Deformation safety of high concrete face rockfill dams

Calculs en déformations de la sécurité des grands barrages en rochement à masque amont en béton

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ABSTRACT

Based on the analysis of the mechanism of serious damages of high concrete face rockfill dams (CFRDs), it is indicated that the causes of the cracking of cushion layer, the structural cracking and squeezed ruptures of concrete face slab are as follows: the deformations of the dam different zones are not coordinated and the deformations of the concrete face slabs are not coordinated synchronously with those of the dam body. The basis of empirical design that the water load on the concrete face enters the foundation upstream from the dam axis is not correct. Therefore the empirical design concept of CFRDs should be changed. The deformation safety is necessary for high CFRDs besides the stability safety and seepage safety for earth-rockfill dams. A new deformation coordination concept and the deformation safety design of high CFRDs including deformation coordination standards, judgment criteria and calculation methods are put forward. The deformation coordination design method for replacing the empirical design concept is shown to be important for high CFRDs through the application of Bakun Dam.

RÉSUMÉ

Dans l'analyse des problèmes de stabilité des barrages en enrochements à parement amont en béton de grande hauteur (CFRD), il a été remarqué que la cause de la fissuration du lit et du masque est le contraste de déformabilité entre les différentes zones constituant le barrage (massif et parement amont). La conception basée sur l'expérience considérant que la chargement dû à l'eau agissant sur le masque amont pénètre la fondation amont est incorrecte, et un changement dans le dimensionnement empirique des CFRDs devrait être envisagé. Il est aussi nécessaire d'assurer un calcul de stabilité en déformations en plus des calculs à la rupture et vis-à-vis des écoulements. Une nouvelle conception intégrant la compatibilité des déformations dans les analyses de stabilité des grands barrages en enrochements à masque amont en béton est établie à partir de normes de distinction et des méthodes de calcul à travers une application au projet de barrage de Bakun qui confirme l'intérêt de cette nouvelle approche par rapport à celles basées sur l'expérience.

KEY WORDs:CFRD, deformation safety, empirical design,deformation coordination, standard,judgment criterion.

1 INTRODUCTION

It takes only 46 years there are more than 500 concrete face rockfill dams(CFRDs) have been completed or under construction in the world. The safety and economic condition of CFRD are so good that CFRD has become the best dam type with the most competitive ability usually. But the design of the CFRD is empirical and is based on experience and precedent. Some serious damages as follows have happened at several high CFRDs since 1990's. Some cracks of cushion zone happened at Tianshengqiao No.1 Dam (178m high) and Xingo Dam(140m high). The top of concrete face slabs separated mostly from cushion layer and then more than 5000 cracks of concrete face slab occurred at Tianshengqiao No.1 Dam. A lot of cracks of concrete face slabs occurred then the seepage discharge reached 1700 L/s at Aguamilpa Dam(187m high). The serious cracks, squeezed ruptures and horizontal overlaps of concrete face slabs occurred at Campos Novos Dam(202m high), Barra Grande Dam(185m high)and Mohale Dam(145m high) then the seepage discharge increased an range from 600L/s to 1300L/s. The crack and squeezed rupture of concrete face slab occurred also at Tianshengqiao No.1 Dam and Shuibuya Dam(233m high).

The reason of cracking of cushion zone, separating of face slab top from cushion layer, and cracking of concrete face slab is that the deformation of dam different zones are not coordinated and the deformation of concrete face slab are not coordinated synchronously with the deformation of dam body. The modulus of deformation of main rockfill zone (upstream rockfill zone) is higher than that of downstream rockfill zone. The deformation of dam body is much larger than the deformation of concrete face slab. If the difference of deformation between dam body and concrete face slab was large enough to exceed the limit, the top of face slab would separate from cushion layer and then cracks of face slab would occur. The direction of the deformation of dam body faces the center of the valley and at this time the friction force facing the center of the valley occurs between concrete face slabs and cushion layer. If the compressive stress at the central area of concrete face slab exceeded the compressive strength limit of concrete that the squeezed ruptures, cracks and horizontal overlaps would occur. Therefore the deformation safety should be satisfied necessarily besides the stability safety and seepage safety for high CFRDs.

2 CONNOTATION OF DEFORMATION SAFETY OF HIGH CFRD

The deformation safety of high CFRD includes the deformation coordination of different zones of dam body and the deformation coordination synchronously between the deformation of dam body and the deformation of concrete face slab.

2.1 *Deformation coordination standards*

1) Coordination standard of dam body settlement

$$\left|\frac{S_{i+1}-S_i}{y_{i+1}-y_i}\right|<[I] \quad (1)$$

$$\left|\frac{S_{i+1}-S_i}{x_{i+1}-x_i}\right|<[I] \quad (2)$$

where S_i and S_{i+1} are settlement at i point and i+1 point of dam body (cm); y_i and y_{i+1} are coordinate at i point and i+1 point at direction of stream(m); x_i and x_{i+1} are coordinate at i point and i+1 point at direction of dam axis(m); [I] is limit of inclination(the difference of settlement)

2) Coordination standard of dam body horizontal displacement

$$\left|\frac{D_{Byi+1}-D_{Byi}}{y_{i+1}-y_i}\right|<[T] \quad (3)$$

$$\left|\frac{D_{Bxi+1}-D_{Bxi}}{x_{i+1}-x_i}\right|<[T] \quad (4)$$

where D_{Byi} and D_{Byi+1} are horizontal displacement at stream direction at i point and i+1 point of dam body(cm); D_{Bxi} and D_{Bxi+1} are horizontal displacement at dam axis direction at i point and i+1 point of dam body(cm); [T] is limit of displacement difference.

3) Coordination synchronously between dam body deformation and concrete face slab deformation

$$(D_{Bfi}\big|_j - d_{fi}\big|_j)_{\max} < [H_s] \quad (5)$$

$$(D_{Bxi}\big|_j - d_{xi}\big|_j)_{\max} < [J] \quad (6)$$

$$[H_s] = f(1/E_c, f_t, t_f, f_y \cdots) \quad (7)$$

$$[J] = f(1/E_c, f_c, t_f, f_y, C_f \cdots) \quad (8)$$

Where $D_{Bfi}\big|_j$ is displacement of dam body i point at normal direction of face slab at j time(cm); $d_{fi}\big|_j$ is deflection of face slab i point at j time(cm); $D_{Bxi}\big|_j$ is displacement of dam body i point at dam axis direction or at direction of face slab slope at j time(cm); $d_{xi}\big|_j$ is displacement of face slab i point at dam axis direction or at direction of face slab slope at j time(cm); [H_s] is limit of separation height of face slab(cm); [J] is limit of displacement difference between dam body and face slab at dam axis direction or at face slab slope direction(cm). E_c is elastic modulus of concrete; f_c is compressive strength of concrete; f_t is tensile strength of concrete; t_f is thickness of concrete face slab; f_y is compressive strength or tensile strength of reinforcement; C_f is friction coefficient between face slab and cushion layer.

2.2 *Deformation coordination judgment criteria*

The above-mentioned deformation coordination judgment criteria including [I], [T], [H_s] and [J] depend on the physical and mechanical properties of dam filling material and concrete, the dimension of face slab, as well as stress condition of dam body and concrete face slab. The above-mentioned judgment criteria could be decided by laboratory tests or back analysis based on prototype observation data. The laboratory tests include large scale simple shear test, large scale triaxial compression or extension test and large scale contact surface test. The real or modified material is used as dam filling material and face slab concrete in laboratory tests. The stress condition of sample in the test should imitate the real stress condition of dam body or face slab during construction or operation.

The prototype observation data from Tianshengqiao No.1 Dam, Aguamilpa Dam, Campos Noves Dam, Barra Grande Dam, Mohale Dam and Shuibuya Dam could be used to analyze the reasons for causing the above-mentioned serious damages.

The above-mentioned judgment criteria also could be obtained from back analysis.

2.3 *Calculation method and contact surface constitutive relation*

A three-dimensional finite element method (FEM) could be used as deformation coordination calculation method. NHRI (Nanjing Hydraulic Research Institute) double yield surface elastic-plastic model and Duncan E-B non-linear elastic model could be used to modeling dam filling material. A contact surface damage constitutive model could be used to modeling contact surface performance as the following formula.

$$\tau=\left(\frac{2\times e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}}{e^{\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}+e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}}\right)\times\frac{\gamma}{\frac{1}{K_I\gamma_w\left(\frac{\sigma_n}{P_a}\right)^n}+\frac{\gamma}{\sigma_n\tan\delta_i}}+$$

$$\frac{e^{\alpha\gamma^{n_1}\left(\frac{\sigma_n}{P_a}\right)^{n_2}}-e^{-\alpha\gamma^{n_1}\left(\frac{\sigma_n}{P_a}\right)^{n_2}}}{e^{\alpha\gamma^{n_1}\left(\frac{\sigma_n}{P_a}\right)^{n_2}}+e^{-\alpha\gamma^{n_1}\left(\frac{\sigma_n}{Pa}\right)^{n_2}}}\times\left(\sigma_n\tan(\delta_d)+c_n\right) \quad (9)$$

Where τ is shear stress of contact surface; σ_n is normal stress of contact surface; γ is shear strain of contact surface; Pa is a standard atmospheric pressure; α、 δ_i、 δ_d、 C_n、 K_1、 n、 n_1 、 n_2 are model parameters. The model parameters of two typical CFRDs are shown in Table 1 Table 1. Parameters of contact surface damage constitutive model

Dam name	K_1	n	δ_i	δ_d	C_n	α	n_1	n_2
Houziyan (223.5m high)	23	0.49	1.2	0.50	5.42	0.040	2.0	-0.95
Jinchuan (112 m high)	20	0.55	1.2	0.47	2.02	0.045	1.6	-0.34

The effectiveness of fitting the contact surface damage constitutive model to contact surface test results for Houziyan Dam is quite good as shown in Figure 1.

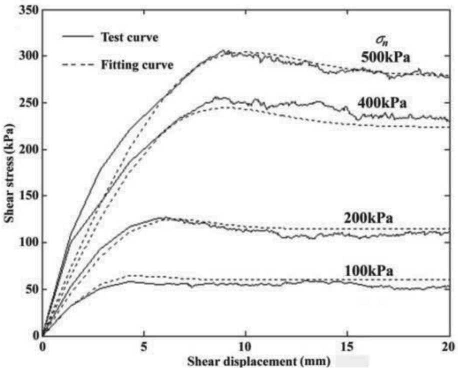


Figure1. Effectiveness of fitting contact surface model to contact surface test result for Houziyan Dam

3. APPLICATION OF DEORMATION COORDINATION DESIGN CONCEPT

The deformation coordination design concept has been applied in Bakun Dam. Bakun Dam is located on Balui River, Sarawak Malaysia. Bakun Dam is the second highest completed CFRD in the world with its height 202m. The former design of Bakun Dam was completed by H.S.Choi, Germany. The former dam zoning of Bakun Dam is shown in Figure 2.

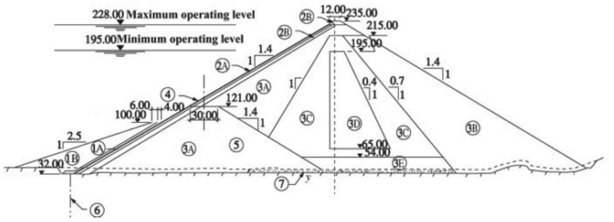


Figure 2 Zoning of Bakun Dam designed by empirical method (unit: m)

Bakun CWZ-Main Civil works tender had been obtained by Malaysia-China Hydro Joint Venture (MCH JV) in 2002. Bakun Dam design has been completed by China Hydro Northwest Investigation Design &Research Institute. Bakun Dam filling material test and 3D FEM analysis has been completed by Nanjing Hydraulic Research Institute. Based on deformation coordination design concept a new dam zoning for Bakun Dam has been put forward as shown in Figure 3.

The main difference between the former design and new deformation coordination design are as follows: The dry mass density of compacted rockfill is 2.09 g/cm^3 for the former and 2.22g/cm^3 for the latter. The water-stop of vertical joint of concrete face slab is bituminizing plate for the former and deformable Pulai Plate for the latter.

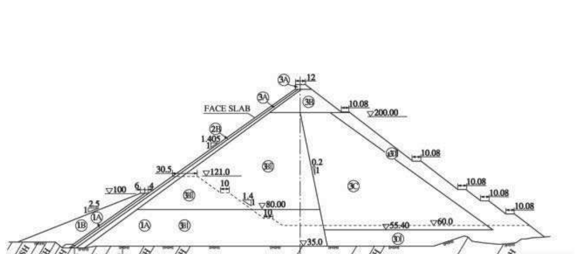


Figure 3 Zoning of Bakun Dam designed by new deformation coordination concept (unit: m)

The results of 3D FEM analysis and the comparison of dam behavior and deformation coordination level between the former design and new design are shown in Figure 4 to Figure 6.

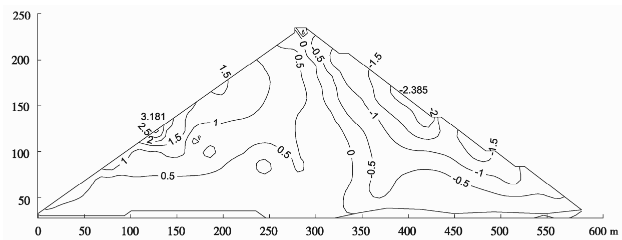
The maximum settlement of dam body at completion is 376.4cm for the former and 230.6cm for the latter. The observed settlement is 227.5cm.The maximum displacement towards downstream of dam body during impoundment is 79.2cm for the former and 48.9cm for the latter. The observed displacement is only 13.0cm. The maximum deflection of face slab at impoundment is 105.7cm for the former and 84.7cm for the latter. The maximum compressive stress at dam axis direction of face slab at impoundment is 19.2MPa for the former and18.3MPa for the latter.

The following results could be obtained from Figures:

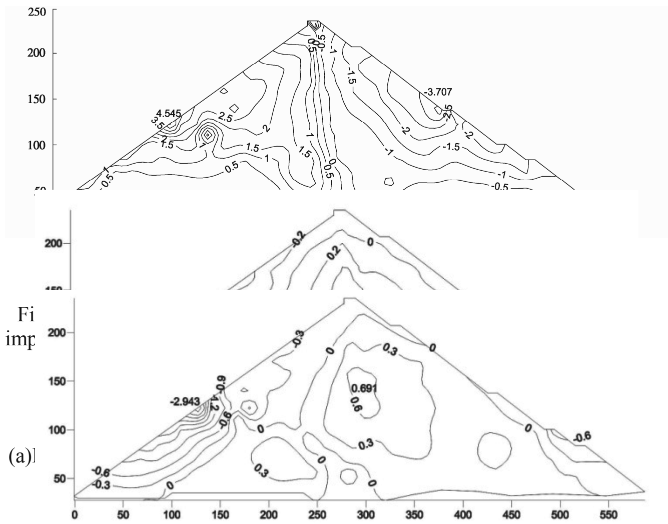
1) The dam deformation of dam body designed by empirical concept is uncoordinated especially at cushion zone and top of the first stage filling. Its maximum difference of dam body settlement is 4.55×10^{-2} (Figure 4) , its maximum difference of horizontal displacement of dam body is -2.94×10^{-2} (Figure 5) .Cracking of its cushion zone would occur probably.

2) The maximum displacement difference at normal direction between face slab and cushion designed by empirical concept reaches 113.5cm. Its top of face slab would separate from cushion and then cracks of face slab would occur probably.

3) The maximum compressive strain at dam axis direction of face slab designed by empirical concept is 670×10^{-6} (Figure 6) .which exceeded the limit of compressive stain (650×10^{-6}) from prototype data of Mohale Dam. In other words, squeezed rupture of concrete face slab would occur probably.

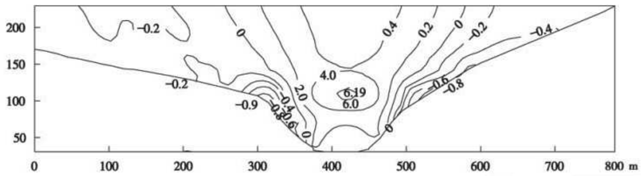


(a)Settlement difference of Bakun Dam body designed by deformation coordination method (unit:10^{-2})



(b)Horizontal displacement difference of Bakun Dam body designed by empirical method (unit: 10^{-2})

Figure 5 Comparison of horizontal displacement difference of Bakun Dam body at water impoundment between empirical method designed and new deformation coordination concept method designed


(a)Strain at dam axis direction of face slab of Bakun Dam designed by deformation coordination method (unit: 10^{-4})

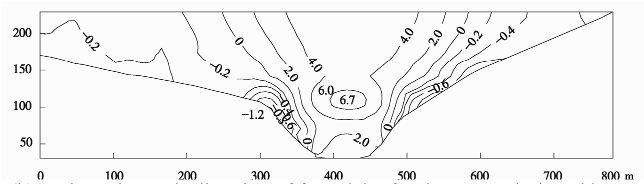

(b)Strain at dam axis direction of face slab of Bakun Dam designed by empirical method (unit: 10^{-4})

Figure 6 Comparison of strains at dam axis direction of concrete face slab at water impoundment of Bakun Dam between .empirical method designed and new deformation coordination concept method designed

4) Based on the calculation results and observation data of Bakun Dam designed by deformation coordination concept and constructed by MCHJV, it could be shown that the deformation of dam different zones is coordinated each other and the deformation of concrete face slab is coordinated synchronously with deformation of dam body. The maximum settlement difference of dam body is only 3.18×10^{-2}, decreasing 51% as compared with that designed by empirical method. The maximum displacement difference at normal direction between face slab and cushion is only 71.0cm, decreasing 60% as compared with that designed by empirical method. The observed maximum compression strain at dam axis direction of face slab is only 565×10^{-6}, decreasing 19% as compared with that designed by empirical method.

5) It could be considered based on Bakun Dam prototype observation data that the predicted behavior by 3D FEM analysis could reflect its real performance. This 3D FEM analysis method is effective and can be used for CFRD deformation coordination concept design.

4 CONCLUSIONS

The following conclusions could be obtained:

1) The reason of the cracking cushion layer, the structural cracking and squeezed rupture of concrete face slab is that the deformations of dam different zones are not coordinated each other and the deformations of face slab are not coordinated synchronously with the deformations of dam body.

2) The deformation safety should be satisfied necessarily for high CFRDs besides the stability safety and seepage safety for earth-rockfill dams as usually.

3) The deformation safety design method including deformation coordination standards, judgment criteria and calculation method is shown to be reasonable and important for high CFRDs through its application to Bakun Dam.

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