A NEW DESIGN CONCEPT AND ANALYSIS METHOD FOR SAFETY OF HIGH CFRDs

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ABSTRACT

Based on the analysis of causes for serious damages of worldwide high concrete face rockfill dams (CFRDs), it could be concluded that the deformation safety is necessary besides the stability safety and seepage safety for high CFRDs. The dam deformation synchronously coordinating with face slab deformation is most important for safety of high CFRDs.

A new constitutive model for rockfill dam materials based on breakage energy and a new constitutive model for interface between cushion and concrete face slab based on damage theory has been developed for numerical analysis of high CFRDs. The influence of the properties cushion material, the roughness of concrete face slab and the stress condition of contact zone on the stress-strain behavior of interface could be considered in the new interface constitutive model. The new deformation safety design concept and the numerical analysis method have been applied in several high concrete face rockfill dams. The performance of these CFRDs is quite good. All these CFRDs have been operated safely up to now.

1. INTRODUCTION

It takes only 30 years 258 concrete face rockfill dam (CFRDs) with dam height above 30m have been completed in China, 135 CFRDs with dam height above 30m have been under construction or deign. In other words, the total number of CFRDs completed or been under construction or design in China is above 50 percent of total number of CFRDs in the world.

But some serious damages have happened at several high CFRDs as follows since 1990's. Some cracks happened at cushion zone of Tianshengqiao No.1 Dam (178m high) and Xingo Dam (140m high). The top of concrete face slab separated mostly from cushion layer and many cracks of concrete face slab occurred at Tianshengqiao No.1 Dam and Aguamilpa Dam(187m high), The serious cracks, squeezed ruptures and horizontal overlaps occurred at concrete face slabs of Campos Novos Dam (202m high), Barra Grande Dam (185m high), Sanbanxi Dam(185.5m high), Tianshengqiao No.1 Dam, Mohale Dam, 145m high and Buxi Dam (135.8m high). And then heavy seepage discharge happened in some of above mentioned dams such as Campos Novos Dam, Barra Grande Dam, Mohale Dam and Buxi Dam.

Based on the analysis on reason of the above-mentioned serious damages it is shown that the deformation of dam different zones was not coordinated and (or) the deformation of concrete face slab was not coordinated synchronously with the deformation of cushion layer and dam body, the damages would happen. The difference of deformation in the normal direction of concrete face slab between dam body and concrete face slab was large enough, the top of face slab would separate from cushion layer and then cracks of slab would occur. The deformation in the dam axis direction of dam body was large enough, the friction force facing the center of the valley between concrete face slab and cushion layer would be large enough, the compressive stress at the central area of concrete face slab would exceed the compressive strength limit of concrete as the result that the squeezed ruptures, cracks and horizontal overlaps would occur [1]. Therefore the deformation safety should be satisfied necessarily besides the stability safety and seepage safety for high CFRDs.

2. NEW DESIGN CONCEPT AND ANALYSIS METHOD

A new design concept and analysis method have been established in China. 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. The new deformation coordination design includes deformation coordination standards, deformation coordination judgment criteria and design calculation method [2, 3]. A three-dimensional finite element method (FEM) could be used as deformation coordination analysis method. NHRI, Nanjing Hydraulic Research Institute double yield surface elastoplastic model and Duncan E-B non-linear elastic model could be used to modeling dam filling material. But the effect of the rockfill particle breakage on the deformation behavior of rockfill body was not considered in two above-mentioned constitutive models. Based on the Ueng's and Chen's dilatancy formula, the dilatancy equation considering the particle breakage was established as the following formula [4]. The relevant methods for its parameters was proposed by analyzing the energy equilibrium problems in the process of triaxial CD tests. The Rowe's dilatancy formula and the proposed dilatancy equation considering the particle breakage have been introduced respectively into the NHRI double-yield face elastoplastic model and the Duncan non-linear elastic model [4].

$$\mu_t = \frac{d\varepsilon_v}{d\varepsilon_1} = 1 - \frac{\frac{\sigma_1}{\sigma_3} - \frac{dE_B}{\sigma_3 d\varepsilon_1}(1+\sin\varphi_m)}{\tan^2(45° + \frac{\varphi_m}{2})} \quad ...(1)$$

A series of systematic tests were performed to study the mechanical behavior of interface between concrete face slab and cushion layer using a new experimentation apparatus [5]. The stress deformation properties of contact zone were measured and analyzed through both macro and micro approaches using PIV technology. The effect of grain size of cushion layer material, roughness of concrete face slab, shear displacement and stress state of contact zone on the thickness and stress-strain behavior have been studied in the interface test. Based on the interface test a contact surface damage constitutive model was established as the following formula [3].

$$\tau = \left(\frac{2 \times e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}}{e^{\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}} + e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}} \right) \times \frac{\gamma}{\frac{1}{K_1\gamma_w\left(\frac{\sigma_n}{P_a}\right)^{n}} + \frac{\gamma}{\sigma_n \tan\delta_i}} + \frac{e^{\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}} - e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}}{e^{\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}} + e^{-\alpha\gamma^{n1}\left(\frac{\sigma_n}{P_a}\right)^{n2}}} \times (\sigma_n \tan(\delta_d) + c_n) \quad ...(2)$$

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, (112m 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.

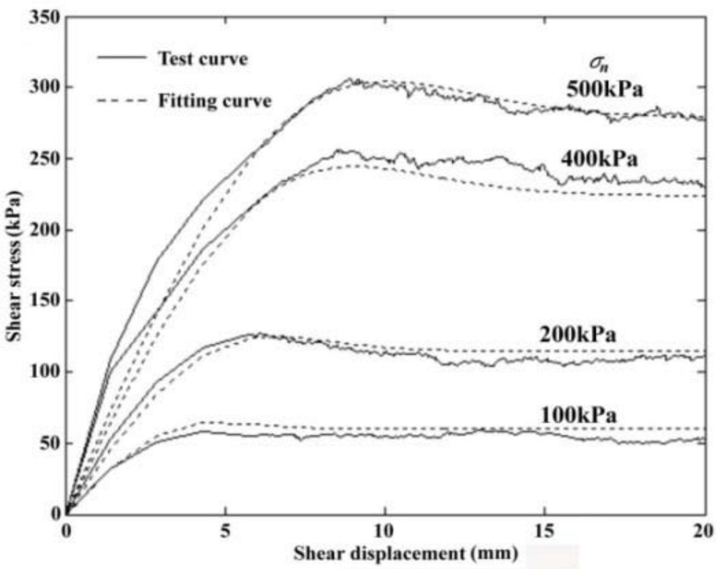


Fig. 1 : Effectiveness of fitting contact surface model to contact surface test result for Houziyan Dam

3. APPLICATION OF DEFORMATION COORDINATION DESIGN

The deformation coordination design concept and method have been applied in Bakun Dam (202m high), Houziyan Dam (223.5m high) and other high CFRDs.

3.1 Application in Bakun Dam

Bakun Dam is located on Balui River, Sarawak Malaysia. The former design of Bakun Dam was completed by H.S.Choi, Germany. The former dam zoning of Bakun Dam was shown in Figure 2.

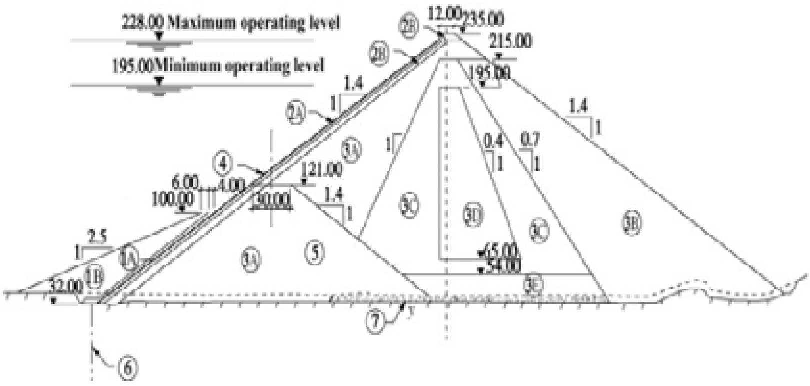


Fig. 2 : Zoning of Bakun Dam designed by empirical method (unit: m)

Bakun Dam design has been completed by China Hydro Northwest Investigation Design &Research Institute. Based on deformation coordination design concept a new dam zoning for Bakun Dam has been put forward as shown in Figure 3[3].

The main difference between the former design and new deformation coordination design are as the following [3]:

(1) An empirical dam zoing for the former and deformation coordination dam zoning for the new design.

(2) The dry mass density of compacted rockfill is 2.09g/cm^3 for the former and 2.22g/cm^3 for the new design.

(3) The water-stop of vertical joint of concrete face slab is bituminizing plate for the former and deformable Pulai plate for the new design.

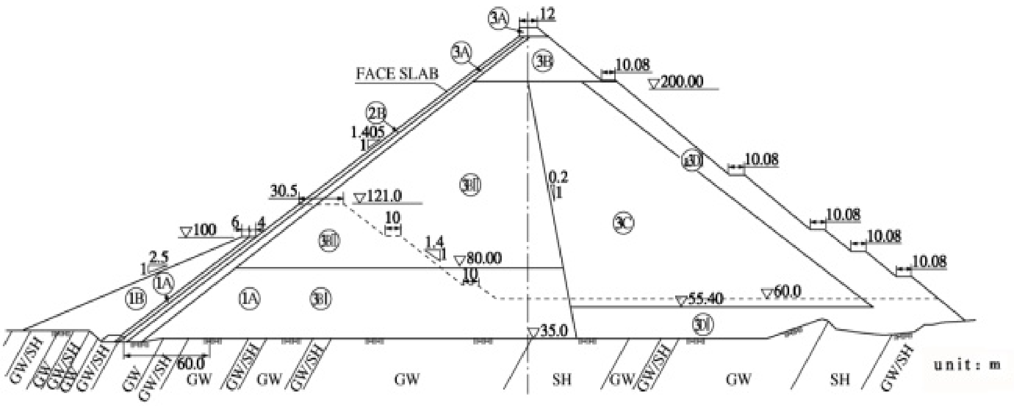


Fig. 3 : Zoning of Bakun Dam designed by new deformation coordination concept (unit: m)

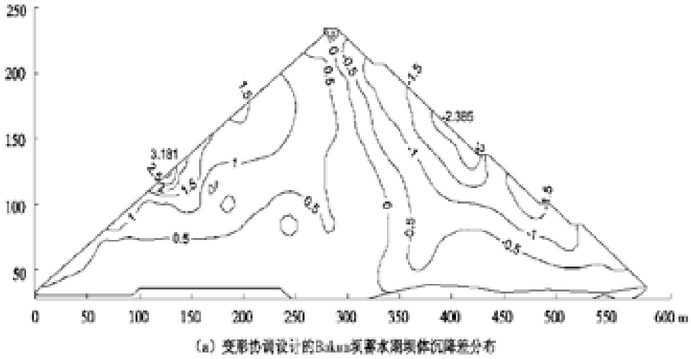
The results of 3D FEM analysis and the comparison of dam behavior and deformation coordination level between the former design and new design are shown in Figure 4 to Figure 6.

The following results could be obtained from the Figures [3]:

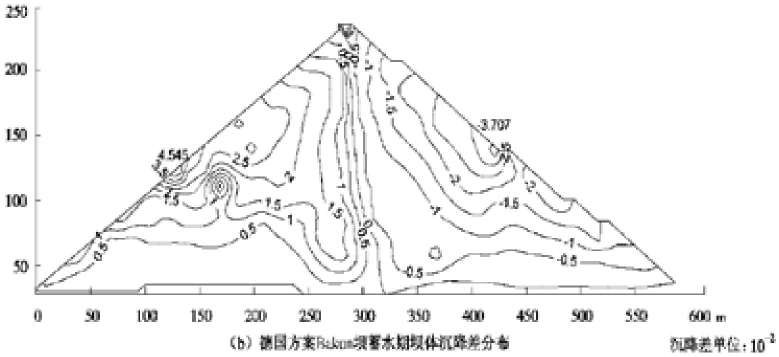
(1) The dam deformation of dam body designed by empirical concept is uncoordinated especially at cushion zone and top of the first stage filling. Its maximum difference of dam body settlement is 4.55×10^{-2} (Figure 4), its maximum difference of horizontal displacement of dam body is -2.94×10^{-2} (Figure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

(2) The maximum displacement difference at normal direction between face slab and cushion zone 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 was 670×10^{-6}(Figure 6), which exceeded the limit of compressive strain (650×10^{-6}) from prototype observation data of Mohale Dam. In other words, squeezed rupture of concrete face slab would occur probably.

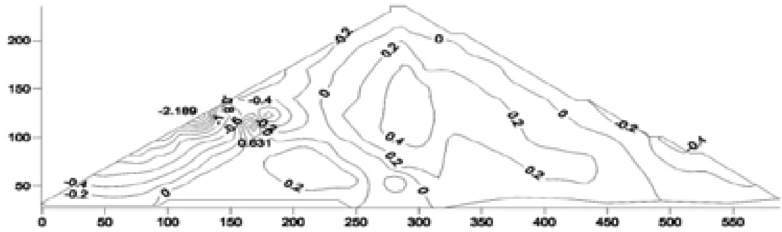


(a) Settlement difference of Bakun Dam body designed by deformation coordination method (unit:10^{-2})

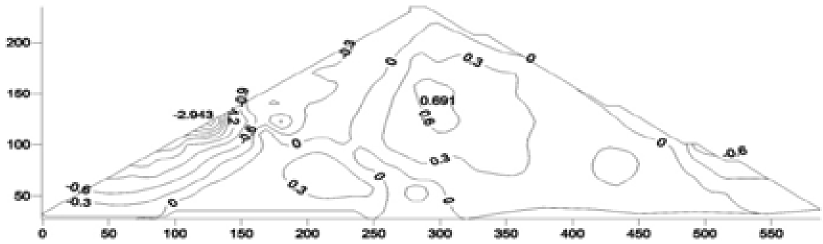


(b) Settlement difference of Bakun Dam body designed by empirical method (unit: 10^{-2})

Fig. 4 : Comparison of settlement difference of Bakun Dam at water impoundment between empirical method designed and new deformation coordination concept method designed

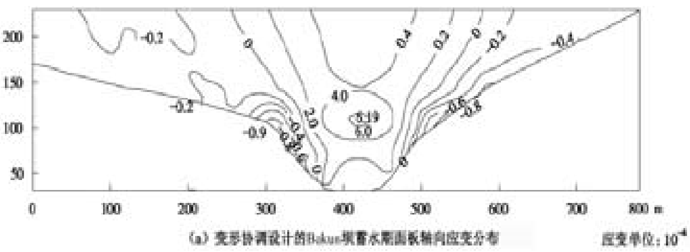


(a) Horizontal displacement difference of Bakun Dam body designed by deformation coordination method (unit: 10^{-2})

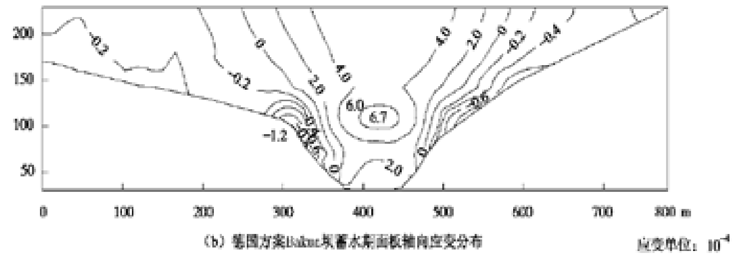


(b) Horizontal displacement difference of Bakun Dam body designed by empirical method (unit: 10^{-2})

Fig. 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})

Fig. 6 : Comparison of strains at dam axis direction of face slab at impoundment of Bakun Dam between empirical method esigned and new deformation coordination concept method designed

3.2 Application in Houziyan Dam

Houziyan Dam is the second highest CFRD in the world with its height 223.5m.The dam is located on Daduhe River, Sichuan Province in China. The typical section of Houziyan Dam is shown in Figure 7. Based on deformation coordination design concept and analysis the following deformation coordination measures have been applied [2, 3, 6] :

(1) A new dam zoning as shown in Figure 7 and a new dam rockfill compaction standard have been used.

(2) The all overburden layers in the range of 90m from plinth were excavated out totally. The sand gravel with fines layer and clayey silt layer in dam foundation area were stripped out totally as shown in Figure 7.

(3) The special rolling compaction zones with lower porosity and higher deformation modulus were set up at the top, bottom and near the bank slope of dam body as shown in Figure 8.

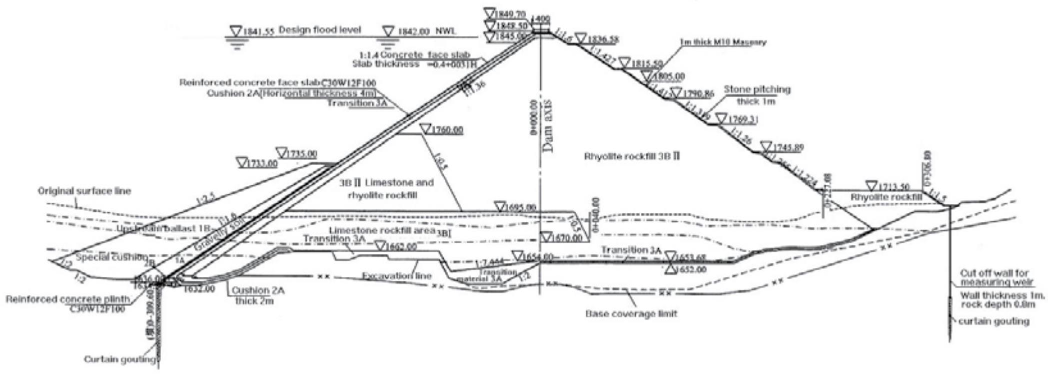
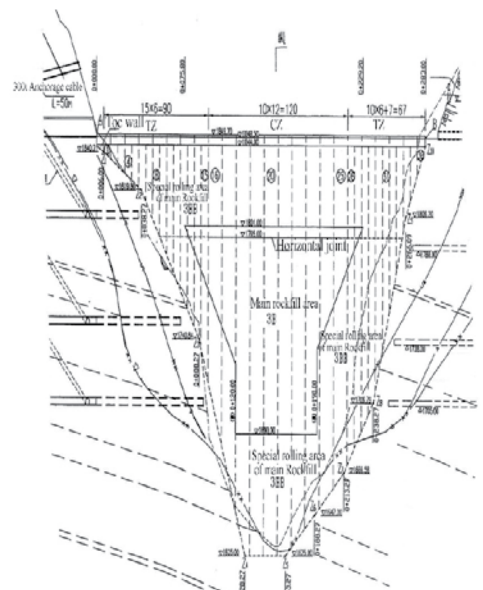


Fig. 7 : The typical section of Houziyan Dam



n—Face slab serial number 3BB—Special rolling compaction main rockfill zone 3B—Main rockfill zone
TZ—Special vertical joints at tensile zone CZ—Special vertical joints at compressive zone

Fig. 8 : Longitudinal section along dam axis of Houziyan CFRD（unit：m）

Bakun Dam, Houziyan Dam and the other high CFRDs including Jilintai-1 Dam (157m high), Kajiwa Dam(171m high) and Upper reservoir of Yixing PSP Dam(138m high) completed according to the new deformation coordination design and have operated safely up to now. The performance of the above-mentioned high CFRDs is quite good. There is no crack in dam body. Face slab is free from structural crack, squeezed rupture and overlap damage.

4. CONCLUSIONS

The following conclusions could be obtained:

1. The deformation safety and deformation coordination design are necessary for high CFRDs besides the stability safety and seepage safety.
2. The new constitutive model considering rockfill particle breakage effect and the new constitutive model for interface between cushion and slab face based on damage theory are important to analyze the stress-strain behavior of CFRDs truthfully. In other words, they are important and necessary part of new deformation coordination design methods.

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