speaking, the pressure stress of the face slab is not big enough to explain cracking, while tensile stress occurring at the top of the face slabs on both sides of the bank is more likely to lead to cracks.

In order to pay close attention to the tensile stress occurring at the top of the face slab, points A–P are selected (cf. Fig. 5). The results reveal that pressure stress occurs in the riverbed (points J–M) and there exists tensile stress on both sides of the bank (points A–I and N–P). Fig. 11 shows the development of stress at points D, K and O. It can be seen that the stresses in these three places are all increasing but will stabilize after 2016. D and O are located on both banks that show tensile stresses. These tensile stresses result in more cracks occurring on the banks relative to the riverbed.

4. Analysis of temperature-induced stresses on the Gongboxia Dam's face slab

Gongboxia hydropower station is located in the northwest region of China. The difference between the day and night temperatures is high. There exist consistently low temperatures and strong winds during winter, with the maximum wind speed at 24 m/s. In these observations, the lowest temperature was under -10 °C in winter. According to our observations, the sudden temperature change and continuous low temperature leads to tensile stress on the panel concrete. When this tensile stress reaches the tensile strength of the panel concrete, cracks will develop in the face slab. It is therefore necessary to analyze the impact of temperature-induced stress on the Gongboxia face slabs.

 Table 1

 Parameters of rockfill materials in EB model.





Fig. 6. Comparison between simulated and measured settlement values at the end of construction.

4.1. Calculation method

In every point of calculation domain *R*, a heat conduction equation of unstable temperature field *T* can be expressed as follows:

$$\partial T/\partial t = a \Big(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2 \Big) + \partial \theta/\partial \tau \quad (\forall (x, y, z) \in \mathbb{R})$$
(5)

Where *T* is temperature, *a* is thermal diffusivity, θ means adiabatic temperature rise of concrete, *t* is time, τ is concrete age.

Based on the variation principle, discretization of Eq. 5 is performed in the space and time domains. With initial and boundary conditions and the backward difference method in time, the finite element method equation for the solution to the problem is as follows:

$$([H] + (1/\Delta t_n)[R]) \{ T_{n+1} \} - (1/\Delta t_n)[\theta] \{ T_n \} + \{ F_{n+1} \} = 0$$
(6)

Where [*H*] is the matrix of thermal conductivity; [*R*] is the complementary matrix of thermal conductivity; $\{T_n\}$ and $\{T_{n+1}\}$ indicate the column matrix of modal temperature at the *n*th and n + 1th time step, respectively; $\{F_{n+1}\}$ means the column matrix of nodal thermal loads at the n + 1th time step; n stands for the number of time steps; Δt_n is the time interval of iteration.

The strain increments of concrete under complex stress state include elastic strain increments, creep strain increments, temperature strain increments, shrinkage strain increments and autogenous volume increments. In this study, we only consider the effect of the temperatureinduced stress, so the equation is as follows:

$$\{\Delta \varepsilon_n\} = \left\{\Delta \varepsilon_n^\varepsilon\right\} + \left\{\Delta \varepsilon_n^T\right\}$$
(7)

Where $\{\Delta \varepsilon_n^{\mathcal{E}}\}$ is an elastic strain increment and $\{\Delta \varepsilon_n^{T}\}$ means a temperature strain increment.

By using physical equation, geometric equation and balance equation, the main finite element equation of every time interval Δt_i in calculation domain R_i can be obtained as follows:

$$[K_i]\{\Delta\delta_i\} = \left\{\Delta P_i^G\right\} + \left\{\Delta P_i^T\right\}$$
(8)

Table 2

Parameters in the Merchant viscoelastic model

Rockfill materials	Mercha	Merchant viscoelastic model parameters							
	α	В	с	d	m_1	m_2	<i>m</i> ₃		
Cushion materials 2A Transitional rockfill 3A Main rockfill 3BI-1 Main rockfill 3BI-2	0.0005 0.0005 0.0006 0.0006	0.0003 0.0003 0.0004 0.0004	0.00018 0.00025 0.00026 0.00026	0.005 0.005 0.006 0.006	0.769 0.769 0.657 0.657	0.635 0.635 0.575 0.575	0.550 0.550 0.455 0.455		
Main rockfill 3BII Downstream rockfill 3C	0.0005 0.0006	0.00025 0.0020	0.00012 0.0008	0.003 0.013	0.615 0.831	0.511 0.714	0.421 0.518		

Where $\{\Delta \delta_i\}$ is displacement increment of three directions of every point in calculation domain R_i ; $\{\Delta P_i^G\}$ and $\{\Delta P_i^T\}$ present increments of equivalent nodal force caused by external loads and temperature in time interval Δt_i , respectively (Zhu, 2013).

4.2. Calculation of the temperature and parameters

There are complete air temperature observations in this project (cf. Fig. 12). The temperature curve is similar to that of a cosine function, so the temperature can be expressed by the following formula:

$$T_{a1} = 8.5 + 16.5 \cos[(\pi/6)(\tau - 6.50)] \tag{9}$$

Where 8.5 is the perennial mean temperature; 16.5 is the average range in temperature change every year; τ is the month.

Because of the lack of water temperature observations, the water temperature is expressed by the following formula based on research by professor Zhu Bofang, a renowned academician in China (Zhu, 2013).

Water temperature change at any depth:

$$T(y,\tau) = T_m(y) + A(y)\cos(\tau - \tau_0 - \varepsilon)$$
⁽¹⁰⁾

Perennial mean water temperature at any depth:

$$T_m(y) = c + (T_s - c)e^{-\alpha y}$$
(11)

Water temperature change range in every year:

$$A(y) = A_0 e^{-\beta y} \tag{12}$$

Water temperature phase difference:

$$\varepsilon = d - f e^{-\gamma y} \tag{13}$$

where *y* is the depth of water, τ is the month, τ_0 is the month that has the highest temperature (6.5 was selected for this project). A_0 is the water temperature change range on the water surface every year, which is 4.0 °C. T_s is the perennial mean water temperature on the water surface, which is 9.0 °C. *c*, *d*, *f*, α , β and γ are calculation constants. According to the relevant measured data of the upstream reservoir and







Fig. 8. Processes of the simulated and measured settlements at gauging point 9.

other relevant references (Zhao et al., 2006), these 6 calculation constants are selected as follows: $\alpha = 0.04$; $\beta = 0.018$; $\gamma = 0.085$;f = 1.3; d = 2.15; $c = (T_b - T_s e^{-0.04H})/(1 - e^{-0.04H})$, where *H* is the normal water level, which is 2005.00 m; T_b is the perennial mean water temperature at the bottom of the reservoir, which is 13.0 °C at the first year, 12.0 °C at the second year and 11.0 °C at the later years.

The temperature of the nodes that are on the surface of the face slab and under the water level is set as the water temperature belonging to the first boundary condition. The nodes on the surface of the face slab above the water level and the nodes at the surface of the rockfill dam both belong to the third boundary condition (Zhu, 2013).

According to the experiments (Zhao et al., 2006), the following thermodynamic parameters are used in these FEM simulations (Table 3).

4.3. Low temperature-induced stress on the concrete face slab

From the air temperature observations, the lowest temperature since impounding was -13.4 °C, occurring on January 29, 2008. According to the records, lower temperatures and larger temperature differences tend to lead to face slab cracking. Hence, in this paper, we reduce the time step length from January 20, 2008 to February 1, 2008, and bring them to the FEM simulation. The lowest temperature (at midnight on January 29 (-13.4 °C)) is chosen to analyze the face



Fig. 9. Face slab's deflection and stress in 2004.



Fig. 10. Face slab's deflection and stress in 2016.



Fig. 11. Stress process in points D, K and O.

slab stress. This FEM simulation only considers the effect of temperature field, so the stress in each dam section is assumed to be similar. We choose the typical dam section in the riverbed and draw its temperature-induced stress distribution, illustrated in Fig. 13.

Fig. 13 shows that tensile stress on the outside surface of the face slab is higher than that on the inside surface. The highest tensile stresses of these two surfaces are 2.6 MPa and 2.0 MPa, respectively. They both occur at the top of the face slab near the water level, where the contour lines are very dense. Since this area possesses the greatest stress gradient, it is an area vulnerable to cracking at the top of face slab near the water level.

5. Combination of structure-induced stress and temperatureinduced stress

The cracks on the face slabs are caused by both temperature-induced stress and structure-induced stress. Maximum temperature tensile stress occurs mostly in the lowest temperature, i.e., at midnight on the evening of January 29, 2008. The temperature-induced stress and structure-induced stress at the top of the face slab at this moment are both evaluated, as shown in Fig. 14.

The temperature-induced stress simulation only considers the effect of the temperature field, so the temperature-induced stress of every dam section is identical. The maximum tensile stress (+) is 2.8 MPa. occurring at the water level on the top of face slab, which corresponds with the fact that the cracks mainly occur at the same place. The area of the face slab at the water level is at the junction between air and water. When in winter, the temperature of the face slab above the water level is low, while the underwater portion has a higher temperature. The temperature gradient at this place is great, leading to high levels of temperature tensile stress. When the air temperature is very low or strong cold waves exist, the temperature gradient at these sections increases even more, leading to cracking in the face slabs. The temperature tensile stress in the middle of one face slab is higher than that in both sides of the face slab, which corresponds to the fact that cracks in the middle of one face slab occur earlier than in both sides of the same slab

In the riverbed section (#6–#14), the structure-induced stress at the top of the face slab presents a pressure stress. The maximum value is 5 MPa, occurring at dam section #10. They are both bearing tensile stresses on the right and left banks. The terrain slopes gently on the left bank and steeply on the right bank, with structural tensile stress values of 1–2 MPa and 1–4 MPa, respectively. The maximum tensile stress occurs at the right end of the face slabs, with a value of 8 MPa. This value is too high because the grids here are next to the boundary, leading to the stress concentration.

Combining the effects of temperature-induced stress with those of structure-induced stress, the causes of face slab cracks can be effectively explained. On the riverbed section, stress is constitutive of temperature tensile stress and structural compressive stress, while on both bank



Fig. 12. Daily mean air temperature observations.

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Table 3
Thermodynamic parameters of the face slab and rockfill materials

Materials	Dry density (kg/m ³)	Thermal diffusivity (m^2/d)	Thermal conductivity (kJ/m · d ·)	Elastic modulus (MPa)	Poisson ratio	Linear expansion coefficient (10 ⁻⁶ /)
Cushion materials	2150	0.0672	127.20	150	0.3	0.30
Transitional rockfill	2130	0.0791	148.32	182	0.3	0.30
Main rockfill	2080	0.0694	106.08	235	0.3	0.85
Face slab	2395	0.0903	211.92	25,000	0.167	10.05

sides, it consists of temperature tensile stress and structural tensile stress. The tensile stress on both sides of the bank are therefore much higher than on the riverbed section, leading to many more cracks occurring on the bank's sides. Furthermore, the steep descent of temperature and a lack of surface heat preservation are the major reasons that the face slab on the riverbed section suffers more tensile stress, which is why there are a few shallow cracks developing in the riverbed section as well.

According to the existing face slab cracks in rockfill dams, most cracks occurring in these present projects are horizontal cracks, while the cracks involved in the Gongboxia rockfill dam are vertical cracks. Table 4 shows the changing water amplitude level for several similar projects. Compared with other similar projects, there is little change in the amplitude of water level at Gongboxia's reservoir. The normal water level is 2005.00 m, while dead water level is 2002.00 m. The difference between these two water levels is very small, only 3.00 m, taking up 2.3% of the total height of the dam. The water level of the reservoir is probably one of the most important factors causing the direction of the face slab cracks. In an effort to evaluate the effect of water level on these cracks, we altered the simulated water level to 1950.00 m and then calculated the temperature-induced stress of the face slab with the same calculating conditions (cf. Fig. 15(a))

Fig. 15(a) shows that the maximum of the temperature tensile stress still occurs near the water level after altering the simulated water level, with a value of 2.46 MPa. In order to learn the direction of this stress, we magnify the area of the face slab in the dotted box and decompose the temperature tensile stress into two orthogonal directions (cf. Fig. 15(b)). The lengths of the vertical lines and horizontal lines present the values of the vertical stress and horizontal stress, respectively. Near the water level, the face slab suffers much more vertical stress than horizontal stress. The maximum of the vertical stress is located in the middle of the face slab near the water level, which is 2.32 MPa. Vertical stress plays the leading role and is the main cause of the horizontal cracks.

Fig. 16 shows the decomposition of the temperature tensile stress on the face slab near the water level when the simulated water level is 2005.00 m (normal water level). It can be seen that the face slab suffers much more horizontal stress than vertical stress, and the maximum of the dam axial stress is 2.48 MPa, occurring in the middle of the face slab near the water level. In this case, the horizontal stress plays a leading role and vertical cracks tend to develop.

From the perspective of mechanics of materials, when the water level is 2005.00 m (which is the normal water level of the Gongboxia's reservoir) the area of the face slab above the water level looks like a rectangle. The length (L) of this rectangle is much bigger than the height (h). For this area of face slab near the water level, the horizontal stress equals $E \cdot \varepsilon \cdot L$, while the vertical stress is $E \cdot \varepsilon \cdot h$, where E is the elastic modulus and ε is the strain of the face slab. L is much bigger than h, so horizontal stress is much greater than vertical stress. This is why vertical cracks tend to develop.



Fig. 13. Temperature-induced stress distribution of one face slab in the typical dam section at the lowest temperature (MPa).



Fig. 14. Cracks, temperature-induced stress and structure-induced stress on the surface of the face slab above an elevation of 2002 m.

Table 4Water level fluctuations in different CFRDs in the world.

Projects	Location	Dam height/ m	Normal water level/m	Dead water level/m	Fluctuation/ m	Fluctuation/ dam height
Shuibuya	China	233	400	350	50	21.46%
Bakun	Malaysia	205	228	195	33	16.10%
Mohale	Lesotho	145	2075	2005	70	48.28%
Barra	Brazil	185	647	617	30	16.22%
Grande						
La Yesca	Mexico	220	575	518	57	25.91%
Karahnjukar	Iceland	193	625	575	50	25.91%
Gongboxia	China	132.2	2005	2002	3	2.27%

6. Conclusions

In this study, the causes of the Gongboxia face slab's cracking are analyzed from the perspective of structural- and temperature-induced stresses. The main points that can be concluded from this study are as follows:

- (1) Temperature-induced stress is the main factor that causes the Gongboxia face slab cracks. The area of the face slab that is near the water level experiences heavy cracking. In this area, there are great temperature gradients in winter, causing a high level of temperature tensile stress that causes the cracking of the face slab. This explains why most cracks tend to occur near the water level.
- (2) Structure-induced stress is produced by the gravity of the dam, the pressure of the water and the rheology of the rockfill. From the FEM simulation, the structure tensile stress mainly occurs





Fig. 15. Temperature tensile stress and its decomposition at a water level of 1950 m.



Fig. 16. Decomposition of temperature tensile stress on the part of face slab at a water level of 2005 m.

on both sides of the bank, while structural pressure stress occurs on the riverbed. Combined with temperature-induced stress, tensile stresses occurring on the bank side of the dam are much higher than those along the riverbed. This explains why many more cracks occur on both sides of the bank.

(3) The water level of the reservoir may be the main reason that the cracks are vertical. Because of the lack of fluctuation in the high water levels, the area of the face slab which is above the water level looks like a rectangle, leading to more horizontal stress and less vertical stress. In other words, the principal tensile stress is horizontal, leading to the development of vertical cracks.

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