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Major Technologies for Safe Construction of High Earth-Rockfill Dams

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ABSTRACT

The earth-rockfill dam is one of the primary dam types in the selection of high dams to be constructed in Western China, since it is characterized by favorable adaptability of the dam foundation; full utilization of local earth, rock, and building-excavated materials; low construction cost; and low cement consumption. Many major technical issues regarding earth-rockfill dams with a height of over 250 m were studied and solved successfully in the construction of the 261.5 m Nuozhadu earth core rockfill dam. This paper describes research achievements and basic conclusions; systematically summarizes the accumulated experiences from the construction of the Nuozhadu Dam and other high earth-rockfill dams; and discusses major technical issues, such as deformation control, seepage control, dam slope stability, safety and control of flood discharging, safety and quality control of dam construction, safety assessments, early warning, and other key technical difficulties. This study also provides a reference and technological support for the future construction of 300 m high earth-rockfill dams.

1. Introduction

Although Western China is rich in hydropower resources, these are located in an area with high mountains and valleys, complicated topographical and geological conditions, and inconvenient access conditions. The earth-rockfill dam has significant advantages for this region, since it is characterized by a favorable adaptability of the dam foundation, full utilization of local materials and building-excavated materials, low construction cost, and low cement consumption. Therefore, the earth-rockfill dam is one of the most promising dam types in dam construction.

Earth-rockfill dam construction has only recently begun, but is developing rapidly in China. In 2001, the Xiaolangdi inclined clay core rockfill dam was built with a maximum dam height of 160 m, and in 2009, the Pubugou gravel-earth core rockfill dam was built with a maximum dam height of 186 m. At the end of 2012, the Nuozhadu gravel-earth core rockfill dam was built with a maximum dam height of 261.5 m, making it the highest earth-rockfill dam in China and the third highest earth-rockfill dam worldwide. The key features of the Nuozhadu Hydropower Project are as follows: It has a total filling volume of 3.432×10^7 m^3, an installed capacity of 5850 MW, an average annual energy output of 23.9 TW·h, and a total reservoir storage capacity of 2.37×10^{10} m^3. The Nuozhadu Dam represents the highest level of earth-rockfill dam construction in China today. In the process of constructing this project, many major technical difficulties were studied and solved.

The Changheba gravel-earth core rockfill dam is now under construction. This is one of the most complex earth-rockfill dams under construction in China, with a maximum dam height of 240 m, a total filling volume of 3.457×10^7 m^3, and a 50 m thickness overburden at the core wall foundation. As of April 2016, 92% of the total filling volume had been completed for the Changheba Dam. With the increased development of hydropower resources in Western China, some higher dams will be constructed in the near future, such as Shuangjiangkou (with a dam height of 314 m), Lianghekou (with a dam height of 295 m), and Rumei in Tibet (with a dam height of 315 m). These 300 m high dams are a challenge to the construction technology of earth-rockfill dams.

This paper summarizes the successful experiences in the construction of Nuozhadu Dam and other typical high earth-rockfill dams, and provides solutions for deformation control, seepage

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control, dam slope stability, safety and control of flood discharging, safety and quality control of dam construction, safety assessment, early warning, and other key technical difficulties for high earth-rockfill dam construction. This article describes research achievements and basic conclusions, and provides a reference and technological support for the future construction of 300 m high earth-rockfill dams.

2. Deformation stability and control of high earth-rockfill dams

Deformation stability and control is the core issue for high earth-rockfill dam construction. The operation of several existing high earth-rockfill dams has demonstrated that deformation, impervious body cracking, and dam seepage are the most important factors affecting the operational safety of the dam. The key technologies involved in the deformation stability and control of a high earth-rockfill dam include: test technology for dam material properties, the modification of earth materials for the core wall, constitutive models of the rockfill material, dam deformation calculations, dam body structure and zoning, crack calculation, and analysis and control.

2.1. Test technology for dam material properties

The necessary test items for the construction materials of a high earth core rockfill dam were determined by the laboratory test, field test, and numerical simulation test done for the Nuozhadu Hydropower Project. Moreover, the number of test groups was suggested through research on the relation between test groups and the deviation of test results (Fig. 1).

In recent years, the granular discrete element method and other numerical methods have been used to simulate the microscale grain composition of rock material. Many sensitive analyses can be conveniently done with numerical tests, and the evolution process of microscale rockfill composition can be observed. These numerical tests provide an effective means of research on the mechanical behaviors and scale effect of rock materials at the microscale level.

2.2. Modification of earth materials for the core wall

Natural impervious soil materials should be modified in order to meet the requirements for seepage prevention, deformation, and strength for the core wall of a high earth-rockfill dam.

There are two main modification methods: ① For the natural earth material with too much clay and low mechanical property, modification by blending gravel manually is a method that has been adopted for Nuozhadu, Shuangjiangkou, Lianghekou, and other projects; and ② for the earth material with too much gravel and a low water content, modification by the manual removal of oversized gravel and the addition of water is the other method that has been adopted for Changheba, Pubugou, Rumei, and other projects. Aside from these two methods, modification may also be conducted by blending different earth materials that are naturally available nearby the damsite. For example, for the Changheba Project, modification is done by blending coarse material (continuous graded gravel earth with a P_5 gravel content of 50%–65%) and fine material (continuous graded gravel earth with a P_5 gravel content less than 35%). This modification process is simple, and permits the full use of locally available earth materials. Any modification method should ensure that the earth materials for the core wall have a good gradation curve and proper gravel content. Based on numerous tests and engineering practices for Nuozhadu, Changheba, and other projects, it is suggested that the P_5 gravel content of earth materials for the core wall be 30%–50% [1] for 200–300 m high earth-rockfill dams.

For the Nuozhadu Project, the designed gravel content of the earth material for the dam core wall was 35%, and the measured average P_5 gravel contents were 36.1%, 36.2%, and 34.1%, respectively, in rolling at three stages. For the Changheba Project, the results of a field inspection on earth materials for the core wall show that the average gravel content is 44.4%, with a maximum content of 56.1% and a minimum content of 32.2%.

2.3. Constitutive models of rockfill materials and dam deformation calculation methods

An analysis and comparison was performed of common constitutive models, such as the Duncan-Chang EB, Tsinghua KG, and Shen Zhujiang double-yield surface elastic-plastic models. A modified Rowe dilatation equation for a rockfill body was put forward, and the Shen Zhujiang double-yield surface model was improved in order to make the calculation results more reliable (as shown in Fig. 2). Based on practical experience with several high earth-rockfill dams in China, the Duncan-Chang EB model is sug-

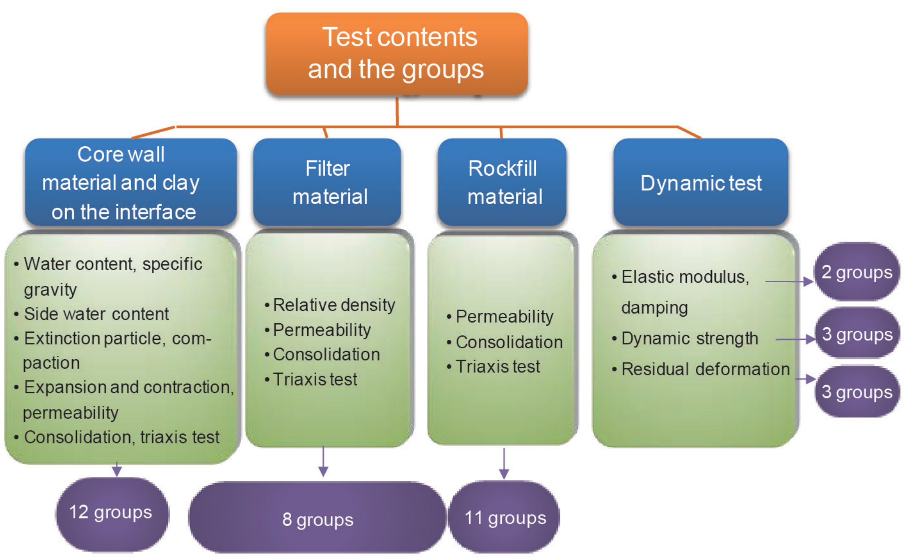

Fig. 1. Suggested test items and groups for dam materials for high earth core rockfill dams.

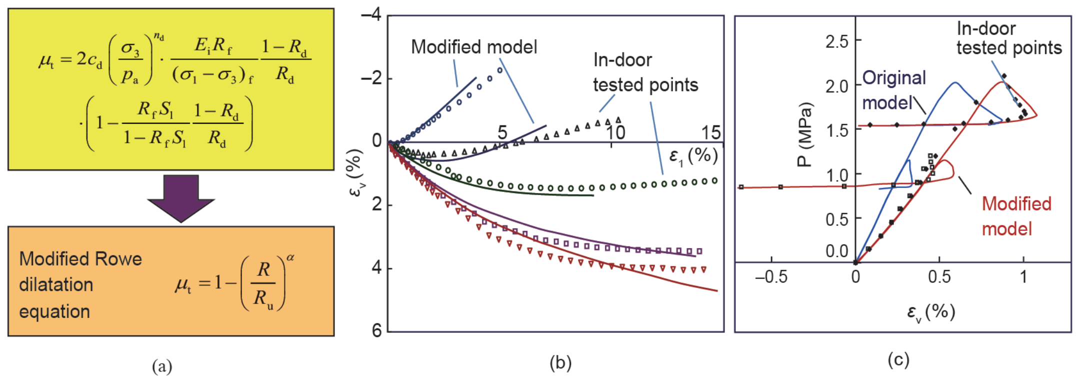

Fig. 2. The modified Shen Zhujiang double-yield surface elastic-plastic model. (a) Modification of the dilatation equation; (b) comparison with the test results of the main rockfill material for the Nuozhadu Project; (c) a complicated stress path.

gested as the basic model for stress and deformation calculations for dams, with the adoption of one or two other models for comparison and verification. The improved Shen Zhujiang double-yield surface elastic-plastic model [1] is recommended as one of the verifying models.

Since the current constitutive models of rockfill materials are limited, and the parameters of dam materials are inaccurate, a inverse analysis may be adopted to modify the calculation model and the parameters. A inverse analysis system for the deformation of a high earth-rockfill dam was built based on the Nuozhadu Project, the artificial neural network model, and the finite element method. Duncan-Chang EB model parameters, rheological parameters, and humidification deformation parameters for dam materials may be obtained by a inverse analysis, and an analysis and prediction of dam deformation may then be conducted using the parameters from the inverse analysis (as shown in Fig. 3).

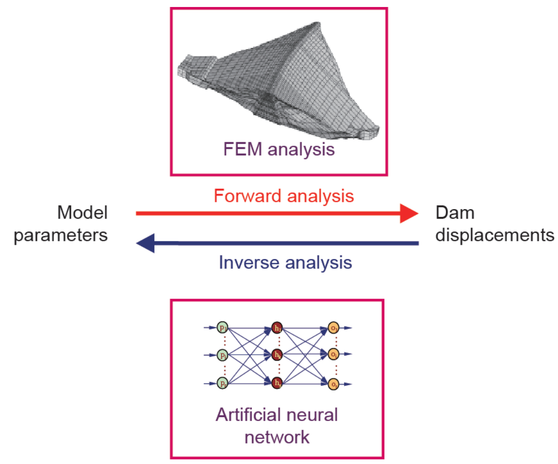

Fig. 3. Inverse analysis procedure for embankment dam deformation. FEM: finite element method.

2.4. Principle of deformation control

The practical experience with high earth-rockfill dam projects in recent years, both at home and abroad, has demonstrated that the measured settlement deformation of most 200 m high earth-rockfill dams exceeds 1% of the maximum dam height. Deformation control for earth core rockfill dams should follow the principle of controlling overall deformation and coordinating the deformation of core and shell materials, according to the actual conditions of projects. To mitigate the arch effect of rockfill materials of the dam shell on the core, increasing the deformation modulus of the earth materials for the core is suggested so as to control the modulus difference between the earth materials for the core and the rockfill of the dam. Based on practical experience with Nuozhadu and other projects, the average median *K* of the deformation modulus of earth materials for the core should be greater than 350.

2.5. Dam structure

Among the 200 m earth core rockfill dams at home and abroad, six dams adopted a vertical core wall and five dams (including the unfinished Rogun Dam) adopted an inclined core wall [1]. An inclined core wall can effectively reduce the arch effect, although it carries great construction difficulty and a high cost. Given suitable topographical and geological conditions, a vertical core wall is recommended because it is characterized by convenient construction, relatively low cost, and good seismic safety. Most earth core dams with a height over 200 m have dam slopes that are 1∶2.2 to 1∶2.6 upstream and 1∶2.0 to 1∶2.2 downstream (with the exception of the Nuozhadu Project). For earth core dams above 200 m, rockfill materials without soft rock have been adopted for the upstream dam shell (with the exception of the Nuozhadu Project). Most of these dams have been built on bedrock (with the exception of the Changheba Project).

The maximum dam height and crest width of the Nuozhadu earth core rockfill dam are 261.5 m and 18 m, respectively. Based on research and verification, the upstream and downstream dam slopes are 1∶1.9 and 1∶1.8, respectively, resulting in a more economical design. The core is vertical, with a top width of 10 m and an upstream and downstream slope of 1∶0.2 (Fig. 4). It has been verified that it is feasible to place rockfill material containing some soft rock (an actual filling volume of 4.78×10^6 m^3) in a carefully chosen location within the upstream zone of the dam shell. In this way, the utilization rate of the building-excavated materials is improved and the project cost can be lowered significantly. This discovery may be useful for subsequent projects.

For the Changheba earth core rockfill dam, the maximum dam height, crest width, and both upstream and downstream slopes are 240 m, 16 m, and 1∶2, respectively. The earth core is vertical, with a top width of 6 m, and upstream and downstream slope ratios of 1∶0.25 (Fig. 5). The dam is built on a deep overburden; the overburden at the core wall zone is about 50 m thick after excavation. Therefore, special requirements for seepage prevention have been taken into consideration for dam zoning. In addition to setting filter zones upstream and downstream of the core wall, two horizontal filter zones with a thickness of 1 m have been set downstream of the foundation cut-off wall at the bottom of the core wall in order to connect the filter zone downstream of the core wall. Filter zones [2] with a thickness of 1 m have been set between the transition zone and the riverbed overburden, and between the rockfill zone and the riverbed overburden downstream of the core wall.

2.6. Crack calculation, analysis, and control

The mechanical mechanism and judgment method of crack occurrence in an earth-rockfill dam are difficult to determine, but deformation inclination may be adopted as the judgment basis of crack occurrence in an earth-rockfill dam. A deformation inclination finite element method was developed during the Nuozhadu Project and based on the finite element deformation calculation. The results of geotechnical centrifuge model testing show that the critical inclination of an earth-rockfill dam is about 1% [1].

Based on the Nuozhadu earth core dam, systematic tests of tensile characteristics were performed, tensile fracture characteristics and mechanisms of soil materials for the core wall were discussed, and a compressive strength criterion and constitutive model for the clay of the core wall were put forward. In addition, an element-free method based on the smeared crack model was proposed for the clay of the core wall, and a 3D calculation program system coupling the element-free method and the finite element method for tensile cracking of an earth-rockfill dam was developed (Fig. 6) [1].

3. Major technologies for seepage control in high earth-rockfill dams

Seepage stability and control is a core safety issue in the construction and operation of high earth-rockfill dams. Based on an in-depth geological and hydrogeological engineering investiga-

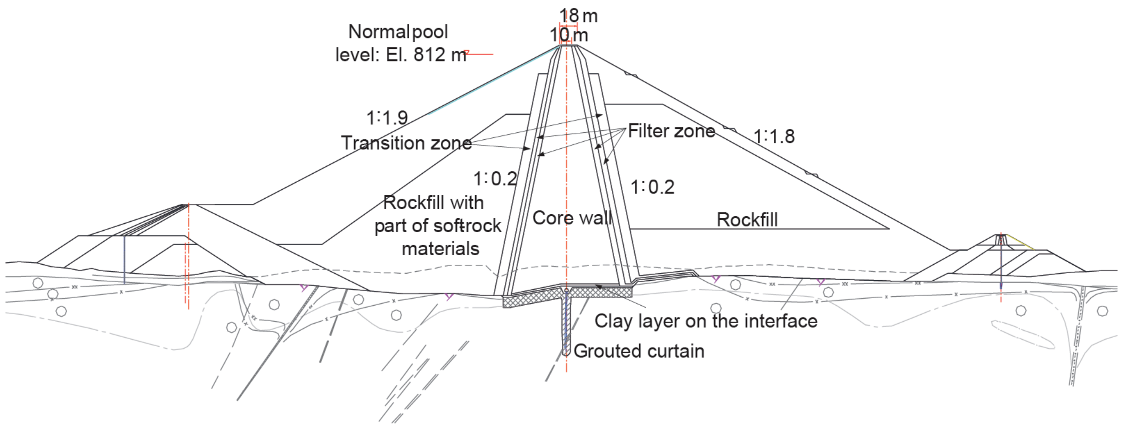

Fig. 4. A typical cross-section of the Nuozhadu Dam.

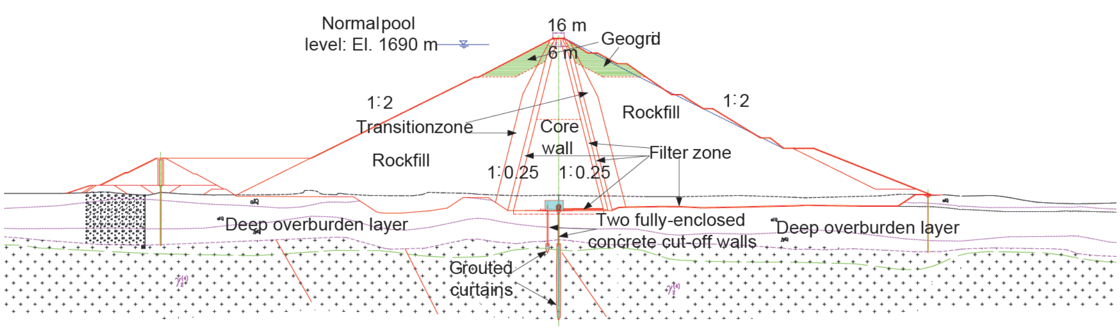

Fig. 5. A typical cross-section of the Changheba core rockfill dam.

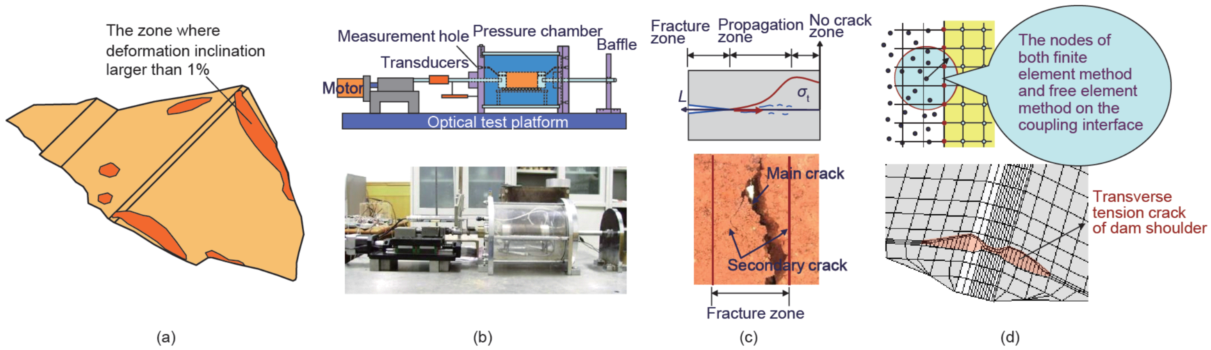

Fig. 6. Crack calculation, analysis, and judgment for earth-rockfill dams. (a) The deformation inclination finite element method; (b) triaxis tensile equipment; (c) the fracture mechanism; (d) the simulation calculation program system.

tion, it is suggested that seepage control for high earth-rockfill dams be fulfilled in accordance with the principle of "integrated control, organic combination, and optimal allocation" in order to properly control the seepage indexes of all zones. In addition, special research into and control of dam foundation seepage should be performed for high earth-rockfill dams that are built on a deep overburden.

3.1. Key technical indexes of seepage control

Seepage control data have been collected from 58 domestic and overseas earth-rockfill dams [1], and key indexes for the seepage control of zones are recommended, as summarized below.

Since the core is the main consideration in seepage prevention, the permeability coefficient of the core material should be controlled at a magnitude of 10^{-6} cm·s^{-1}, and the average allowable seepage gradient should be about 2.5. Because the curtain is a key measure in seepage prevention for the dam foundation and bank slope, its permeability should be no more than 3 Lu, and the permeation resistance of the grouted rock mass should be about 30. The filter zones, which serve as an important defense, need to be verified by testing, and make the core wall have a permeation gradient resistance of above 100. The protection range of the filter zones should be 0.33H (where H is the water head) for the dam foundation overburden, and 0.5H to H for the fault and soft rock foundation. This range should be further enlarged for a foundation on a deep overburden. Continuous gradation material should be required for the transition zones, with a maximum grain size not exceeding 300 mm, and a transition zone top width greater than 3 m. The permeability coefficient should generally be greater than 1×10^{-3} cm·s^{-1}. For rockfill zones, the permeability coefficient should not be less than that of the outermost filter or transition zone, and should generally be greater than 1×10^{-2} cm·s^{-1} so as to ensure quick drawdown of the seepage line. For drainage zones, a rock material that is composed of high-strength and weatherproof medium- to large-sized rubble should mainly be adopted, with a permeability coefficient of around 1 cm·s^{-1}, which is the greatest permeability coefficient of all the zones. Moreover, the upstream slope protection should not only prevent reservoir water scouring, but also ensure quick drainage, and the downstream slope protection should prevent rainwater scouring.

For the Nuozhadu Dam, *in situ* permeability tests of earth materials were carried out during the rolling of the core wall. The test results showed that the permeability coefficient of the earth materials ranged from 2.02×10^{-7} cm·s^{-1} to 8.47×10^{-6} cm·s^{-1}, with an average value of 4.05×10^{-6} cm·s^{-1}.

For the Changheba Dam, the results of seepage deformation tests of the earth core are as follows: The average permeability coefficient is 2.07×10^{-6} cm·s^{-1}, with a minimum value of 1.54×10^{-7} cm·s^{-1} and a maximum value of 8.8×10^{-6} cm·s^{-1}, and the average failure gradient is 7.22, with a minimum value of 2.71 and a maximum value of 9.9.

3.2. Hydraulic fracture mechanism and numerical simulation

Research on the arch effect and on the hydraulic fracture mechanism of the core wall, based on the Nuozhadu Dam, indicated that the weak infiltration plane is the main cause for a hydraulic fracture of the core, and revealed the hydraulic fracture mechanism of the core wall. A calculation model for the hydraulic fracture of the core wall and a finite element algorithm [1] for the expansion process were established by combining the smeared crack theory with Biot's consolidation theory (Fig. 7).

3.3. Seepage prevention technology for a dam foundation on a deep overburden

Seepage prevention technology for a high earth-rockfill dam foundation on a deep overburden has been researched and practiced in the Changheba Project, and includes the following measures: setting two fully enclosed concrete cut-off walls at the dam foundation overburden beneath the core wall; grouting impervious curtains for strongly pervious bedrock at both banks and at the bottom of the cut-off walls; and placing filter zones in the downstream transition zone of the core wall and between the rockfill zone and the riverbed overburden in order to strengthen the protection of the overburden against seepage damage (Fig. 5).

The main technical parameters of the cut-off wall and the impervious curtain of the Changheba Project are as follows. The main impervious plane is constituted by the dam axis and the plane of the main cut-off wall. The bedrock above the main impervious plane, with a permeability of no more than 3 Lu, is taken as the limit of the relatively impervious layer, and the grout curtains penetrate into the relatively impervious layer for 5 m. There are two rows of the main impervious curtains, which have a hole spacing of 2 m. For the curtains grouted by pipe laying beneath the main cut-off wall, the row spacing is 1 m, and for the curtains on both banks, the row spacing is 1.5 m. The auxiliary cut-off wall is set in front of the main cut-off wall, and the net distance between both walls is 14 m. To mitigate seepage around both banks and to increase the proportion of the head that is borne by the auxiliary cut-off wall, a grout curtain (with a depth of about 30 m) was adopted for a strongly pervious rock mass within the plane of the auxiliary cut-off wall, and a connecting curtain (with a depth of about 40 m) was set between the two cut-off walls, with two rows of grout curtains and a hole spacing of 2 m.

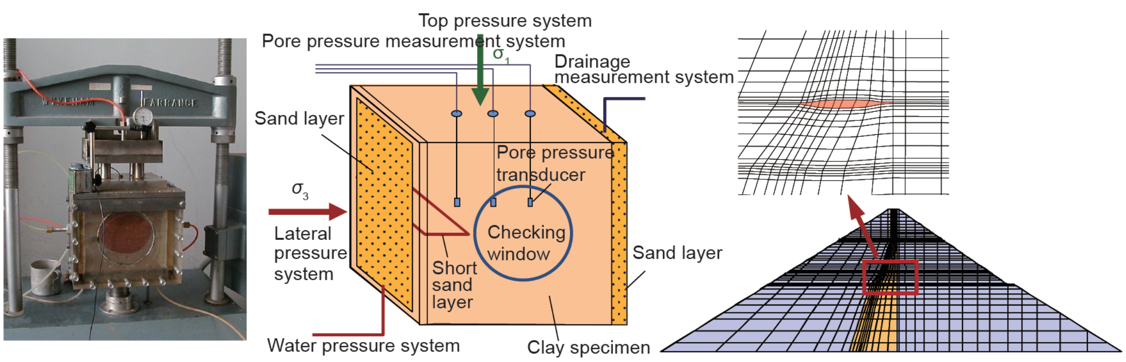

Fig. 7. Model test and numerical simulation for hydraulic fracture.

4. Major technologies for slope stability against sliding and seismic performance of high embankment dams

Since the earth and rock materials used for earth-rockfill dams are granular, a high proportion of dam failures are due to dam slope instability. Therefore, it is necessary to research the dam slope stability of an earth-rockfill dam, and particularly the response of the dam slope to an earthquake. The key technical issues of slope stability analysis and seismic performance of a high earth-rockfill dam include: the suggested value of the factor of safety for dam slope stability, the rationality and applicability of the non-linear strength indexes of the dam materials, static/dynamic slope stability analysis methods, a safety control standard for permanent deformation by earthquake, and seismic reinforcement measures.

4.1. Safety factor of dam slope

Current Chinese codes specify that the safety factor of slope stability for a Class 1 earth-rockfill dam is 1.5, and that the corresponding target reliability index is 4.2 (with a failure probability of 1.33×10^{-5}). However, this safety factor is only applicable to earth-rockfill dams below 200 m. The literature [3,4] contains an analysis and a demonstration of built-up and planned projects with a construction height above 200 m. For normal operating modes, it is suggested that target reliability indexes may be 4.45 (with a corresponding failure probability of 5×10^{-6}) for the slopes of 200–250 m high earth-rockfill dams, and may be 4.7 (with a corresponding failure probability of 10^{-6}) for the slopes of earth-rockfill dams that are higher than 250 m. These indexes may be under the same risk control standard, with a minimum safety factor of 1.6 and 1.7, respectively, for slope stability against sliding.

4.2. Rationality and applicability of the non-linear strength of rockfill materials

Many tests have demonstrated that rockfill and other coarse granular materials suffer from grain breakage, lower internal friction angle, and downward bending of the Mohr strength envelope (Fig. 8) with an increase of confining pressure. In addition, in dam slope stability analyses, a critical slip surface with practical physical significance cannot be found using linear parameters, while non-linear parameters can reasonably reflect the actual sliding and safety state of the dam slope. Thus, it is suggested that non-linear strength parameters be adopted for the analysis of dam slope stability. The average of the lower half values of the specified groups should be used as non-linear indexes. In this way, the standard for the allowable safety factor of dam slope stability that is specified in the current Chinese codes can be used directly, without adjustment.

4.3. The key factor for dam slope stability: Dynamic stability against sliding

The key factor for maintaining dam slope stability is the dynamic slope stability under seismic action. There are four common methods for analyzing dynamic slope stability; of these, the quasi-static method is generally used. Hence, abundant engineering experience in this method has been accumulated, and this is the main calculation method used to carry out the seismic stability analysis for an earth-rockfill dam. Aside from this method, the finite element method, strength-reduction method, and Newmark sliding block method have also been advanced; however, those methods lack a corresponding safety control standard.

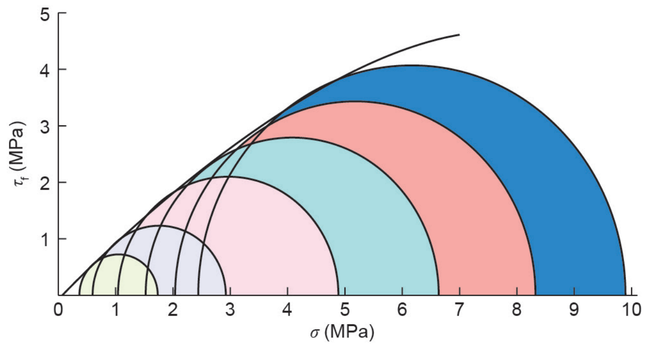

Fig. 8. The Mohr strength envelope of rockfill materials determined by testing.

It is recommended that multiple methods be applied in order to comprehensively analyze the slope dynamic stability of a high earth-rockfill dam. Taking the Nuozhadu earth core rockfill dam as an example, multiple methods were used to analyze the dam slope dynamic stability against sliding, including the quasi-static method, the quasi-static method with different acceleration distribution coefficients, the reliability method, the strength-reduction finite element method, the finite element method, the Newmark sliding block method, and a stability analysis method based on the variation principle. The analysis results showed that the adopted static and designed seismic conditions meet the code requirements and have a high safety margin.

4.4. Safety control standard for permanent deformation by earthquake

Cracks on the embankment are a common result of seismic damage to an earth-rockfill dam. If the cracks continue to intensify, a landslide will be induced. The permanent deformation standard for an earth-rockfill dam should correspond to the standard of cracks that may result in slope failure. For the control standard of permanent deformation for an earth-rockfill dam with a height of 200 m or above, it is recommended that the standard be controlled based on the ratio of the seismic deformation at the upper part of the dam to the total dam height; that is, that the upper 1/2 (or 1/3) of the dam be taken as the research object. If the earthquake subsidence ratio of this part of the dam is lower than 1.5%, the deformation is considered to be tolerated by the dam. The inclination of the dam body due to unequal earthquake subsidence should be controlled to within 1.2%.

4.5. Reinforcement measures for seismic stability

The middle and upper parts of a high earth-rockfill dam are the main sections that require reinforcement. Common anti-seismic measures include geogrids, concrete girders, precast concrete frame beams, and anti-seismic rebars. A geogrid combines ease of construction with the capability to improve the integrality of the dam body as well as the seismic stability of the dam crest; a geogrid has already been applied to the Pubugou Project. The concrete girder was used in the Nurek Project, and the precast concrete frame beam is proposed for use in the Lianghekou Project. Based on comprehensive research and on a comparison with conventional anti-seismic measures, an anti-seismic measure that is applicable to an earth-rockfill dam in an area with a high (9 degrees) earthquake probability (Fig. 9) has been developed and was adopted in the Nuozhadu Project. It combines internal stainless steel reinforcement of the dam body with a stainless steel grid on the surface and provides a masonry block revetment upstream and downstream of the dam facing of the crest. According to research, this measure improves the integrality and seismic stability of the dam crest, and reduces the probability of sliding at the superficial layer (the surface) of the dam slope.

For a high earth-rockfill dam that is built on a deep deposit, anti-seismic measures should be taken to strengthen the dam foundation. For example, in the Changheba Project, the sand layer downstream of the dam foundation and the sand lens distributed upstream of the dam foundation have been excavated in order to prevent potential liquefaction.

5. Flood discharge safety and control technologies for high earth-rockfill dams

The failure of earth-rockfill dams due to flood-caused structural problems (especially those due to insufficient discharging capacity) account for 44% of all failures. Hence, more attention should be paid to the release structures of these dams. Key technical issues for the flood discharge safety of high earth-rockfill dams include: a flood control standard, the layout of release structures, energy dissipation and erosion control, aeration and cavitation mitigation, and atomization during flood discharge.

5.1. Flood control standard

Regarding the flood control standard for a high earth-rockfill dam, the upper limit value and the probable maximum flood (PMF) should be generally adopted. It is recommended that the safety control standards for the release structures be determined according to the principle of combining the dam freeboard with super discharging capacity of the release structure. The discharging capacity of some release structures should be taken as the safety reserve, so as to ensure that no overtopping occurs under any working mode. In addition, emptying facilities should be provided.

5.2. Layout principles of release structures

The terrain, geological conditions, and general layout of the project should be considered when determining the layout of the flood discharge structures. In addition, a suitable shape and the connection requirements of the downstream water flow should be taken into consideration, and the layout should be subjected to a hydraulic model test for verification. The structural axis in a plane should be as straight as possible, and factors such as atomization during flood discharge should be considered. It is recommended that a spillway (tunnel) with super discharging capacity be used as the main release structure and a discharge tunnel as the auxiliary release structure, and that the flood-discharging capacity of the surface outlets be made as high as possible.

For the Nuozhadu Project, the flood-releasing structures consist of an open spillway on the left bank and two discharge tunnels (with emptying function) on the left and right banks (Fig. 10). For the Changheba Project, two spillways, one deep-discharge tunnel, and one emptying tunnel are provided on the right bank.

5.3. Energy dissipation and erosion control

Flip trajectory buckets are used in high earth-rockfill dams for energy dissipation: A big differential flip bucket, a slit-type flip bucket, and a deflecting flow collision flip bucket may be adopted to disperse the inflowing nappe horizontally and longitudinally, and to dissipate inflowing energy. The erosion control design should be based on the permissible erosion-resistant flow velocity of the bedrock, and the erosion resistance of the riverbank can be improved by setting a plunge pool, increasing the depth of the water cushion, and providing a riverbank protective structure. With appropriate deep excavation and an expansion of the plunge pool size, bank protection without bottom protection could be adopted.

5.4. Aeration and cavitation mitigation

Aeration and cavitation mitigation are important for a high dam, since the release structures of a high dam have both large flow and high-speed flow. The design shape of release structures may be optimized through numerical simulation, followed by a physical modeling test on the optimized shape for verification. Engineering measures should focus on optimizing the shape of the flow channel and augmenting it with scour-resistant and erosion-resistant materials. When the flow rate is higher than 30 $m \cdot s^{-1}$, aeration and cavitation mitigation facilities should be provided. Forced aeration should be applied at the bottom, and a flip bucket or slot-type facility may be used for aeration. To ensure sufficient aeration for the discharge tunnel, the space re-

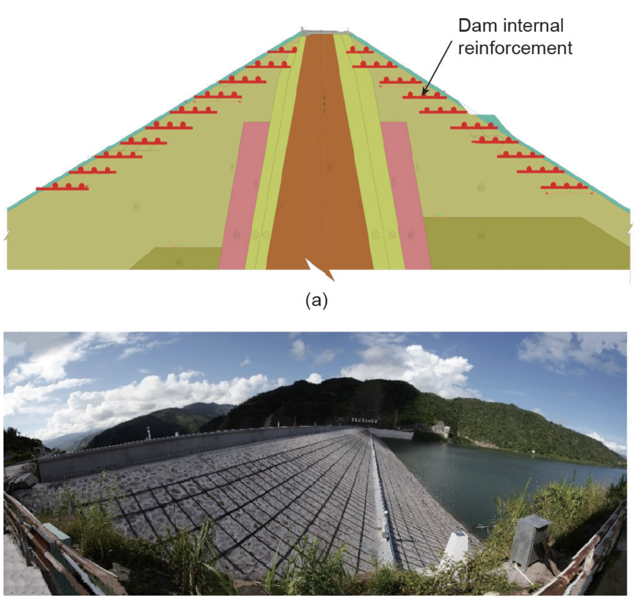

Fig. 9. New anti-seismic measures taken for the Nuozhadu earth core rockfill dam.

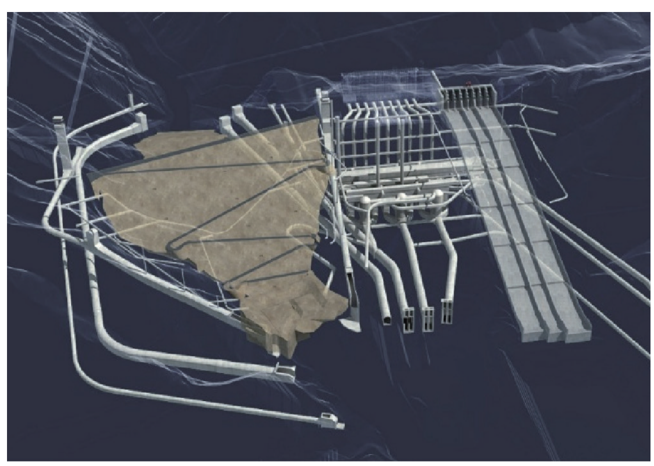

Fig. 10. Layout of the Nuozhadu Hydropower Station.

served at the top of the non-pressure tunnel should not be less than 30%, and vent shafts should be provided on the tunnel roof. Sudden-expansion and sudden-drop aerators should be applied to the transition section between the pressure flow and the non-pressure region, and aeration should be performed by the side cavity and the bottom cavity.

5.5. Atomization during flood discharge

Atomization during flood discharge is a complex phenomenon (Fig. 11), the mechanism of which is still not thoroughly understood. Therefore, a comprehensive analysis of such a phenomenon must be conducted by prototype observation, numerical simulation, and theoretical analysis. Control measures to reduce the risk of atomization focus on the structural layout and on slope protection at the atomization area. Thus, structures that are sensitive to the atomization effect should be set far away from the atomization area. Surface drainage and internal drainage measures should be provided for the side slope in the atomization area, so as to ensure the stability of the slope.

6. Major technologies for safe construction and quality control

Effective control of dam construction quality is essential to ensure the safety of a high earth-rockfill dam. This paper summarizes the key technologies for the safe construction and quality control of a high earth-rockfill dam, with reference to projects such as Nuozhadu, Pubugou, and Changheba earth-rockfill dams. These key technologies include the modification of earth material for the core wall, the application of "digital dam" technology for supervising and controlling construction quality, the use of a control criterion for earth material compaction, and the use of the quick detection method for filling quality.

Fig. 11. A flood discharge at the Nuozhadu Hydropower Project.

6.1. Modification of earth material for the core

In order to meet the requirements of the Nuozhadu Dam for modified artificial gravel, a comprehensive construction technology was proposed for mixing artificial crushed stone into gravel soil. The detailed technique (Fig. 12) involves exploiting natural earth material vertically (height: 5–8 m), using dumpers to transport the exploited material to the blending yard, and then alternately spreading a natural earth layer and an artificial gravel layer. Each single earth layer is 1.03 m thick, and each single gravel layer is 0.5 m thick, and the earth or gravel layer is leveled by bulldozers. This spreading and leveling is repeated three times to reach a total height of about 5 m. The earth material and gravel are mixed by excavators three times through vertical exploiting. The material is then transported to the dam surface by 20-t dumpers. On the dam surface, a backward method is used to unload the materials and level them using road graders, with a spreading layer thickness of 25–30 cm. A 20-t self-propelled pad foot vibratory roller (with an exciting vibration force of over 400 kN) is used to vibrate-roll eight times, with a travel speed no greater than 3 km·h^{-1} [5].

A secondary sieving process was proposed to meet the requirements for modification of the core wall material in the Pubugou Project. This process reduces the waste materials in sieving. The sieving flow is as follows: The material is transported by dumper, and the first sieving is conducted with a bar screen to remove gravel larger than 250 mm; the second sieving is conducted using a square-hole vibrating screen to remove gravel larger than 60–80 mm; the modified material is delivered by a belt conveyor, stockpiled at the stockyard, and finally delivered to the dam by a dumper [6].

The process of blending coarse and fine earth was adopted for the modification of the core material in the Changheba Project. The flow of this process is as follows: Raw material is exploited vertically and then spread horizontally, with a spread thickness of 0.5 m for coarse material; the spread thickness of fine material is determined according to the measured loose dry density of each soil layer, with coarse material in the first layer, fine material in the second layer, coarse material in the third layer, and fine material in the fourth layer, spreading the coarse and fine materials alternately until the spread height meets the working conditions of the blending machinery; a forward excavator is used for vertical exploiting and an excavator bucket is used for the gravity discharge of materials; this process is repeated three to six times to fully blend the materials.

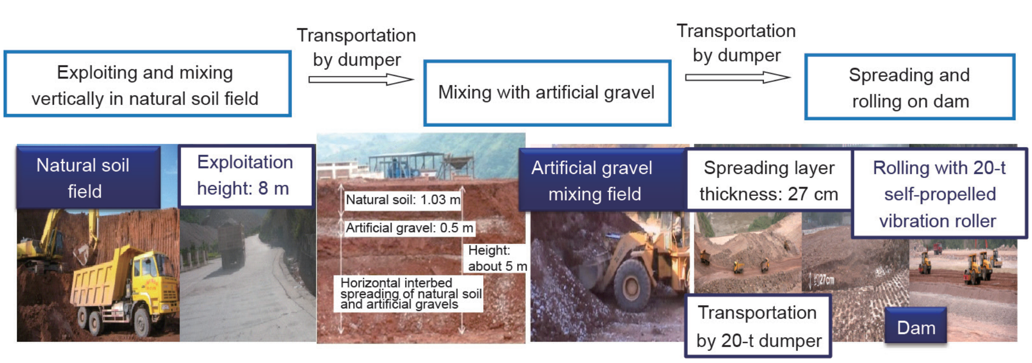

Fig. 12. Construction process of artificial gravel mixed with earth for the Nuozhadu earth core rockfill dam.

6.2. "Digital dam": A monitoring system for the construction quality of high earth-rockfill dams

The "digital dam" monitoring system, used to monitor and control the quality of high earth-rockfill dam construction, was developed during the Nuozhadu Project. By employing the Global Positioning System (GPS), a personal digital assistant (PDA), and information technology, the system can achieve real-time monitoring and information feedback on the dam materials' allocation and transportation, damming parameters, test results, and monitoring data; thus, it can provide an information application and support platform for quality control and a safety diagnosis of the dam body during the construction of the dam (Fig. 13). The system also monitors the vibrating roller's speed, rolling pass, exciting vibration force, and rolling track in real time, in order to ensure rolling and placement quality (Fig. 14). In addition, on-board GPS positioning devices are used to monitor transportation vehicles from the dam to the stockyard, providing a reference for correct material unloading on the dam and for the optimized dispatch of transportation vehicles [7].

The "digital dam" system provides a new method for high-standard control of a high earth-rockfill dam's construction quality. It has effectively improved the construction quality monitoring level and the efficiency, and has ensured the control of construction quality. From 2009 to 2011, the average annual filling of the Nuozhadu Dam reached 9.4×10^6 m^3, causing it to be completed one year in advance. Clearly, the "digital dam" system plays an important supporting role. This system was later popularized and applied in subsequent high earth-rockfill dams, such as Changheba.

6.3. A control criterion for earth material compaction and the quick detection method for soil compactness

It is suggested that a relatively large compaction energy should be adopted in order to improve filling density, permeability, and deformation stability. The maximum size of the soil material used in the Nuozhadu Project is 120 mm, so a super-large compaction instrument with a diameter of 600 mm was developed to study the compaction characteristics of gravel soil. According to research results, when the gravel content is less than 50%, it is feasible to conduct quality control of all materials mixed with gravel soil by replacing the original ultra-large compaction results with large compaction results, as shown in Fig. 15(a). As shown in Fig. 15(b), 95% of all materials' compactness (2690 kJ·m^{-3}) can meet the requirement for 100% of all materials' compactness (595 kJ·m^{-3}).

Various control methods were compared and analyzed for quick detection of the filling quality of mixed gravel soil, including all-material compaction control, all-material compaction pre-control, and fine material compaction control. The all-material compaction control method required a heavy workload and was time-consuming during onsite testing. The fine material compaction control method required a small compaction energy and had a low workload during onsite testing, so it met the requirements of the construction progress. Therefore, it is recommended that the three-point quick compaction method for fine material (595 kJ·m^{-3}) be used for onsite testing, while a certain proportion of the large compaction tests should be performed in a laboratory to check the all-material compactness. An additional quality method for filling compaction detection was developed during the construction of the Nuozhadu Project; this method is quick and non-destructive and can greatly accelerate detection, so it is recommended for future projects.

7. Safety assessment of high earth-rockfill dams and early-warning management information system

Based on onsite monitoring data and advanced information technology, an information system for the safety assessment and early-warning management of an earth-rockfill dam was established. This system is of great significance for safety construction, impoundment acceptance, and the safe operation of a high earth-rockfill dam throughout its life cycle.

7.1. Dam safety assessment and early-warning management information system

By taking into account the actual demands of the reservoir impoundment at the Nuozhadu project, a management information system based on Internet remote control was developed for

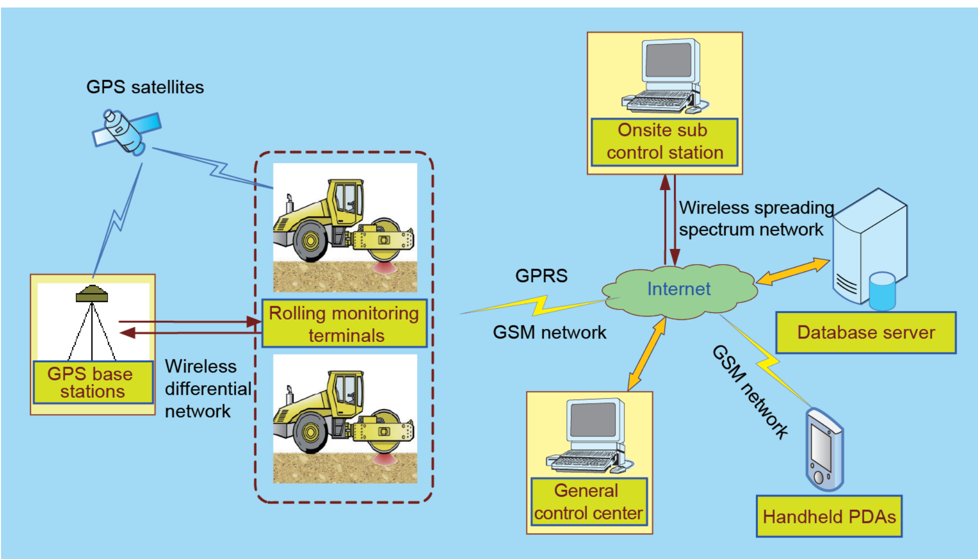

Fig. 13. A schematic of the real-time monitoring of filling quality using the "digital dam" system. GPS: Global Positioning System; GPRS: general packet radio service; GSM: global system for mobile communication; PDA: personal digital assistant.

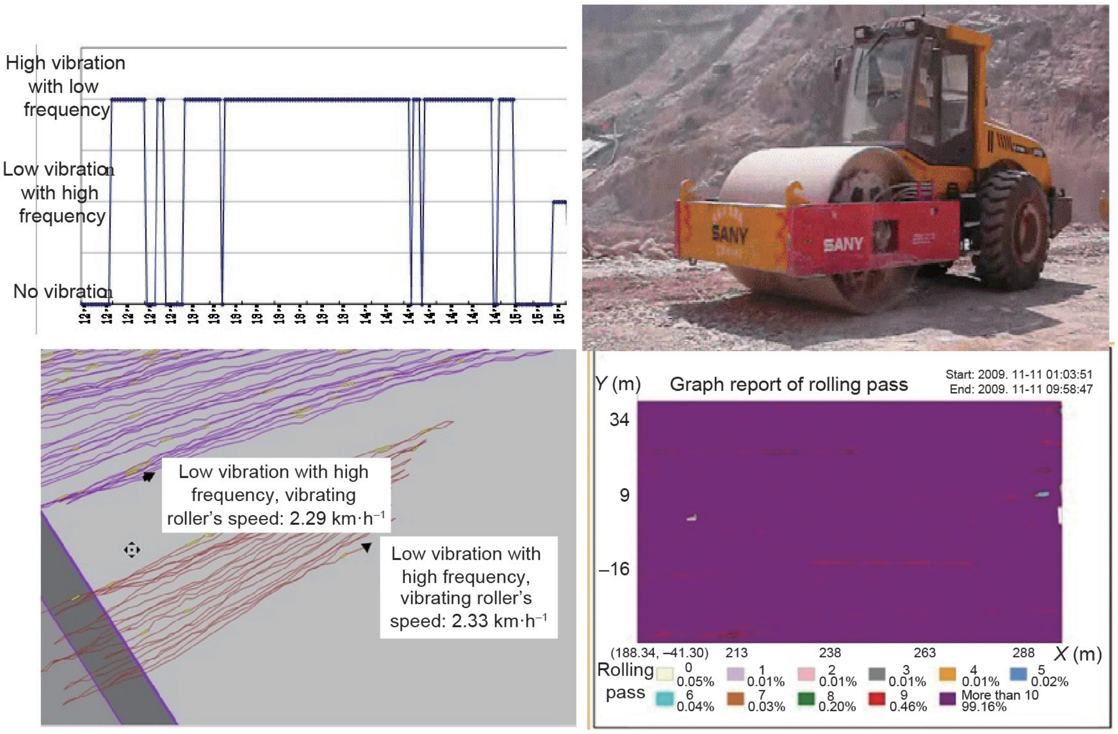

Fig. 14. Real-time monitoring of filling quality of the Nuozhadu Dam core wall.

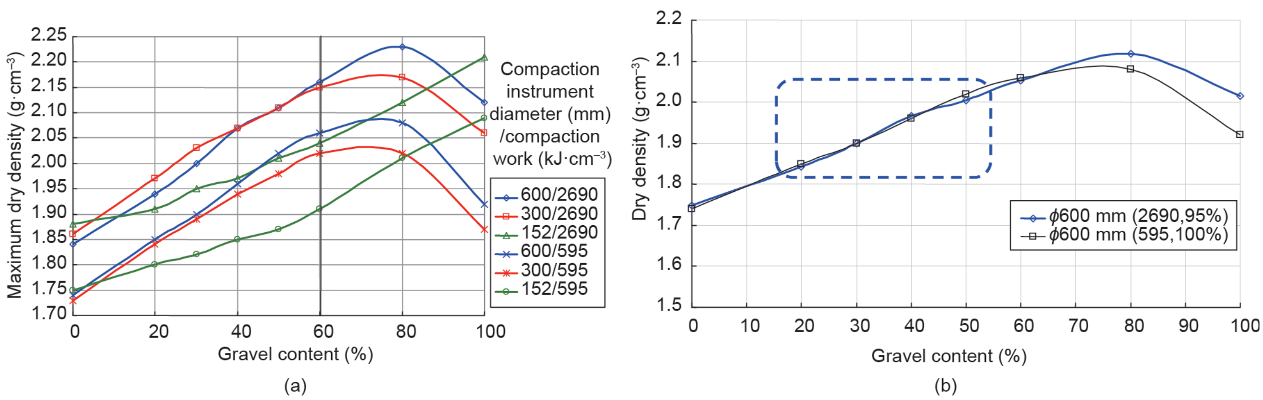

Fig. 15. Test results for the control criterion for soil compaction at the Nuozhadu earth core rockfill dam. (a) A comparison of the maximum dry density under different compaction work and compaction apparatus diameters; (b) a comparison of the dry density of all materials under different compaction work and compactness.

the safety evaluation and pre-warning of an ultra-high earth core rockfill dam (Fig. 16). This system is integrated with monitoring data acquisition and analysis management, dam numerical calculation and inverse analysis, a comprehensive safety evaluation index system and pre-warning system, an itinerant inspection record, and document management. It plays a vital role in dam monitoring information management, condition analysis, safety evaluation, and pre-warning.

7.2. Safety assessment index system

To provide support for safety assessment and early warning at the Nuozhadu Dam, a safety assessment and early-warning management information system was applied. Overall and sub-item safety monitoring indexes for the earth core rockfill dam were introduced to the system, involving reservoir water level, seepage stability, structure stability, dam slope stability, and dam cracking. The overall security indexes of the dam mainly include dam seepage flow, the maximum settlement of the dam body and crest, upstream/downstream dam slope deformation, and dam crest cracking; the sub-item safety indexes are mainly composed of dam horizontal displacement along the river, dam settlement, seepage discharge, pore pressure, soil pressure, and cracking.

7.3. New types of safety monitoring equipment

During the Nuozhadu Project, devices were developed such as a layered settlement meter, a new type of pressure-based water-level settlement gauge, a four-pipe water-level settlement gauge, an electrical-logging string-pieced settlement meter, a string-type settlement meter, a shearing deformation gauge, a 500 mm wide-range potentiometric displacement meter, and a six-direction earth pressure meter. Using these instruments, the following indexes can be measured: settlement within the upstream rockfill and within the core wall; relative deformation between the core wall and the filter, or between the core wall and the concrete

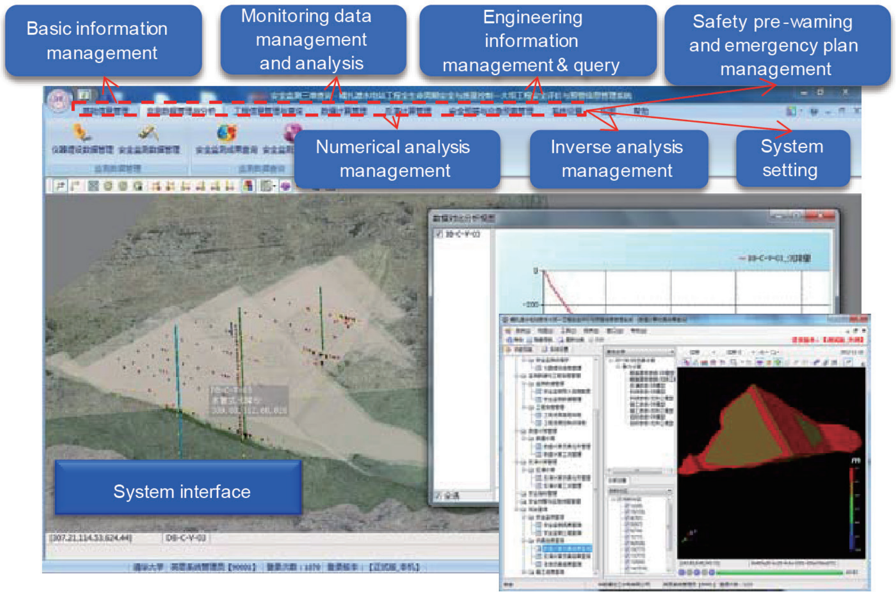

Fig. 16. The Nuozhadu Dam safety assessment and early-warning management information system.

cushion; and spatial stress of the core wall. The system is integrated with a measurement robot, a Global Navigation Satellite System (GNSS) deformation monitoring system, and an internal and exterior automatic system, and realizes high-precision monitoring and real-time online monitoring data compensation.

Three new instruments (a string-type settlement meter, an intelligent settlement meter, and a potentiometric displacement meter) have been adopted for settlement monitoring at the Changheba Project. According to recent monitoring results, the most successful instrument is the potentiometric displacement meter. A potentiometric displacement meter with a maximum range of 1200 mm has been used in the measurement of overburden settlement, and can meet the requirements for settlement monitoring of the deep overburden at the Changheba Project.

To meet the safety monitoring needs of 300 m high earth-rockfill dams, a feasibility study was conducted on the latest technologies, such as interferometric synthetic aperture radar (InSAR) deformation monitoring, pipeline robots, flexible clinometers, and monitoring galleries.

8. Safety monitoring data analysis and performance evaluation for the Nuozhadu earth core rockfill dam

In November 2011, the reservoir of the Nuozhadu Hydropower Project started to impound, and in September 2012, the first generating unit was put into operation. In 2013 and 2014, the reservoir was impounded to the normal pool level, with a retaining head of 252 m (Fig. 17).

By the end of 2015, the distribution of dam deformations corresponded to the general deformation law of a high earth core rockfill dam. The maximum crest settlement measured was 790.67 mm, which was about 0.3% of the maximum dam height and was less than the reference index, a crest settlement proportion of 0.5% after dam completion. The maximum cumulative settlement of the dam was 4305 mm, which is about 1.65% of the maximum height of the dam, and was less than the reference index, a settlement proportion of 3%. No obvious cracks were found on the dam surface.

Most shear deformation gauges between the core wall and the filter were subjected to pressure. The maximum relative deformation measured was about −103.82 mm, and occurred at the maximum settlement area of the core wall. The settlement of the filter was less than that of the core wall. The measured values of the joint gauges between the dam foundation and the concrete cushion ranged from −19.7 mm to 2.74 mm, which indicated that most sections were closed. A certain amount of saturated collapse might have occurred in the upstream rockfill due to the influence of water storage, but it did not have a significant impact on the deformation of the core wall, and the core wall had no obvious deformation trend downstream.

Fig. 17. Overall view of the Nuozhadu Hydropower Project.

The water level in the upstream rockfill was consistent with the reservoir water level. The excess pore water pressure was measured within the core wall, and the water level behind the core wall was low. This finding showed that the core wall, cushion layer, and impervious curtain had good impervious effects. The measured hydraulic head in piezometers at the dam foundation drainage gallery ranged from −1.93 m to 127.95 m. Most of the seepage flow at the measuring weir in the dam foundation gallery was stable. The total seepage flow was about 4.14 $L \cdot s^{-1}$, while the seepage flow measured at the trapezoidal weir downstream of the dam was 5.42 $L \cdot s^{-1}$. By summing the seepage flow in the dam foundation gallery with the seepage flow at the measuring weir downstream of the dam, the total seepage flow of the dam was found to be about 9.56 $L \cdot s^{-1}$.

The stress distribution in both the core wall and the rockfill was in accordance with the general requirements of a high earth core rockfill dam. In addition, the pore water pressure in the core wall was slowly dissipating.

The above-mentioned data showed that the deformation, seepage, seepage pressure, and stress state at the Nuozhadu Dam were steady. It also indicated that the main indexes of deformation and seepage were much less than the indexes at other similar projects at home and abroad; hence, the Nuozhadu earth core rockfill dam is in a good operating condition.

9. Conclusions

During the process of constructing earth core rockfill dams such as the Nuozhadu Project, three major stability issues (deformation stability, seepage stability, and dam slope stability against sliding) and important technical problems regarding the construction safety of a high earth-rockfill dam were systematically investigated. The principle of emphasizing the control of earth core deformation and the coordination of the deformation of the core wall and the dam shell material was put forward, and the parameters for the calculation model were improved. For seepage control, the principle of a "seepage prevention/filter/drainage combination and optimal configuration" and a seepage control criterion were proposed. It is suggested that the weak surface of seepage is the main reason for hydraulic fracturing of the core wall; hence, the understanding of the mechanism of hydraulic fracturing is updated. Four analysis methods of dynamic stability against the sliding of the dam slope were compared. It is suggested that multiple methods be used to carry out a comprehensive analysis and assessment, and common anti-seismic measures in China were put forward. Information technology, such as GPS and PDA, was applied in the real-time monitoring and feedback control of dam material transportation, construction parameters, test results, and safety monitoring data. This technology was first used in the Nuozhadu Project, and is a major innovation for dam construction quality control. These breakthroughs in dam construction technology provide an important reference and a technical support for the safe construction of similar high earth-rockfill dams in future.

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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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