Key technologies for the construction of the Xiluodu high arch dam on the Jinsha River in the development of hydropower in western China

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Abstract: Hydropower development in China is concentrated in the country's western regions. Among all the rivers in China, the lower course of the Jinsha River contains the richest hydro-energy resource, and therefore, 4 mammoth hydropower plants are under construction on this particular section of the river at Wudongde, Baihetan, Xiluodu, and Xiangjiaba. The water-blocking structures of the hydropower facilities at Wudongde, Baihetan and Xiluodu are all arch dams of around 300 m high. In view of changes in the geological conditions at the foundation of the Xiluodu dam on the riverbed after excavation started, the designs of expanding foundation surface excavation and dovetailing the dam body and foundation rock on both upstream and downstream sides were introduced, allowing the arch dam and foundation to fit each other and improving the stress conditions of the dam body and foundation. By dividing the dam body into various concrete sections, the dynamic properties of concrete were adequately adjusted to the distribution of stress in the dam body. In addition, the use of the most optimal concrete material and mixture ratio allowed thermodynamics of concrete to satisfy the requirements of the strength, durability, temperature control and crack prevention of the concrete. Moreover, rigorous temperature control measures were introduced to prevent harmful cracking, thus enhancing the integrity of the arch dam. Furthermore, sophisticated construction machinery, scientific testing methods, and sound construction techniques were employed to ensure the uniformity and reliability of concrete placement. The "Digital Dam" for the Xiluodu project, which is based on the theory of total life cycle, has supplied strong support for construction process control and decision-making.

Key words: high arch dam; key technologies; Xiluodu; hydropower development

1 Overview of hydropower development on the lower course of the Jinsha River

1.1 The hydro-energy resources of China mainly concentrate in western regions

The distribution of hydro-energy resources in China is highly uneven. There are more hydro-energy resources in the western regions than that in the eastern regions, and the bulk of the hydro-energy resources is located in the southwestern regions, so it is necessary to transmit power from the western to the eastern regions. Yet, the eastern regions have a higher level of exploitation of hydro-energy resources than that in the western regions; thus, it's necessary to speed up the development of hydro-energy resources in the western regions to meet national and regional socioeconomic development needs, to reduce poverty for relocated rural residents and to improve the ecological environment.

The Jinsha River is on the upper course of the Yangtze River. The lower course of the Jinsha River stretches 782 km from Panzhihua to Yibin, with a drop of 729 m. From upstream to downstream, 4 cascade hydropower plants are under planning or construction. All of these 4 mammoth hydropower plants are located on the river that demarcates Yunnan Province and Sichuan Province. The bulk of power from these plants will be supplied to China's eastern and southern regions, and some will be supplied to Yunnan Province and Sichuan Province. Table 1 presents the fundamental data of the 4 cascades on the lower course of the Jinsha River.

In 2002, the Chinese government authorized the China Three Gorges Corporation to build and operate the 4 cascade hydropower plants on the lower course of the Jinsha River. As a group of power sources, the hydropower plants at Xiangjiaba and Xiluodu are the projects of the first phase, and their main structures are currently under construction. They are expected to become operational in 2012 and 2013, respectively. The other two hydropower plants at Wudongde and Baihetan are the projects of the second phase. Preliminary feasibility studies are currently underway for these two plants.

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Table 1 Fundamental data of the 4 cascade hydropower plants on the lower course of the Jinsha River

Description	Wudongde	Baihetan	Xiluodu	Xiangjiaba	Total
Drainage area controlled/($\times 10^3$ km^2)	406.1	430.3	454.4	458.8	473.2
Average annual runoff/($m^3 \cdot s^{-1}$)	3 870	4 110	4 570	4 570	4 920
Normal water storage level/ m	975	825	600	380	—
Reservoir storage at normal water storage level/ ($\times 10^9$ m^3)	5.863	19.006	11.57	4.977	41.416
Flood-control water storage/($\times 10^9$ m^3)	1.860	7.500	4.650	0.903	14.913
Installed capacity/ MW	8 700	14 004	13 860	6 400	42 964
Average annual power generation/($\times 10^9$ kW · h)	38.67	60.241	57.12	30.747	186.8
Guaranteed output/ MW	3 284	5 100	6 657	2 009	17 050

1.2 High arch dam is the most common type for large-scaled hydropower plant in southwestern regions

To ensure that the development objective is met, the main structure of the hydropower plant is comprised of a dam across the river, powerhouses, and hydraulic facilities for flood discharge, sediment flushing, water supply and emptying. The hydropower complex is laid out in line with the local topographic and geological conditions, hydraulic conditions, and operating safety requirements. Through comprehensive technical, economic, ecological and environmental analysis, an optimal layout design is developed for each structure, thereby allowing the hydropower complex to serve its intended comprehensive functions. Arch dams featuring pressure arches block water through the combined effect of "dam plus the foundation". This, along with flood discharge through the arch dam body and advances in energy dissipation technology for the secondary dam of the plunge pool under the dam, makes arch dam be one of the most cost-effective and safe types of dams for V-shaped and U-shaped valleys. Table 2 presents the main parameters of the 4 cascade hydropower plants in the lower course of the Jinsha River and typical arch dams under construction in China's western regions.

Table 2 Main parameters of the 4 cascade hydropower plants in the lower course of the Jinsha River and typical arch dams under construction in China's western regions

Description	Lower course of Jinsha River				Jinping level 1, Yalong River	Dagangshan, Dadu River	Xiaowan, Lancang River
	Wudongde	Baihetan	Xiluodu	Xiangjiaba			
Dam height/ m	265	289	285.5	162	305.0	210.0	294.5
Type of concrete dam	Double curvature arch dam	Double curvature arch dam	Double curvature arch dam	Gravity dam	Double curvature arch dam	Double curvature arch dam	Double curvature arch dam
Ratio of valley width to height	~ 0.95	~1.75	2.06	—	1.57	2.52	2.71
Total hydraulic thrust / ($\times 10^6$ t)	6.4	16.4	14	—	12.8	6.2	19.75
Basic seismic intensity	VII	VIII	VIII	VII	VII	VIII	VIII
Seismic design standard / Gal	265	325	321	222	200	558	313
Seismic checking standard / Gal	315	420	396	281.8	—	663	359
The maximum flood discharge from hydropower complex /($m^3 \cdot s^{-1}$)	37 362	42 356	50 900	48 660	13 897	8 814	20 700
Flood discharge power of hydropower complex / MW	50 114	90 000	100 000	40 000	33 456	15 400	45 600
The maximum flood discharge in dam body/($m^3 \cdot s^{-1}$)	27 184	30 000	32 278	48 660	10 577	5 462	16 889
Development status	Feasibility study underway	Feasibility study underway	Under construction	Under construction	Under construction	Under construction	Construction completed

Note: For the seismic design and checking standard, the probabilities of exceedance over the 100-year benchmark period are considered to be 2 % and 1 %, respectively, according to *The Seismic Design Code for Hydraulic Structures* (DL5073-2000) and *The Interim Regulations on the Seismic Research and Designs and Reporting of Hydropower Projects* (appendix to *Hydropower Planning and Design Document* No. [2008]24). 1 Gal = 0.01 m/s^2

Comprehensive analysis of Table 1 and Table 2 indicates that most of high arch dams are located in the gorges lined by high mountains and areas with high seismic intensity ratings. As such dams are typically high and have a sizable reservoir and large flood discharge in the dam body, it's important to resolve key technical issues relating to the research of topographic and geological conditions, the layout, seismic safety, physical shape, and structural design of hydropower complexes, foundation treatment, flood discharge and energy dissipation, concrete quality control, temperature monitoring and crack prevention, and assessment of the impact on the aquatic ecosystem and environment. As the Xiluodu Gorge has favorable topographical and geological conditions, both double-curvature arch dam and gravity arch dam would be suitable. After considering all related factors, such as the anti-slip stability deep inside the dam body, the distribution of stress in the dam body, flood discharge and energy dissipation, construction schedule and project cost, a decision was eventually made to opt for double-curvature arch dam with 7 surface holes, 8 deep holes and 10 bottom diversion holes during the construction period. The construction of the Xiluodu high arch dam requires the employment of key technologies for treating geological changes after excavation on the foundation surface, controlling concrete temperatures, and preventing crack. Through the real-time monitoring and simulation of the status of all the construction phases of the arch dam and its foundation with Xiluodu's "Digital Dam" system, the construction quality and safety of the dam are maintained within the permissible range as outlined in the design at any time.

2 Key technologies for the construction of the Xiluodu high arch dam

2.1 Foundation surface optimization and structural design of the arch dam

The gorge at Xiluodu where the dam is located is 4 km long, with a straight riverbed. The valley is U-shaped with steep slopes and massive mountains and no ravines or faults. The lithology of the exposed rocks at the dam site features dyas upper Permian Emeishan basalt ($P_2\beta$). The basalt can be divided into 14 rock flowage layers ($P_2\beta^{14} \sim P_2\beta^{1}$) by changes in lithology. A total of 10 rock flowage layers were identified on the dam foundation surface in descending order of elevation. The upper 1/5 ~ 1/4 of each rock flowage layer features breccia, while the lower part is primarily basalt. The dyas lower Permian limestone of the Maokou formation (P_{1m}) is located about 90 m deep down the dam foundation. The base rocks of the foundation of the dam at Xiluodu involve 5 rock levels and 7 rock sub-levels, including I, II, III_1, III_2, IV_1, IV_2 and V. Table 3 presents the integrated quality ratings and dynamic parameters of the rock masses.

Table 3 Integrated quality ratings and dynamic parameters of rock masses on the site of Xiluodu arch dam

Rock level	Rock sub-level		Structural type of rock mass	Longitudinal acoustic wave velocity Vp /(m· s^{-1})	Recommended deformation modulus level E_0/GPa		Recommended elasticity modulus level E/GPa		Permissible load/MPa
					Horizontal	Vertical	Horizontal	Vertical	
	I		Monolithic block structure	>5 500	24 ~ 36	24 ~ 36	33 ~ 50	33 ~ 50	—
	II		Blocky structure	4 800 ~ 5 500	17 ~ 26	12 ~ 16	22 ~ 30	16 ~ 22	12 ~ 20
III	III_1	Tuffaceous breccia lava	Blocky structure	4 000 ~ 4 800	10 ~ 12		14 ~ 20	13 ~ 16	7 ~ 9
		Basalt breccia lava	Sub-blocky structure	4 500 ~ 5 200	11 ~ 16	9 ~ 11			
	III_2		Embedded structure	3 500 ~ 4 500	5 ~ 7	4 ~ 6	7 ~ 9	5 ~ 8	5 ~ 7
IV	IV_1		Fractured structure	2 700 ~ 4 000	3 ~ 4	2.5 ~ 3.5	4 ~ 5	4 ~ 5	2 ~ 3
	IV_2		Fractured structure	2 500 ~ 4 000	0.9 ~ 2.0	0.5 ~ 1.0	1.0 ~ 2.6	0.7 ~ 1.2	
	V		Segmented structure	<2 500	0.5 ~ 0.8	0.3 ~ 0.4	0.7 ~ 1.1	0.4 ~ 0.5	—

Note: Tuffaceous breccia lava is located on the top of layers 3, 4 and 6 (at an elevation of about 340, 360 m and 380 m on the left bank, and at elevation of about 340, 370 m and 400 m on the right bank)

During the feasibility study phase of the Xiluodu project, the slightly weathered and fresh rock masses in the dam foundation on both banks of the river were used, while at certain spots, slightly weathered lower-part rock masses were used. The dam foundation on the riverbed has an elevation of 332 m, and the foundation surfaces on the left and right banks have an embedment depth of 42 m and 54 m. With the progress of the design work, a deeper understanding was gained of the quality and dynamic properties of the rock masses in the dam foundation and of the dynamic characteristics and structure design features of the arch dam. Engineers also drew upon the success experience in China and abroad and considered the bearing capacity of the rock masses, the stress conditions of the dam body, the stability of the rock masses at the dam abutment, the durability and impermeability of concrete, as well as safety, economic and construction factors. It was eventually decided that the rock masses of III_1 and III_2 levels on the medium-upper parts would be used to optimize the foundation surface. On the foundation surface of the Xiluodu arch dam, at certain spots with an elevation below 430 m, slightly weathered rock masses towards the lower end of the range of III_1 were used; the steep cliff zones with an elevation of 430 ~ 560 m were primarily placed on rock masses of the III_1 level; rock masses of the III_2 level were used at certain spots with an elevation above 560 m. For rock masses of the IV_1 level exposed at an elevation of 332 m on the riverbed, the original scheme of shaft slot excavation was replaced by the scheme of connecting the shaft slot bottom at an elevation of 324.5 m to the construction foundation surface on both sides with an optimal design.

The topography of the dam site at Xiluodu is relatively symmetrical and the geological conditions are uniform. All linear arch rings suit the topographical and geological conditions well, and the parabolic-curve and the unified quadratic-curve arch dam body has optimally distributed stress. Engineers also conducted in-depth comparisons through stress analysis using the finite element method and analysis of the dam abutment stability using the limit equilibrium method for rigid blocks, and considered various factors, such as the project geology, design, construction and engineering experience. They eventually opted for hyperbolic parabola as the linear shape for the horizontal arch rings for the Xiluodu arch dam; they also optimized the arch dam shape in light of the foundation surface. The arch crown of the dam crest is 14.00 m thick, while the arch dam of the dam base is 60.00 m thick; the maximum central angle is 95.13 °; the central linear arch of the crest arch is 681.49 m long; the ratio of the thickness to height is 0.216; the ratio of the arch length to height is 2.451; the upstream overhang degree is 0.141, and the flexibility coefficient stands at 11.10.

Under the basic portfolio of the load combinations of the Xiluodu arch dam, the dam body has the maximum tensile stress of no more than 1.2 MPa, and the maximum tensile stress on the sections of the arch dam which have not been sealed up should preferably be capped at 0.5 MPa; the allowable compressive strength should not exceed 9.0 MPa, and the concrete compressive strength has a safety coefficient of 4.0. Engineers also conducted computation analysis and project comparisons with regard to the foundation surface and shape optimization of the Xiluodu arch dam. The results indicate that stress shift in the Xiluodu arch dam occurs in a regular manner and remains steady, and that the dam has relatively high overall stability and safety levels and strong bearing capacity. The Xiluodu arch dam has a crack-inducing load exceedance coefficient of $K_1 = 2P_0$, a nonlinear deforming load exceedance coefficient of $K_2 = (3 \sim 4)P_0$, and the maximum load exceedance coefficient of $K_3 = 8.5P_0$. With the integrated load exceedance and intensity reduction methods, it is determined that Xiluodu has a load exceedance coefficient of 4.8. By and large, with the optimization of the designs for the foundation surface and physical shape of the arch dam, all individual loads of the arch dam and the shift and stress of the dam body under the combined effects of the loads, as well as the shift and stress of the dam body during the construction period, are adequate to meet the design requirements. Both the upstream and downstream surfaces of the arch dam are largely under pressure, and tensile stress only occurs over a small area around both ends of the arch dam. The arch dam has considerable adaptability to changes in the integrated deformation modulus of the dam body and the foundation. Following the optimization, the horizontal embedment depth of the left-bank and right-bank downstream arch abutments on the foundation surface on the riverbed is reduced by approximately 18.7 m and 41.6 m, respectively (as they originally were approximately 73.0 m and 87.7 m in feasibility scheme, and 54.3 m and 64.1 m in optimized scheme). The embedment depth of the downstream arch abutments on the foundation surface on the left and right banks is decreased by about 13 m. The maximum excavated slope on the left and right banks was reduced by 40 m; the amount of foundation excavation dropped by about 1.61 million m^3, and the amount of concrete required for the dam body decreased by 1.13 million m^3.

The structural design for the Xiluodu arch dam also features non-radial excavation along the arch abutment on the upstream side, as well as setup of dovetailing angles along the downstream side.

2.2 Intensive excavation technology for the arch dam foundation surface

The Xiluodu dam site features monoclinal strata with a mild downstream inclination towards the left bank, and has no faults. Its main structural planes are inter-stratum and intra-stratum disturbed belts and joint fissures. At low to medium elevations, the inter-stratum disturbed belts have weak development, while at medium to high elevations, they have strong development. The distribution of the inter-stratum disturbed belts is rather random and complex. Most of such belts are found inside the basalt in the medium and lower parts of the rock flowage layers, with varying degrees of development. Under the constraining effects of the inter-stratum and intra-stratum disturbed belts, fissures at the dam foundation are characterized by strong randomness, extensive distribution, numerousness, and short extensions, exerting an impact on the integrity of the rock masses.

To ensure the shaping quality of the foundation surface of the arch dam and minimize the impact of blasting operations on the foundation, a large number of blasting experiments and blasting safety inspections were carried out. Thanks to technological advances and intensive management, a comprehensive set of high precision intensive blasting techniques were eventually developed. First, the method of side-slope excavation blasting that deep-hole terraces and pre-splitting blasting were combined was optimized. The number of rows on which explosives were ignited was carefully controlled, and the total amount of blasting explosives was optimized, thereby establishing standard specifications for blasting operations. Second, blasting parameters and networks were optimized in order to control blasting sources. Pre-splitting blasting was introduced to cut off the path of transmission, and the terminal was reinforced to enhance vibration resistance. With all these measures, vibration damage was minimized. Third, sample drilling machines were renovated; specific personnel were designated to supervise special machines at specific locations; drilling permits, explosive charge loading permits, and blasting permits were introduced; all holes drilled were checked for 3 times. With these techniques and management measures, the excavation of the foundation surface of the Xiluodu arch dam had superior quality. The average over-excavation, under-excavation and the degree of levelness in the normal direction are 10.0 cm, 3.7 cm and 6.6 cm respectively, and the residual porosity is 95.7 %. The overall conformance rates are 95.7 % (over-excavation and under-excavation), 98.2 % (degree of levelness) and 98.1 % (residual porosity) respectively. At 97 % of the measuring points, the particle vibration velocity was less than 10 cm/s; the average blasting impact depth was less than 1.0 m; the rate of acoustic attenuation was less than 10 % at 1.0 m below the foundation surface, both conforming to the requirements in the design.

During the foundation surface excavation for the sections of the dam on the riverbed, in light of the existence of the inter-stratum and inter-stratum disturbed belts and the development of joints and fissures inside the riverbed, and considering the point and face seepage of groundwater at various locations inside the riverbed, geo-technical engineers drilled through the inter-stratum and intra-stratum disturbed belts inside the dam foundation so that groundwater which had accumulated inside the rock mass would gush out; thus, the foundation pit had considerable seepage water. Through "enclosing, blocking, draining and grouting", a closed curtain was formed around the foundation pit to reduce seepage. Moreover, the holes drilled for geo-technical surveys were filled up; water on the riverbed foundation surface was drained, and the face seepage on the foundation surface received consolidation grouting. With these comprehensive treatment measures, seepage within the limits of the closed curtain significantly dropped, allowing excavation for the foundation surface of the arch dam and subsequent concrete placement to proceed smoothly.

2.3 Geological changes and solutions in the foundation of the sections of the arch dam on the riverbed

To eliminate the geological flaws on the foundation surface once and for all, with the progress of excavation, 9 locations with considerable geological flaws were excavated and swapped at 3 levels of elevations of 500 ~ 610 m, 400 ~ 500 m, and below 400 m. In the design phase, basalt on the third layer of the dam foundation was primarily rock masses of the III_1 level, with a deformation modulus of 10 GPa, while rock masses of the III_2 level had deformation modulus of 5 GPa. Additional geo-technical surveys and actual excavations showed that, under the effects of weathered unloading and intra-stratum disturbed belts, certain rock masses on the sections of the dam on the riverbed had poor integrity, and some rock masses of the III_2 level were exposed. Most of the rock masses less than 20 m deep down the foundation surface on the riverbed with an elevation of 328 ~ 324.5 m had a III_1 level, accounting for approximately 86 % of the total, while rock masses of the III_2 level made up approximately 14.1 % and their lowest elevation was about 300 m. On the downstream side of the right bank with elevation of 360 ~ 400 m, rock masses of the III_3 level and with a thickness of 2 ~ 3 m were exposed. At certain locations on both banks, there were small concentrations of highly developed disturbed belts. Post-excavation acoustic wave tests showed that, overall, the rock masses in the dam foundation on the riverbed conformed to the requirements set forth in the design, and only at certain locations of the inter-stratum and intra-stratum disturbed belts did the developed parts occur in low positions. Given the fact that distribution of the inter-stratum and intra-stratum disturbed belts in the rock masses inside the sections of the dam on the riverbed was nearly perpendicular to the load on the arch dam beams, and that these belts were key locations with foundation deformation, it was necessary to expand the bearing area of the foundation and increase consolidation grouting in order to improve the uniformity of the rock masses and the rigidity of the foundation. In light of changes in the geological conditions after excavation, the foundation surface of the sections of the arch dam on the riverbed was maintained at the minimum elevation of 324.5 m, and a comprehensive treatment scheme featuring "expanded excavation, increased consolidation grouting, integral structure, and continuous concrete placement" was adopted.

"Expanded excavation" refers to expanding the excavation of rock masses of IV_1 and III_2 levels in entirety at elevation above 324.5 m, removing rock masses of III_2 level from the surface layer of the foundation surface, and grooving and swapping of the inter-stratum and intra-stratum disturbed belts on the foundation surface and the strongly weathered inter-layers. In order to facilitate the treatment of the downstream geological flows of the foundation and to minimize the adverse influence of the abrupt changes in the geometrical shape of the swapped foundation surface on the structure of the dam body, the swapping excavation range was expanded towards both banks and by 5 ~ 10 m downstream. With swapping excavation on the riverbed and the expanded excavation of the foundation surface, the riverbed dam foundation was placed on integrate rock masses of III_2 level, while dam foundation bedrocks on both banks with an elevation of 332 ~ 400 m remained on rock masses of II and III_1 levels, and the distraction range of rock masses of II level was slightly increased. Swapping excavation totaled approximately 190 000 m^3 and involved 12 sections of the dam. The upstream dam face was expanded by about 3 500 m^2; the amount of concrete required rose by 300 000 m^3, and the commencement date of concrete placement was moved backwards by about 7 months. Fig. 1 and Fig. 2 show the quality ratings of foundation surface of Xiluodu arch dam after optimized design and excavation treatment of the geological flaws.

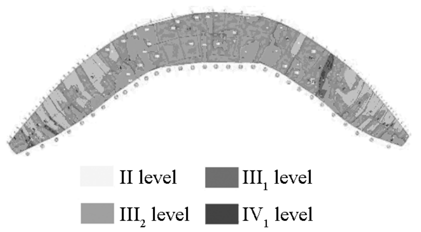

Fig. 1 Actual quality ratings of rock masses on the foundation surface after optimized design

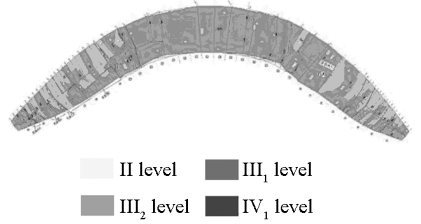

Fig. 2 Quality ratings of rock masses on the foundation surface after expanded swapping excavation

"Increased consolidation grouting" refers to increasing consolidation grouting for rock masses below the elevation of 324.5 m, especially about 14 % of level III_2 rock masses not more than 20 m deep down the foundation surface in order to enhance the integrity and deformation resistance of the foundation. Level III_2 rock masses below the foundation surface on the riverbed were mainly under the effect of the inter-stratum disturbed belts and affected belts with a gentle dip and had weak weathering; the distributed belts were mostly angular gravels with some debris, no mud, and V_p = 2 500 ~ 4 000 m/s, indicating poor integrity and uniformity. They had a largely flat spatial distribution, and were distributed as inter-layers at different elevations, with poor spatial continuity; the plane extension was typically 10 ~ 30 m long and 2 ~ 3 m thick. Consolidation grouting was increased in 4 steps. First, the depth of grouting holes was increased, and with a penetration of level II rock masses by 5 m, the grouting depth of 30 m was adopted. Second, the density of grouting was raised, with the interval between final grouting holes changed from 3.0 m × 1.5 m (river crossing direction × river flowing direction) to 1.5 m × 1.5 m. Third, the grouting pressure and process were adjusted. The ratio of water to cement was changed, and finely ground cement was introduced. In the original design, it was required to adopt 2 ∶ 1 of water cement ratio at the part of foundation rock where the rock seepage ratio is $q < 10$ Lu, 1 ∶ 1 of water cement ratio at the part of $q \geqslant 10$ Lu. While later it was adjusted to adopt 2 ∶ 1 of water cement ratio at the part of $q < 10$ Lu, 1 ∶ 1 for 10 Lu $\leqslant q <$ 30 Lu, 0.8 ∶ 1 for $q \geqslant 30$ Lu, and 3 ∶ 1 for the part where absorbing water but against grout. Fourth, more piles with anchors ($3\phi32$) were placed in the grouting holes. The quality of the consolidation grouting for the dam foundation on the riverbed was made the integrated analysis and assessment by checking the equality against the final inspection standards for dam foundation consolidation grouting, the objectives of the consolidation grouting for the dam foundation, the design requirements of the foundation surface of the arch dam, and the results of the treatment of weak spots on the dam foundation. Acoustic wave tests, permeability tests, and the deformation modulus tests of the drilling holes indicated that the integrity and uniformity of the rock masses in the dam foundation on the riverbed were effectively improved, and the impermeability of the rock masses in the superficial layers of the dam foundation was also enhanced; thus, the desired effect and objectives of consolidation grouting were realized, and the inspection standards and design requirements were met. Measurement using high precision leveling instruments showed that by the time of July 2011, the foundation of the dam sections on the riverbed had made subsidence deformation of 5.58 ~ 8.28 mm, which was within the normal range of deformation, indicating that the dam foundation had been working normally.

"Integral structure" refers to the adoption of the scheme of an expanded integral foundation structure after comparing the two schemes of "the independent foundation pad" and "the expanding integral structure" after the expanded excavation and swapping excavation for the foundation. Normative methods, linear elasticity and nonlinear finite element method were employed to verify the stress and stability of the arch dam, and the results of foundation treatment and the overall stability and dynamics of the arch dam were also analyzed. Computations for the "integral structure" scheme indicate that, after the expansion of excavation for the foundation at the base of the arch dam, although the hydraulic thrust has increased, the rigidity and strength of the dam foundation have also improved. The expansion of excavation for the foundation has not impacted upon the overall pattern of the distribution of the shift and stress of the arch dam. The level of the integrated deformation modulus of the foundation at medium to lower elevations of the arch dam has improved modestly compared with the optimized design, and the integrated deformation modulus at adjacent elevations on the foundation surface of the arch dam is more uniform than that of the optimized design. The shift and stress of the arch dam have almost the same pattern of distribution, and the magnitudes of the shift and stress are identical. The shift and stress of the dam body under the effect of load portfolio and during the construction conform to design requirements. Tests using geological dynamics models indicated that after integral excavation on the foundation surface to the elevation of 324.5 m, the dam height increased slightly and the total load rose; however, as there was dovetailing concrete in downstream and concrete swapping had been carried out on the dam abutments in lower strength, the rigidity of the foundation improved modestly; the damaging process of the upstream and downstream faces and the foundation was largely consistent with the feasibility study and the optimized scheme, but the safety level was higher, with the crack-inducing load at the upstream dam heel $K_1 = (2.0 \sim 2.5) P_0$, non-linear deformation load $K_2 = (5.0 \sim 6.0) P_0$, and the maximum load $K_3 = (9.0 \sim 9.5) P_0$. On the basis of computation analysis of the arch dam structure, engineers carried out the comprehensive comparative analysis of the long-term safety of the structure, control of construction quality, and the construction schedule, and eventually opted for the scheme of expanding the integral structure of the foundation. They also set up sound demarcation lines for concrete swapping, concrete with dovetailing angles, and concrete for the structure of the dam body, and formulated rationalized designs for locations with structural changes to prevent stress concentration. Fig. 3 shows a cross section of the integral structure of the arch dam after the swapping excavation and expanded excavation on the riverbed at Xiluodu arch dam.

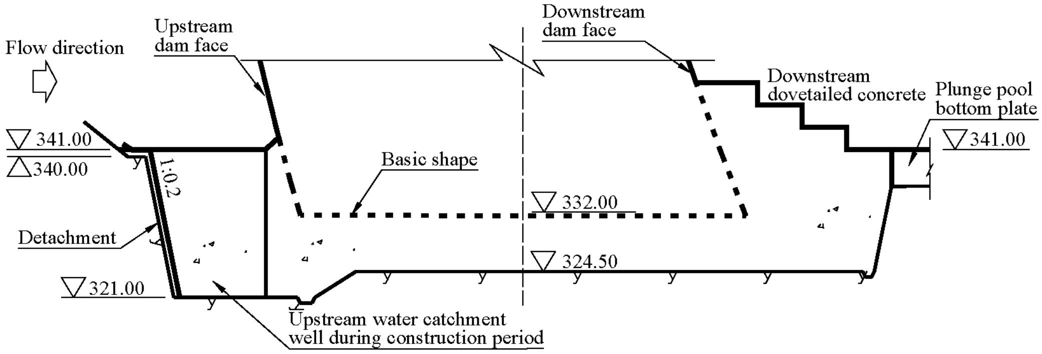

Fig. 3 Cross section of the expanded integral structure of the foundation of Xiluodu arch dam (No. 15 cross joint profile) (unit: m)

"Continuous concrete placement" refers to continuous concrete placement at an elevation above 324.5 m in accordance with the technical requirements of concrete construction in the foundation constraint zones. To ensure the quality of consolidation grouting, covered grouting (6 m) was introduced, and to reduce concrete cracking due to extended stoppage, 5 consolidation grouting operations are carried out simultaneously (namely construction in order of lifting holes and diversion holes, grouting holes, and inspection holes). "Continuous concrete placement" also means that concrete placement at the expanded excavation zones as angle dovetailing at the dam toes is carried out at the time of concrete placement for the dam body.

2.4 Anti-crack design and temperature control for the arch dam

2.4.1 Overall anti-crack requirements of the arch dam

Given the fact that the overall bearing structure of concrete arch dams is characterized by compressive stress and relatively even distribution of stress, the concrete itself must have good dynamic properties in order to meet the strength and durability requirements of the arch dam, and the uniformity and integrity of the concrete must also be ensured in order to give full play to the arching effects and to improve the safety of the arch dam. On one hand, the arch dam structure must have seismic resistance design and level of seismic safety below the checking earthquake standards, especially in the phase of project operations. In the wake of the devastating earthquake in Wenchuan, systematic anti-crack steel meshes (beam direction $\phi40@300$ and horizontal direction $\phi28@500$) were installed on the upstream and downstream surfaces of the Xiluodu arch dam, and working-face steel meshes ($\phi32@500\times500$) were set up in the joint conjunction areas of the foundation constraint zones and the sections of the dam with steep slopes. On the other hand, during the construction period, no harmful cracks should occur, and primarily no penetrative temperature-induced cracks or splitting cracks in the foundation or structural cracks under the cantilever conditions should occur. The foregoing structural reinforcement measures against cracking have played a significant role in preventing temperature-induced concrete cracking and their subsequent expansion.

2.4.2 Concrete performance and mixture ratio design

Concrete in the dam body is divided into 4 areas by class of strength level according to the stress distribution of arch dam, characteristics of the structural layout of the dam body, concrete strength and durability, scouring resistance, erosion resistance, and cracking resistance during the construction period. Concrete of area A ($C_{180}40F300W15$) is located in the foundation and around the deep holes and surface holes. Concrete of area B ($C_{180}35F300W14$) is located over a certain range above the foundation of each section of the dam. Concrete of area C ($C_{180}30F300W13$) is located at upper elevations of No. 6 ~ No. 10 and No. 21 ~ No. 24 dam sections. Additionally, there is concrete at tunnel openings and gate pier zones ($C_{90}42F300W15$). Concrete of area A has ultimate tensile strain of not less than 1.00×10^{-4} and volume shrinkage deformation of not more than -20×10^{-6}. The concrete design envisions an age of 180 d to make full use of the strength of the concrete in subsequent phases. Given the divided-joint structure and concrete zoning characteristics of the Xiluodu arch dam, the foundation constraint zones and the opening constraint zones are the key areas for temperature control aiming at preventing cracking in the arch dam.

Coarse basalt aggregates are used for the production of concrete for the Xiluodu arch dam. The concrete mixture ratio for the Xiluodu arch dam has the following characteristics. First, the coarse aggregates were made of excavated basalt during underground work. To improve concrete properties, the aggregate processing system was renovated; the sieve mesh size of the screening system was adjusted to minimize powder among the aggregates; the secondary sieving system of the mixing plant was used to enhance the conformance rate of exceeding and inferior grains in the aggregates. Second, the fineness modulus of the limestone aggregates was capped at 2.6 ± 0.1 and the water content was capped at $\leqslant 6\ \%$. Third, moderate-heat cement with high content of MgO was used. In addition to full compliance with applicable national standards, cement strength was set at (50 ± 2.5) MPa, specific surface area at $\leqslant 320\ m^2/kg$, and MgO content at 4 % ~5 %. Fourth, Grade I flyash was used and its content was set at 35 %. Fifth, new-generation water reducers and high-quality air entraining agents were introduced. Water reducers were selected from the naphthalene series of JM-ⅡC and ZB-1A, and air entraining agents were selected from AIR202, ZB-1G and JM-2000. Sixth, concrete mixed with KS-1500 modified PVA (polyvinyl alcohol) fiber (with density of $1.28\ g/cm^3$, tensile strength $>1\ 500$ MPa, elasticity modulus >38 GPa, and fracture elongation of 7 % ~ 8 %) was placed at the foundation of the dam sections on steep slopes and concrete working face where placement might be halted for extended periods. At the ages of 7 d and 28 d, concrete mixed with modified PVA can improve the ultimate tensile strain by about 10 %

and reduce its autogenous volume deformation by 15.0×10^{-6}. Seventh, tap water was used to mix the concrete. Grade 4 concrete (with a slump of 2 ~ 4 cm) for area A of the Xiluodu arch dam had unit water requirement of 81 kg, cement requirement of 129 kg, flyash requirement of 69 kg, and total gel requirement of 198 kg. Actual tests show that the concrete materials for the Xiluodu dam and the parameters of concrete compressive strength, splitting tensile strength, ultimate tensile strain, frost resistance, and impermeability all conform to design requirements. The high content of MgO played a role in improving the concrete autogenous volume deformation, but the effect was limited. Most tests showed that the concrete autogenous volume deformation could barely meet the design requirement of -20×10^{-6}.

Therefore, stringent temperature control techniques and construction measures were introduced for the Xiluodu arch dam, and even more stringent standards and processes were established for the maximum concrete temperature, temperature process, and surface insulation and curing, in order to ensure the concrete safety in cracking resistance.

2.4.3 Temperature control for concrete placement in total-process

The outlet temperature of concrete for the Xiluodu arch dam was maintained at 7 ℃ in hot seasons (from May to September) and 9 ℃ in cold seasons (from October to April). The temperature of concrete upon entry into the silo was capped not higher than 11 ℃ in cold seasons and 9 ℃ in hot seasons. Placement temperature was capped not higher than 12 ℃ all year round. The maximum concrete temperature was capped at 27 ℃. A leeway of 1 ~ 2 ℃ was allowed during the hottest summer days after the concrete was detached from the foundation constraint zone, and concrete temperature in the foundation constraint zones on the sections of the dam on both banks was capped not higher than 25 ℃. Thus, the coarse aggregates were subjected to secondary air cooling and mixed with flake ice and cold water. There were 3 concrete mixing plants of $4\times4.5\ m^3$ with an hourly output capacity of $750\ m^3$ of 7 ℃ concrete. For horizontal transport, side dumpers were used instead of rear dumpers, and concrete transport cycling tunnels were dug. The skills of side dumper drivers and cable car drivers were enhanced. Five 30-ton translation cable cranes were deployed, with point location techniques and trajectory analysis system to ensure rapid entry into the silo. Large-scaled spreaders and vibrators were used, and seamless integrated coordination and management were provided for concrete placement. In summer, time slots for concrete placement were carefully controlled, and mist spraying on the working face was increased (when the temperature inside the placement silo exceeds 23 ℃) to bring down the ambient temperature of the working face. Refrigerating water was supplied through pre-embedded pipes for cooling purpose, and the interval of placement for concrete layers was capped within 14 d.

In hot seasons, concrete was cured with flowing water, and in the upstream and downstream areas, temperature was maintained at constant level to ensure curing. In cold seasons, concrete was cured primarily through insulation, and freshly placed concrete which could not be insulated was kept moist. The working face was cured through jet spraying, while the upstream and downstream surfaces and the cross-joint face were cured with flowing water. On the basis of field tests of different types of insulation materials, engineers introduced extruded polystyrene (XPS) foam boards with thickness of 5 cm and 3 cm for the upstream and downstream dam surfaces, but in the downstream surface of the foundation constraint zones on the sections of the dam on steep slopes, polystyrene boards with thickness of 5 cm were used, and polyethylene coils (EPE) with thickness of 5 cm were used for the cross-joint face. The walls of tunnels inside the dam body were insulated with sprayed coats of polyurethane with thickness of 2 ~ 4 cm, and the upstream and downstream tunnel openings were sealed up.

2.4.4 Cooling and temperature controlling techniques for concrete water pipe

The water pipe cooling process for controlling the temperature of concrete at Xiluodu was carried out in 3 phases, the first phase, the medium phase and the second phase. Cooling water pipes were typically spaced 1.5 m (horizontal) × 1.5 m (vertical). For concrete placed in the foundation constraint zones and during hot seasons, cooling water pipes were spaced 1.0 m (horizontal) × 1.5 m (vertical). Considering temperature change after the dam body was exposed to water, two cooling water supply systems were set up, with one supplying 8 ~ 10 ℃ water and the other supplying 14 ~ 16 ℃ water. In the first phase, cooling water was supplied for about 21 d at a stretch, and in the medium phase, the second phase and joint grouting phase, the temperature reduction and supply of cooling water lasted more than 45 d, 90 d and 120 d at a stretch respectively. For cooling in the first phase and temperature control in the medium phase, 14 ~ 16 ℃ water was used, while for temperature control in the first phase and cooling in the second phase, 8 ~ 10 ℃ water was used. In the first, medium and second phases, the target temperatures of the concrete for the Xiluodu arch dam were set at 21 ℃, 17 ℃ and the arch sealing temperature (12 ~ 16 ℃) in all locations, respectively. During the temperature control stage, concrete temperature in all phases was to be brought down as close to the target temperature as possible, and temperature rebound was to be minimized. In actual operation, through the "Digital Dam" information system, temperature rose and fell and temperature control was monitored on a real-time basis, and water flows and temperature were promptly regulated, thus ensuring "small temperature difference, slow cooling, and early cooling" during the temperature control process.

The important concrete temperature control measures for the Xiluodu arch dam included individualized intensive cooling by water in stages, comprehensive year-round surface insulation and curing, and strict control of placement intermission. With effective temperature control measures, the temperature of concrete for the Xiluodu arch dam was well controlled, with target temperature, temperature drop rate, and temperature change magnitude enjoying a high conformance rate. In 2010, a total of 1.59 million m^3 concrete was placed, with the highest monthly placement standing at 170 000 m^3; the 7.0 ℃ outlet temperature had a conformance rate of 99.5 %; the placement temperature had a conformance rate of 96.5 %, and the highest temperature was largely capped at 25 ℃. Concrete temperature reduction and actual temperature control processes conformed to design requirements. No temperature-induced cracks occurred in 3 million m^3 concrete continuously placed after the consolidation grouting for the sections of the dam on the riverbed.

2.5 Grouting of joints

Joints on the Xiluodu arch dam were grouted vertically. From top to bottom, the dam is divided into 5 areas: grouted area, to-be-grouted area, simultaneous cooling area, transitional area, and weight covering area. There are two simultaneous cooling areas below the elevation of 515 m, and one simultaneous cooling area above the elevation of 515 m. The height of joint grouting areas typically is 9 ~ 12 m. In principle, the age of concrete on the sections of the dam on both sides should not be less than 120 d, and the joint grouting openness should not be smaller than 0.5 mm; joint faces smaller than 0.5 mm are grouted using finely ground cement, and chemical grouting can be introduced when necessary. During the grouting of joints, temperature of the concrete on two adjacent sections of the dam in the grouting area at the same elevation should be simultaneously brought down to the arch-sealing temperature, and it's important to ensure that the grouting area and the simultaneous cooling area, transitional area, and weight covering area meet the temperature cascade requirements. So, first, it's important to minimize the height difference of two adjacent concrete blocks and the height difference of the entire dam. The height difference of two adjacent concrete blocks should be capped at 12 m and can be fine-tuned in certain locations, and the height difference of the entire dam is capped at 30 m to ensure that the dam can rise rapidly and evenly. Second, the cantilever height should be strictly controlled. It's important to ensure that concrete placement for all dam sections and joint grouting go up evenly. When concrete placement for the arch dam is carried out at an elevation below 410 m, the cantilever height should be capped not more than 80 m. When the elevation exceeds 410 m, the maximum cantilever height on the dam sections at the tunnel openings can be set at ≤50 m, while the maximum cantilever height on the dam sections at the non-tunnel openings can be set at ≤60 m. If the cantilever height limit is to be exceeded, technical feasibility should be established before hand. Third, it's also important to coordinate the time slots for cooling in stages and temperature control, and to ensure that the temperatures in all upper areas during joint grouting and temperature drops form a proper cascade. Moreover, it is also necessary to consider the possibility of temperature differences caused by inconsistent progress of construction on different dam sections, with a view of minimizing concrete cascade temperature stress and preventing concrete cracking.

Uniform concrete placement for the arch dam is essential to the quality of joint grouting, and has a considerable effect on the adjustment of the stress conditions during the construction period. In the summer of 2011, concrete was placed for the arch dam at the lowest elevation of 459 m and the highest elevation of 488 m. So far, the bottom diversion holes have been completed, and construction of deep holes for flood discharge is underway. The entire dam is inclined towards to the upstream side; the joint grouting elevation stands at 413 m, and the largest cantilever height stands at 75 m, but the cantilever height of the arch dam during certain periods exceeds design requirements. Simulation analysis indicates that the bulk of stress on the joint face towards the arch is slight tension, and the upstream locations with dovetailing angles have tensile stress of 0.7 ~ 1.0 MPa. There is noticeable concentration of stress in the locations between the dovetailing angles and bedrocks, but the design requirements are still satisfied.

3 Construction and initiative of Xiluodu "Digital Dam"

3.1 Purpose

The China Three Gorges Corporation has built the Xiluodu "Digital Dam" in collaboration with scientific research institutes and higher-education institutions. Based on the theory of total life cycle management, this particular system is characterized by "unified models, platforms and interfaces, accurate data, comprehensive and timely information sharing, full alignment with production needs, accurate forecasting and early warning, and simple, straightforward and graphic applications". The "Digital Dam" covers the arch dam design research stage, construction execution stage, and operation maintenance stage. It has unified three-dimensional system models, platforms and interfaces, and provides management for the total process of design, planning, construction, production, quality control, and application of research findings. Since the very beginning of dam construction, the "Digital Dam" system has been providing comprehensive, accurate and timely data on all construction disciplines throughout the process. It also offers access to data collected, analyzes data, provides feedback, and presents the data in a graphic manner. In line with construction progress, the "Digital Dam" system provides digital simulation and analytical computations, formulates technical standards and threshold values, establishes threshold levels, and offers scientific forecasting and early warning. The system serves the primary purpose of effectively monitoring the risks of concrete cracking and the state of stress deformation of the arch dam. It's dedicated to facilitating quality control for field concrete placement, prevention of concrete cracking through temperature control, and foundation treatment, as well as the determination of safety status of the arch dam during the construction period and all stages of the operating phase. It plays a vital role in ensuring the high quality of the Xiluodu project.

3.2 System composition

The Xiluodu "Digital Dam" system consists of two parts: the construction monitoring system and the simulation analysis system. The construction monitoring system collects and displays information on field designs, project progress, quality, and construction monitoring. It collects data relating to concrete placement plans, raw material testing, concrete production, concrete transport, field placement, concrete temperature control, field safety monitoring, consolidation grouting, curtain grouting, joint grouting, and installation of metal structures. It is an information sharing and working platform which covers the entire process of dam construction and involves all builders. On the basis of analysis of the data from the construction monitoring system, the simulation analysis system assesses the dam overall safety status, stress conditions, risks of cracking, and thorny construction issues. It collects and displays information on three-dimensional geological models, computational boundary conditions, gridding, stress, and strain computation results. The construction monitoring system is the foundation of the simulation analysis system; the mass data collected by the construction monitoring system ensures the reliability of the results of simulation analysis; the simulation analysis system is the application and extension of the construction monitoring system; both systems serve the quality of field construction.

3.3 Preliminary application results

Since its inauguration, the Xiluodu "Digital Dam" system has collected a vast amount of data. Through an unified platform and interface, this particular system enables design and research institutes to completely play their roles. With the field and back office support of scientific research institutes and higher-learning institutions, numerous thorny technical issues in the field have been studied in advance and resolved, paving the way for the smooth placement of concrete for the Xiluodu Dam and for the prevention of cracking in the concrete.

With the integrated analytical curves of concrete temperatures from the "Digital Dam", engineers are able to monitor any situation on the real-time basis and dynamically regulate water temperatures and flows to ensure "small temperature difference, slow cooling, and early cooling". The maximum concrete temperature, temperature drop rates in all stages, and magnitude of temperature changes in the temperature control stage all conform to design requirements. The curves of actual changes in concrete temperatures largely match the curves of designed temperature processes.

Efforts to prevent temperature-induced cracking in concrete are focused on tunnel openings and concrete in winter. According to the research results, the China Institute of Water Resources and Hydropower Research (IWHR) recommended that in the first phase, the concrete of the bottom diversion holes in higher locations should be cooled down in 3 stages in a slow but steady manner to prevent concrete cracking around the tunnel openings. In the first phase, the target temperature was set at 25 ℃; in the second phase, concrete temperature was maintained at about 25 ℃ for 5 ~ 7 d; in the third phase, concrete temperature was gradually brought down to 20 ~ 22 ℃. In the first phase, temperature drop was maintained at not higher than

0.3 ℃/d for at least 30 d. In view of the findings of *Research of Concrete Temperature Control Measures in the Winter of 2010*, the IWHR recommended strengthening surface temperature insulation, optimizing and modestly accelerating the medium-phase and second-phase cooling process, providing adequate surface insulation for early-age concrete, and reducing temperature differences in and outside concrete. With the above measures, in the winter of 2010, no single crack was discovered in the concrete. In view of the extended intermission of concrete placement in winter for the No. 3 bottom diversion hole on the Xiluodu arch dam and the considerable risks of cracking, Tsinghua University carried out the comparative analysis of two placement schemes (1.0 m and 1.5 m thin layers for the first placement of top plates). Simulation results indicated that in the 1.5 m placement scheme, tensile stress was significantly reduced, thus enhancing the prevention of concrete cracking. So the 1.5 m placement scheme was adopted in actual construction and received good results.

On the basis of data collected by the "Digital Dam" system, engineers used distributed optical fibers to monitor the cold shock of old concrete by freshly placed concrete, and analyzed the feedback. The results showed that in hot seasons, freshly placed concrete had significant cold-shock effect on old concrete below, causing the surface temperature drop of the old concrete in the lower layer by more than 10 ℃ and the tensile stress increase up to 1.0 MPa. Thus, the time of opening up concrete silos depended on weather conditions, and concrete placement in high-temperature time slots was avoided. Working faces where concrete was to be placed were usually sprayed with water or mist for 2 h in advance, thereby bringing down the working-face and ambient temperature.

4 Conclusions

By the end of August 2011, the Xiluodu arch dam had reached the highest elevation of 488 m and the lowest elevation of 360.5 m, the cumulative concrete load of 3 170 000 m^3, and the monthly highest grouting load of 210 000 m^3. The researches on the essential technical issues of the arch dam have laid solid foundation for the smooth and successful progress of the project and the research results have been well proven in practice. According to the construction experience of the arch dam, the following issues need to be emphasized in the construction of high arch dams of western hydropower projects.

Firstly, it is necessary to attach great importance to the geological conditions of the dam section along the riverbed and the safety of the dam structural designs. 4 major design amendments have been made in the process of the excavation of the arch dam base below the elevation of 400 m. The construction of the arch dam of Baihetan Hydropower Project will confront such problems as uneven terrains and geologies as well as deformed and loosened basalts at columnar joints at the low parts. The arch dam of Wudongde Hydropower Plant will confront such problems as thick coverings and deep weathered troughs at the dam section along the riverbed. Considering the complexity of geological conditions and the serious safety risks associated with geological surveys on the main riverbed of the main stream, it is necessary to take effective measures to know about the geological conditions at the dam site, particularly where the riverbed is located, and hence minimize the negative impact of geological uncertainties on structural designs and constructions. Meanwhile, the structural design of the arch dam shall be able to accommodate the changes in geological conditions and systematic researches shall be conducted on the designs and applications of the arch dam's pillow so as to make sufficient technical preparations for the complicated geological conditions that may be encountered in the construction of high arch dams of hydropower projects in Southwest China.

Secondly, it is necessary to choose high quality raw concrete materials to guarantee sound temperature control and anti-cracking effect of the concrete. Concrete with microswelling property and deformability are insensitive to temperature change and resistant to cracks and hence can guarantee safety of the dam. Massive concrete tests on the arch dam of Xiluodu Hydropower Project demonstrate that the ultimate drawing length of concrete primarily depends on the elasticity modulus of aggregates; the volumetric deformation of concrete primarily depends on the mineral elements of cement. The tested cement still has contractibility although the MgO content approaches the high limit of 5.0 %. In order to compensate for such contractibility of cement, first, it is necessary to select limestone aggregates and also the raw materials, forging techniques and mixed grinding techniques that are conducive to the productions of MgO-containing microswelling cement and properly design the mixing ratio of concrete on one hand. Second, it is necessary to conduct researches on the mixing of softly-burnt MgO in cement and preferentially guarantee the technical process and quality of softly-burnt MgO. The softly-burnt MgO crystals with the forging temperature below 1 000 ℃ have well-developed structures and high activity and their hydration reactions can be completed at the early stage to avoid the adverse impact of delayed hydration reactions on the concrete durability. Third, it is necessary to increase application of low-heat Portland cement in the arch dam and conduct necessary large-scale construction experiments on low-heat cement. Compared with medium-heat cement, 42.5 low-heat cement can reduce the concrete temperature rise by 7.5 ℃ if it is adopted in the wear-resistant concrete C9060 (secondary aggregates). Today, low-heat cement has already applied at the Longluowei Section of the flood-discharge tunnel of Xiluodu Hydropower Plant and the parts of the bottom plates of Xiangjiaba stilling basin where cracks may easily take place. In the next stage, researches will be conducted on the concrete design and construction technologies for the applications of low-heat cement in the whole arch dam.

Thirdly, it is necessary to strengthen systematic researches on the temperature control and joint grouting technologies of super high arch dams and understand the rules thereof. The arch dam of Xiluodu Hydropower Plant is characterized by the methodology of "long-term temperature preservation and full-year full-dam low-temperature concrete grouting and refrigerating pipe cooling" and the guideline of "small-range temperature difference, early cooling and gradual cooling" for real-time concrete temperature control. Measures are also taken to continuously strengthen understanding of the rules of concrete temperature change at the steep dam sections and orifices, at high summer temperatures and upon sharp temperature declines in winter. A dynamic temperature grading is created from the top to down, including the grouting zone, cooling zone, transitional zone and covering zone, having the height of the restrictive zone being the unit in the vertical direction so as to ensure the quality of joint grouting and the integrity of the dam.

Fourthly, it is necessary to further study the temperature conditions and flood dissipation features of the reservoir at the arch dam so as to guarantee environment friendliness of the hydropower plant. In order to guarantee that the water inlets of the plant are accessible by the upper and medium-layer water of the reservoir in different working conditions, the water inlet of Xiluodu Hydropower Plant is designed to be a 4-layered stoplog (single leaf height of 12 m) for water intake in 5 layers. This stoplog design is expected to have higher water temperature in spring and lower water temperature in winter (closer to natural water temperature) compared with the single-layer water inlet. For that reason, the impact on the downstream water temperature is minimized to maintain the original ecological conditions in downstream river courses. Ski-jump energy dissipation is adopted for the dam and flood-discharge tunnel of Xiluodu Hydropower Plant. Oversaturated condition observation and model test of gases in the downstream river courses have been conducted. The flood discharge method that has the minimum impact on gas over-saturation is adopted according to different flood frequencies, the ecological habits of fishes and the distribution of water temperature.

Fifthly, it is necessary to further improve the "Digital Dam" system in the full working life of the arch dam. Based on continuous improvement of information integration, inquiry and display, efforts will be taken to strengthen prediction and forecast of data and improve the level of intelligentization. It is necessary to cross-verify the prototype monitoring results and the digital simulation results, keep improving the model of digital simulation and adjusting the model parameters, and dynamically recheck and forecast the working properties of the dam, so that the system can be more useful and instructive.

Sixthly, it is necessary to implement professional and stable management of the dam construction and establish a professional work team to ensure the construction quality of the dam.

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