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Technical Progress on Researches for the Safety of High Concrete-Faced Rockfill Dams

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ABSTRACT

The concrete-faced rockfill dam (CFRD) is an important dam type in the selection of high dams to be constructed in Western China, owing to its direct utilization of local materials, good adaptability, and distinct economic advantages. Over the past decades, China has gained successful experience in the construction of 200 m CFRDs, providing the necessary technical accumulation for the development of 250–300 m ultra-high CFRDs. This paper summarizes these successful experiences and analyzes the problems of a number of major 200 m CFRDs around the world. In addition, it discusses the key technologies and latest research progress regarding safety in the construction of 250–300 m ultra-high CFRDs, and suggests focuses and general ideas for future research.

1. Introduction

Western China has abundant hydropower resources and great potential for hydropower development. However, these resources are difficult to exploit due to the high altitude, harsh natural environment, complex topographical and geological conditions, inconvenient transportation routes, and high seismic intensity of potential dam sites. Under these circumstances, dams constructed with local materials have better adaptability. In particular, the concrete-faced rockfill dam (CFRD) is one of the most promising dam types for this region, since it can make full use of local materials to reduce the transportation of construction materials out to the dam site, and has high adaptability, distinct economic advantages, and an excellent capability for earthquake resistance. A number of ultra-high dams that are 250–300 m in height, including the Gushui (dam height 240 m), Rumei (dam height 315 m), Maji (dam height 277.5 m), and Cihaxia (dam height 257.5 m) dams, are planned for construction in Western China. If the situation permits, the CFRD will be the preferred dam type.

At present, there are more than 600 CFRDs around the world, including constructed, under-construction, and proposed dams. China possesses the largest number of CFRDs. According to the Technical Committee on CFRDs of the China Society for Hydropower Engineering [1–3], at the end of 2013, there were 325 CFRDs with heights greater than 30 m in China and 16 CFRDs with heights greater than 200 m around the world—10 of which were in China. The Shuibuya Dam in China, which is 233 m high and was completed in 2008, is currently the world's highest CFRD.

Since the 1980s, China's CFRD construction technologies have made significant progress through the introduction, digestion, absorption, and re-innovation of advanced technologies, as well as through the construction of many CFRDs, including Tianshengqiao-1 (dam height 178 m, built in 2000), Hongjiadu (dam height 179.5 m, built in 2005), Sanbanxi (dam height 185.5 m, built in 2006), and Shuibuya (dam height 233 m, built in 2008). These efforts have provided the necessary technical reserves for the development of 250–300 m ultra-high CFRDs.

This paper summarizes China's successful experiences and analyzes the problems of a number of major 200 m CFRDs around the world. In addition, it systematically discusses the key tech-

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2. Primary issues and successful experiences of 200 m concrete-faced rockfill dams (CFRDs)

2.1. Primary issues

Cooke and Sherard [4–7] considered the design of CFRDs to be empirical, and many 200 m CFRDs that were built before 2000 were designed and constructed using the empirical approach. During the operation of these dams, many problems have occurred, such as cracks in the face slab and cushion layer, separation of the face slab from the cushion layer, concrete rupture along the vertical joints between face slabs, and excessive leakage.

2.1.1. Aguamilpa Dam

The Aguamilpa Dam in Mexico was built in 1995, with a dam height of 187 m, crest elevation of 235 m, crest length of 660 m, and normal water level of 220 m. The main rockfill zone, located upstream of the dam axis, was filled with natural sandy gravels, while the downstream dam body was filled with excavated granite rockfill materials. A modulus transitional zone was set in the middle.

The leakage rate reached 257.7 $L\cdot s^{-1}$ when the reservoir water level rose to an elevation of 218.8 m. At the same time, dense horizontal and curved fine cracks appeared on the face slab about 30 m from the top, and a horizontal tensile crack, 160 m long and 15 mm wide, was found 50 m from the top.

Cooke [7] suggested that the horizontal structural tensile cracks were caused by excessive differential settlement between the upstream and downstream rockfill zones. The compressive moduli of the rockfill in the upstream and transitional zones were 260 MPa and 136 MPa, respectively, while that of the rockfill in the downstream zone was only 47 MPa. Thus, the moduli of the upstream and downstream rockfill had a more than 5-fold difference, which led to excessive differential settlement. Based on the experiences from the Aguamilpa Dam and the Salvajina Dam, Cooke [7] proposed that the width of the upstream gravel zone of gravel and rockfill mixed dams should be at least 2/3 of the dam width.

Some Chinese experts believed that the curved cracks on the face slab of the Aguamilpa Dam were related to insufficient pre-settlement time for the rockfill. If the face slab had been cast after the settlement rate decreased to 6 mm per month, the deflection on the top of the face slab would have decreased to 15 mm, thus greatly reducing the possibility of horizontal curved cracks on the face slab [8].

2.1.2. Tianshengqiao-1 CFRD

The Tianshengqiao-1 CFRD is located in Guizhou, China. Its maximum dam height, crest length, crest elevation, and normal water level are 178 m, 1104 m, 791 m, and 780 m, respectively. The main rockfill zone upstream of the dam axis was filled with limestone materials obtained from spillway excavation, while the downstream rockfill zone was filled with excavated sandstone and mudstone materials. Their compressive moduli were 45 MPa and 22 MPa, respectively. The following problems occurred during the construction and initial operation of the dam.

Firstly, cracks formed in the cushion layer. During the sixth filling stage, 37 cracks were found in the cushion layer at elevations from 748 m to 768 m; among these cracks, the largest length, width, and depth were 79 m, 5 cm, and 1.5 m, respectively. Excessive differential settlement between upstream and downstream caused by the incorrect filling sequence of upstream and downstream rockfill was considered to be the main reason.

Secondly, there was separation of the face slab from the cushion layer, and horizontal cracks formed on the face slab. Due to excessive settlement of the rockfill, a total of 104 face slabs separated from the underlying cushion layer, with a maximum gap length of 10 m and a maximum gap depth of 15 cm. Influenced by both excessive deformation of the rockfill and separation from the cushion layer, the face slabs lost effective support, thus resulting in horizontal cracks. The number of cracks on face slabs in the area above 748.6 m reached 4537 [9].

Thirdly, face slab rupture damage occurred. The concrete on both sides of the vertical joint between the longest face slabs, L3 and L4, was damaged in July 2003 due to the excessive compression stresses. The damage zone extended from an elevation of 787.3 m to an elevation of 748.2 m, with a maximum width of 4 m, average width of 1 m, maximum depth of 30 cm, and average depth of 24 cm. Later, this damage zone between L3 and L4 was repaired and the joint was filled with embedded rubber plate, which showed good performance during the subsequent operation.

Finally, the leakage rate was large. It reached 80–140 $L\cdot s^{-1}$ and fluctuated with changes in the reservoir water level [10].

2.1.3. Campos Novos CFRD

The Campos Novos CFRD [11] is located in Brazil, and has a maximum dam height of 202 m, crest length of 590 m, and normal water level of 660 m. When the water level reached above 642 m at the end of 2005, face slab rupture occurred at the middle of the vertical joint between face slabs 17 and 18, rapidly extending both upward and downward. The gap between the face slab and the cushion layer reached 4 cm and the leakage rate reached 1300 $L\cdot s^{-1}$. Slab rupture was later found along the vertical joints between face slabs 22 and 23, as well as between 25 and 26. When the reservoir was emptied in 2006, a horizontal crack that was 300 m long was found between the second-stage and third-stage slabs, where concrete extrusion and exfoliation was severe and the steel-bar cage was deformed and exposed. Research indicated that the horizontal cracks were mainly caused by the large compression stress along the slope and were related to the separation of the face slab.

2.1.4. Barra Grande CFRD

The Barra Grande CFRD in Brazil [11] has a maximum dam height of 185 m, crest length of 665 m, and normal water level of 647 m. When the water level reached 634 m in September 2005, the leakage rate reached 428 $L\cdot s^{-1}$, face slab rupture occurred in the middle of the vertical joint between slabs 19 and 20, and the damage zone extended to about 100 m underwater. A gap between the face slab and cushion layer was found in the damage zone, with a maximum depth of 12 cm. The leakage rate was as high as 1284 $L\cdot s^{-1}$ in November 2005. Through underwater inspection, face slab rupture along the horizontal direction was found in the middle of the dam height.

The four 200 m CFRDs mentioned above all suffered from problems, including face slab separation, cracks, face slab rupture, waterstop failure, and excessive leakage. The direct cause was excessive settlement and uneven deformation of the rockfill. A deep analysis revealed the following three main reasons:

(1) Low compaction density of the rockfill: Regarding the compaction requirements of the Tianshengqiao-1 Dam, the porosities of the upstream and downstream rockfill were controlled at 22% and 24%, respectively. The lift thickness of the upstream rockfill was 80 cm, with six passes of a 10-ton self-propelled vibratory

roller, while that of the downstream rockfill was 160 cm, with six passes of an 18-ton traction vibratory roller. Both the weight of the vibratory rollers and the number of passes were low, which led to the low compaction density of the rockfill.

(2) Large modulus difference between the upstream and downstream rockfill: For the Tianshengqiao-1 Dam, the modulus of the downstream rockfill was only half that of the upstream rockfill, and for the Aguamilpa Dam, the moduli of the upstream and downstream rockfill had a 5-fold difference, which aggravated the differential settlement between the upstream and downstream rockfill zones.

(3) Unreasonable filling sequence of the section: To retain water in flood season, the priority section of the dam required the filling progress of the upstream rockfill zone to be quicker than that of the downstream rockfill zone. For the Tianshengqiao-1 Dam, the upstream water-retaining section was 123 m higher than the downstream rockfill zone for flood control during the construction period. After the flood season, the downstream rockfill zone was required to rise and level up at a rate of 1 m per day, which caused excessive differential settlement between the upstream and downstream rockfill zones.

2.2. Major successful experiences

The four case studies of high CFRDs with problems indicated that 200 m CFRDs have exceeded the scope of empirical design and should be designed and constructed according to the principle of deformation control. In high CFRDs built after 2000, such as Sanbanxi, Hongjiadu, and Shuibuya, the issues described above have been reduced significantly. The overall operation of these dams is satisfactory, as engineering measures were adopted to control the deformation of the embankment. The major successful deformation control measures are listed below.

2.2.1. Rockfill zoning

For a 200 m CFRD, part of the water load can be transmitted across the dam axis to the downstream rockfill zone. The zoning boundaries between the upstream and downstream rockfill zones of the three dams mentioned above inclined toward the downstream (with slope gradients ranging from 1∶0.2 to 1∶0.5), which expanded the area of the upstream rockfill zone and reduced the impacts of downstream rockfill deformation on the concrete face slab. It was also necessary to reduce the modulus difference and uneven deformation between the upstream and downstream rockfill as much as possible. Special rolling zones (also known as increased modulus zones) were arranged at the upper part of the embankment and in the area near the abutments where the slope was steep. In addition, vertical and horizontal drainage zones were required to keep the dam body above the downstream water level in dry condition.

2.2.2. Compaction of rockfill

Rockfill materials with medium strength and good gradation were required, and the degree of compaction was increased. For the above three dams, the porosity of the upstream rockfill was controlled at 19%–20%. For most projects, 25-ton vibratory rollers were used, with 32-ton vibratory rollers being used for some projects. Impact compaction rollers (with an impact force of 200–250 t) were employed in the Hongjiadu project, and the number of rolling passes was increased. Thus, the degree of compaction of the rockfill was greatly increased. In addition, new technologies such as global positioning system (GPS) real-time compaction quality monitoring and the additional mass method were applied to ensure that the designed compaction requirements were satisfied. The measured data showed that the porosities of the upstream rockfill of the Sanbanxi, Hongjiadu, and Shuibuya CFRDs reached 17.62%, 19.6%, and 19.6%, respectively, and that those of the downstream rockfill reached 19.48%, 20.02%, and 20.7%, respectively. In general, these were 2%–4% lower than those of the Tianshengqiao-1 CFRD [12].

2.2.3. Rockfill filling procedure

Based on the lessons learned from the Tianshengqiao-1 CFRD, attention was paid to combining the filling stages with the control of embankment deformation. The rise of the rockfill upstream and downstream, as well as on the left and right banks, was required to be as balanced as possible. “Upstream side high and downstream side low” was not allowed, and if the situation permitted, “downstream side high and upstream side low” might be adopted in order to mitigate adverse influence on the tensile deformation of the concrete face slab by taking advantage of the rules of embankment settlement development.

2.2.4. Timing of concrete face slab construction

A pre-settlement measure was taken to avoid the peak of rockfill settlement development so that the deformation of the rockfill would not cause structural cracks on the concrete face slabs after its construction. Before face slab construction, a pre-settlement period of about 6 months was generally arranged. The construction of the face slab commenced when the settlement rate was less than 5 mm per month and the top elevation of the first-stage face slab was 20 m lower than that of the rockfill body.

2.2.5. Compression joints between concrete face slabs and waterstop structure

In order to prevent face slab rupture, wide joints that were filled with elastic materials with good deformation absorption capability were set in order to allow deformation between face slabs under compression. In addition to increasing the strength of the concrete, anti-spalling reinforcement was installed in a certain range on both sides of the joint. The height of the copper waterstop at the bottom was also reduced in order to maintain the sufficient effective area of the face slab that bears compressive stress.

The waterstop structure of the joints was evolved into a combination of sealing and self-healing types. In most of the Chinese projects, central sealing could be cancelled on the premise of strengthening surface sealing to improve the reliability of the sealing structure. The bottom waterstop plate was usually made of soft copper; two main kinds of products, GB and SR, were developed for use as self-healing plastic filler.

2.3. Problems exposed

The three typical 200 m CFRDs that were built after 2000 provided successful experience in the engineering technologies of deformation control and, to a certain extent, resulted in a solution for the cracking problem of the face slab. However, regarding the core of deformation control—that is, deformation prediction—a number of key scientific problems in the following aspects have not yet been well resolved.

(1) There is an urgent need for a breakthrough in the theory of numerical analysis and method of dam deformation. Rockfill is a granular material and has complicated mechanical properties. It shows evident nonlinearity, stress-path dependency, dilatancy, creep, and other more complex characteristics such as degradation due to wetting and particle breakage under high confining pressure. At present, the commonly used constitutive models, such as the Duncan-Chang E-B model, the Tsinghua nonlinear uncoupled K-G model, and the Nanshui double-yield surface elasto-

plastic model, are all based on continuum mechanics, which generalize the granular nature of the rockfill material; thus, it is difficult to use these models to completely and accurately describe all the mechanical behaviors of the rockfill.

(2) The scale effects of rockfill material testing have not yet been solved. In CFRD design, ordinary and large-scale laboratory triaxial tests are usually used to obtain the material parameters of the rockfill. However, there are significant differences between material parameters obtained in the laboratory and those of the true rockfill material used in the dam, due to the limited size and loading capacity of the testing equipment. The scale effects often result in a smaller calculated deformation than the measured data for high dams but a larger calculated deformation than the measured data for low dams; this is one of the main reasons for inaccurate deformation prediction for high dams.

(3) The mechanism of face slab rupture has not yet been explained well. According to the results of qualitative analyses, the main reasons are that excessive rockfill deformation leads to closing and compression of the vertical joint; friction between the face slab and underlying rockfill further increases the compressive stress; and the waterstop structure of the vertical joint reduces the effective bearing thickness of the face slab. However, the mechanism of face slab rupture has not been accurately studied, and no quantitative control indices are available.

3. Research advances in 250–300 m CFRDs

Since 2010, due to the need for hydropower development in Western China, further studies on the safety and key technical problems of 250–300 m CFRDs have been performed in the dam industry, especially regarding deformation prediction and control technologies. Numerous innovative research results have been obtained.

3.1. Safety control standards and evaluation methods

Based on summative research on 200 m CFRDs that have been built both in China and abroad, combined with research on four typical projects—Gushui and Rumei on the Lancang River, Cihaxia on the Yellow River, and Maji on the Nujiang River—a summary of safety control principles and standards is proposed, covering flood control, seismic criterion, safety freeboard of dam crest, dam deformation, face slab deformation and stress, joint deformation, slope stability, dam seepage, and so forth, in order to provide a reference for the safety evaluation and control of 250–300 m CFRDs [13].

In addition to deterministic assessment methods, risk analysis methods have been applied to the risk identification and analysis of typical high CFRDs. The probability characteristics of the variability of shear strength and Duncan-Chang E-B model parameters have been analyzed. Using these parameters, the deformation reliability indices of typical CFRDs at completion and during water storage are calculated to be 2.223 and 2.016, respectively, and the reliability index of face slab deflection during the impounding period is 1.766 [14]. The study suggests that for 250–300 m rockfill dams, the reliability index of slope stability in normal operation conditions requires 4.7 (the corresponding failure probability is 10^{-6}), which is roughly equivalent to a factor of safety of 1.7 [14].

3.2. Material and section zoning

The heights of the above-mentioned four typical dams (Gushui, Rumei, Cihaxia, and Maji) range from 240 m to 315 m. The design uses medium- to high-strength rock (or sand gravel) materials with good gradation that are compacted with high density. The recommended range of the dam slope is 1:1.4–1:1.7, which is gentler than that of the 200 m CFRDs. Considering the specific construction conditions of each project, compaction requirements of the rockfill for 300 m CFRDs are proposed. The porosity of the rockfill should be 17%–20%, and the relative density of the sand gravel materials should be 0.95–0.98. The porosities of upstream and downstream rockfill will be controlled at 18% for the Gushui CFRD, 19% for the Rumei CFRD, and 19%–20% for the Maji CFRD. The relative density of the upstream sand gravel of the Cihaxia CFRD will be controlled at 0.95 and the porosity of the downstream rockfill will be controlled at 17%. Compared to their 200 m CFRD counterparts, the compaction requirements for these four CFRDs are generally increased. Taking the Gushui CFRD as an example, the typical material zoning profile is shown in Fig. 1.

It is worth mentioning that the upper reservoir CFRD of Jiangsu Liyang Pumped Storage Power Station used 25-ton vibratory rollers and had a rolling layer thickness of 60–80 cm. The porosities of the increased modulus zone and the upstream and downstream rockfill zones reached 16.8%, 18%, and 18.6%, respectively. Therefore, the designed compaction requirements of the above four CFRDs could be achieved with current construction technologies.

3.3. Material testing technology

In order to focus on the scale effects of rockfill material testing, exploratory comparative studies have been performed using various approaches, such as large-scale laboratory experiments, *in-situ* field tests, and numerical rockfill shear tests.

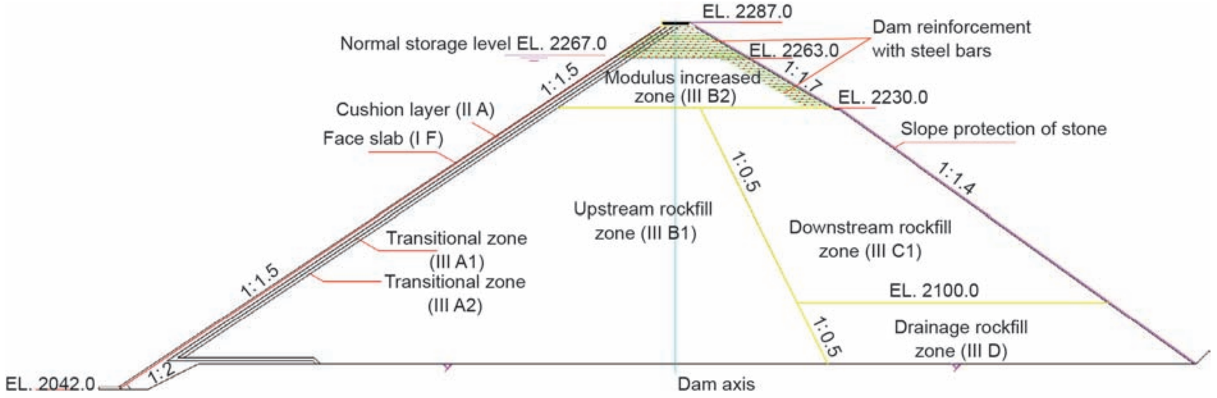

Fig. 1. Material zoning profile of the Gushui CFRD (unit: m).

(1) Large-scale laboratory experiments: The four hydropower projects conducted large-scale indoor triaxial shear test (with a specimen diameter of 300 mm). The mechanisms and deformation properties of the rockfill material were systematically analyzed, including the stress-strain relationship, strength characteristics, scale effect, grain breakage, creep deformation behavior, and so forth.

To further reduce the scale effects of indoor test, the China Institute of Water Resources and Hydropower Research (IWHR) and some other research institutes are developing 1500-ton triaxial testing equipment, which will increase the diameter of the test specimen from 300 mm to 1000 mm, thereby laying a foundation for future research on indoor scale effects.

(2) Field tests: The maximum rockfill particle size of a high rockfill dam is 600–800 mm; therefore, it is necessary to perform large-scale tests in the field. Combined with field compaction tests on dam construction materials, compression tests with the original grain size have been conducted in a tunnel (Fig. 2) for the Cihaxia project. The maximum pressure is 6 MPa, with a bearing plate area of 1.72 m^2 and a maximum load of 10 320 kN [15].

(3) Numerical rockfill shear tests: Recently, many researchers have used discrete element methods to simulate the mesoscopic structure of rockfill and perform numerical experiments (Fig. 3). With numerical experiments, extensive sensitivity analyses can be performed and the mesoscopic structure evolution of rockfill can be revealed, providing an effective means for the study of mesoscopic mechanical behaviors of rockfill and scale effects.

(4) A new exploration of the mechanism of the scale effects of rockfill: Factors of the scale effects of rockfill include the method of grain size reduction, compaction requirements, particle properties, and so forth.

Using mesoscopic numerical models, numerical shear tests were performed on the rockfill materials of the Gushui, Rumei, and Cihaxia projects. The results show that, compared with laboratory test results, the deformation parameters of the Duncan-Chang E-B model, i.e., k, n, and k_b, all decrease with an increase of specimen size. For the rockfill of Gushui and Rumei, the values of k and k_b decreased by 10%–17% and 17%–19%, respectively, while for the downstream rockfill of Cihaxia, these values decreased by 25% and 29%, respectively, indicating significant scale effects. For the upstream sandy gravel material of Cihaxia, the values of k and k_b decreased by 4% and 10%, respectively, indicating relatively small scale effects [15]. In addition, the scale effects of the rockfill increase with an increase of confining pressure and rock strength. However, the laboratory triaxial tests (with a maximum diameter of 300 mm) show that the deformation parameters of rockfill increase with an increase of specimen size.

Recent studies [15] presented two size-related mesoscopic mechanisms for particle breakage in rockfill. One is that large particles are easily broken, resulting in the deformation modulus parameters of large specimens being smaller than those of small specimens; the other is that the interlocking of large particles is stronger than that of small particles, resulting in the deformation modulus parameters of large specimens being larger than those of small specimens.

We think that these two mechanisms coexist and act alternatively. The rockfill structure is subjected to confining pressure due to the influence of vibratory compaction, rockfill gravity, and water load. When the confining pressure is relatively low, the interlocking of rockfill particles (the skeleton effect) maintains the stability of the structure; when the confining pressure increases beyond the bearing capacity of the rockfill structure, rockfill particles break and the structure changes and evolves into a new stable state; these two actions repeat alternatively until the rockfill structure reaches a stable equilibrium state. In the above process, the contrast between the interlocking and breakage of rockfill particles determines the scale effects.

For modern high CFRDs, rockfill particle breakage will unavoidably occur during the compaction process due to the employment of heavy rolling equipment. During the construction and impounding periods, secondary particle breakage will occur under the combined action of rockfill gravity and the water load, and material degradation caused by wetting will further aggravate rockfill particle breakage and then increase dam deformation. Thus, the effect of rockfill particle breakage is stronger overall than the skeleton effect. Currently, due to limited specimen size, laboratory triaxial tests have difficulty reproducing the real working status of rockfill materials in high CFRDs. This explains why the monitored deformations of high dams are greater than the calculated predicted values, and why the actual deformation parameters of rockfill materials in high dams are lower than those obtained from laboratory triaxial tests.


Fig. 2. Testing device for a tunnel compression test (Cihaxia).

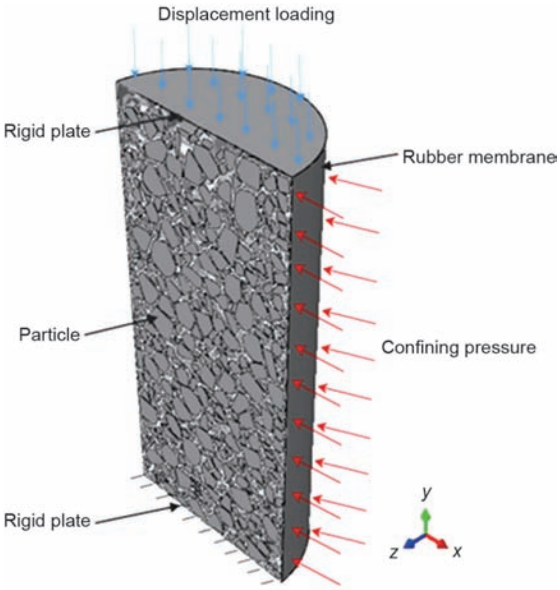

Fig. 3. Schematic diagram of a mesoscopic numerical shear test.

3.4. Constitutive models of rockfill and numerical simulation methods

Based on studies of the engineering properties of rockfill materials and the concept of crushing energy, a constitutive model that can reasonably describe the volumetric deformation of rockfill was obtained by modifying the tangent volume ratio in the Nanshui double-yield surface elasto-plastic model. By analyzing existing rockfill material testing data, a generalized plastic constitutive model of rockfill was established with directly defined plastic flow direction, loading direction, and plastic modulus. Based on large-scale laboratory tests, a nonlinear model for the interface between rockfill and the concrete face slab, along with a corresponding computation method, was developed. A refined modeling method was proposed to simulate the construction process and the detailed structure of the face slab, and a refined simulation of the deformation and stress of high CFRDs was achieved through large-scale parallel computing [16].

3.5. Exploration of the stress deformation laws of ultra-high CFRDs

Using computational models of standard CFRDs, the stress and deformation characteristics of typical 200–300 m high CFRDs were systematically analyzed. The results show that the deformation of the embankment and face slab will be roughly doubled as the dam height increases from 200 m to 300 m, and the stresses in the rockfill and face slab will also increase significantly [16].

Through refined simulation, it was found that the stress and deformation distributions of the four high CFRDs, that is, Gushui, Cihaxia, Rumei, and Maji, comply with the general laws of high CFRDs. For the Gushui and Cihaxia CFRDs, due to their slightly lower dam heights, the total dam deformation can be controlled at a level that is roughly equivalent to that of a 200 m CFRD, provided that certain deformation control measures are taken to ensure dam safety. However, for the Rumei and Maji CFRDs, due to their relatively large dam heights, stresses in the concrete face slab will be larger after reservoir impounding, and measures to improve stresses in the face slab should be further studied.

3.6. Exploration of the mechanism of concrete face slab rupture

Recent studies have shown that the macroscopic factor of face slab rupture along vertical joints in high CFRDs is excessive rockfill deformation, and that the direct cause is the translational compression and rotational extrusion of face slabs along the vertical joint [16], as shown in Fig. 4. In addition to excessive deformation of the rockfill, local bending deflection of the face slab is a reason for the rupture of the face slab near horizontal joints [17].

The latest research results indicate that, since materials of the cushion, transitional, and rockfill zones are all granular materials, their mechanical behavior has distinct discontinuous, inhomogeneous, and anisotropic characteristics; therefore, their deformation should be divided into two parts: macroscopic deformation and mesoscopic deformation. Macroscopic deformation—that is, deformation on the dam scale—can be evaluated with constitutive models describing macroscopic mechanical behaviors. Mesoscopic deformation—that is, deformation on the particle scale—requires mesoscopic mechanical models to describe it. The non-uniform contact force among the face slab, cushion, and transitional zones is one of the factors in the local compressive damage of the face slab, while the particle size distribution and the thickness of the cushion and transitional zones affect the local state of stress in the face slab. The mesoscopic process of force transmission from the face slab through the cushion to the transitional zone was simulated using the particle discrete element method, and it was found that the inhomogeneity of the contact force decreases with an increase in thicknesses of the cushion and transitional zones. Taking the Gushui CFRD as an example, as the minimum thicknesses of the cushion and transitional zones increase above 2 m and 4 m, respectively, the non-uniform coefficient of the contact force between the face slab and cushion tends to converge.

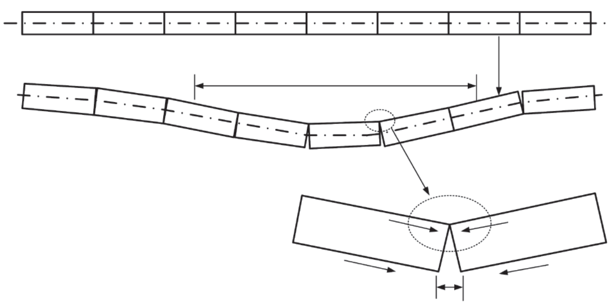

Fig. 4. Translational compression and rotational extrusion.

3.7. Seepage stability and control standards

As the second defensive line of the seepage control system of the dam, the design principle of the cushion is that seepage failure shall not occur, even if the face slab is completely destroyed. A permeability coefficient that has an order of magnitude of $10^{-4}\,\mathrm{cm{\cdot}s^{-1}}$ is recommended for the cushion materials used in 300 m high CFRDs. Based on experimental studies, the particle size distribution of cushion materials is suggested as follows, as shown in Fig. 5: $d_{\max}$ = 40–100 mm, the content of fine grains with $d < 5$ mm should be between 35% and 50%, the content of fine grains with $d < 1$ mm should be between 20% and 32%, and d_{20} = 0.35–1 mm. Considering construction quality uniformity, dam deformation, and allowable hydraulic gradient, the horizontal width of the cushion in a 300 m high CFRD should be no less than 5 m [16]. The transitional zone shall function as a filter zone to the cushion and shall be designed according to the filter criteria.

3.8. Anti-seismic engineering measures

A number of comprehensive strengthening measures for earthquake resistance have been proposed, such as designing a reasonably complex layout, selecting a solid dam foundation and stiff dam construction materials, reserving the dam crest free-

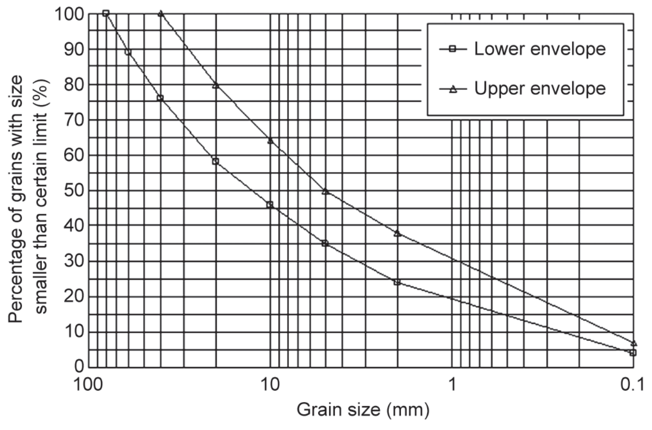

Fig. 5. Recommended particle size distribution of cushion materials used in 300 m CFRDs.

board, decreasing the dam slope on the top, reinforcing the upper dam slope, using concrete frame beams, and strengthening the face slab and sealing structure. Plans for the Gushui Dam take measures such as using a gentle slope at the upper part of the downstream slope and reinforcing the dam crest with steel bars (Fig. 1). Recently, the Dalian University of Technology proposed a measure for the release of dynamic stresses of the face slab during an earthquake: the placement of local, permanent horizontal joints shown in Fig. 6. A reasonable and effective region for the placement of horizontal joints was determined through a dynamic stress response analysis of the face slab [18]. The suggested area is $0.75H$–$0.85H$ (where H is the maximum dam height) in elevation, with an allowed extension of $0.05H$ and a horizontal length of $0.3L$ (where L is the length of the dam axis). In addition, it is suggested that concrete with added steel fiber should be used in high dynamic stress zones of the face slab in order to improve its crack-resistance capacity during an earthquake.

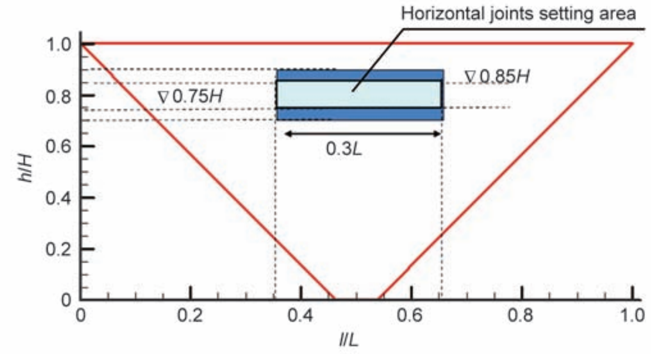

Fig. 6. Schematic diagram of placement of horizontal joints.

3.9. New safety monitoring techniques

Because of their inherent drawbacks and limited installation techniques, it is difficult to use the inner deformation monitoring techniques and apparatus for 200 m CFRDs to meet the requirements of 300 m high CFRDs. A number of new technologies have been studied for the safety monitoring of 300 m high CFRDs, such as interferometric synthetic aperture radar (InSAR) deformation monitoring technology, pipeline robots, flexible inclinometers, and monitoring galleries in earth-rockfill dams [19].

InSAR is a combination of microwave imaging remote sensing and interference techniques. It can accurately measure the three-dimensional spatial position of earth surface targets and small deformation along the radar sight line and achieve a wide range of continuous coverage. Therefore, its application to the surface deformation monitoring of 300 m CFRDs is promising. A flexible inclinometer is composed of multiple series-connected inclinometers. The deformation of the structure being monitored at an arbitrary position along the sensor can be obtained from the relative spatial coordinates of the peak of each inclinometer with respect to its base, by measuring the inclination of each axis. The instrument's accuracy can satisfy the monitoring requirements of 300 m high rockfill dams. Combining computer vision technologies and joint width measurement techniques, pipeline robots can monitor horizontal displacement inside a dam. Monitoring galleries in rockfill dams are convenient for inner deformation observation, maintenance, and the replacement of monitoring instruments, as well as for the placing and protection of cables in the dam.

4. Conclusions

Over the past decades, China has obtained successful experience in the construction of 200 m high CFRDs. Recently, systematic studies have been performed on the adaptability and key safety construction technologies of 250–300 m ultra-high CFRDs. Abundant and innovative results have been achieved, which demonstrate the safety of 250 m ultra-high CFRDs and the effectiveness of related engineering measures. Subsequent studies will focus on constitutive models of rockfill and scale effects, dam stress and deformation analyses based on mesomechanics, the transmission mechanism of non-uniform deformation in the cushion and transitional zones, the mechanism of face slab extrusion damage and control measures, large-scale testing technologies, and practical safety monitoring instruments for 300 m dams.

With the progress of preliminary research on the Gushui and Cihaxia projects, China's high CFRD technology is achieving a breakthrough from 230 m to 250 m. We believe that, with a combination of practice, study, and research, along with stepwise advancement, China will achieve successive breakthroughs from 230 m to 250 m, then from 250 m to 270 m, and will finally construct and operate 300 m ultra-high CFRDs safely.

Compliance with ethics guidelines

Hongqi Ma and Fudong Chi declare that they have no conflict of interest or financial conflicts to disclose.

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