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SUPER ENGINEERING

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Key technical innovations in the construction of Baihetan Hydropower Station Project

Keywords ultra-high arch dam, columnar jointed basalt, low-heat cement concrete, temperature controlled crack prevention, million-kilowatt unit, intelligent construction

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Supervisors: Yangtze Three Gorges Technology & Economy Development Co., Ltd., Yangtze River Design Group Co., Ltd., Sichuan Ertan International Engineering Consulting Co., Ltd.

Construction units: China Energy Engineering Co., Ltd., Power Construction Corporation of China

1 Project positioning

Baihetan Hydropower Station is classified as the second of the four hydropower cascades in the lower reaches of the Jinsha River: Wudongde, Baihetan, Xiluodu and Xiangjiaba. As an important backbone project for China to implement the strategy of West-to-East Power Transmission and optimize the energy structure, it constitutes an important part of the Yangtze River flood control system. Located at the junction of Ningnan County, Sichuan Province and Qiaojia County, Yunnan Province, the hydropower station is the largest hydropower project under construction in the world, with a unit capacity of million-kilowatts ranking the highest in the world and a total installed capacity of 16 million kW, second only to the Three Gorges Project, ranking the second in the world.

As the world’s largest hydropower project under construction, Baihetan Project has won many of the world’s best: Ranking first in the world in terms of the scale of underground cavern group, the unit capacity, the seismic fortification index of 300 m high dam, the scale of cylindrical tailrace surge shaft, the scale of non-pressure direct spillway tunnel, and the use of low-heat cement concrete for the whole 300 m high dam.

2 Project overview

The controlled basin area of the dam site of Baihetan Hydropower Station (Fig. 1) covers 430300 km^2, accounting for 91% of the basin area above the Jinsha River. The normal pool level of the reservoir is 825 m, the limited flood control water level is 785 m, the total storage capacity is 20.627 billion m^3, the regulating storage capacity is 10.436 billion m^3, and the average annual power generation is 62.443 billion kWh. The power station hub (Fig. 2) is mainly composed of river dam, flood discharge and energy dissipation facilities, water diversion and power generation system, etc. The dam is designed as a concrete double-curvature arch dam. The arch length of the dam crest is 709 m, the maximum dam height is 289 m, and the “eggshell” design of the dam can withstand the hydraulic thrust at 16.5 million tons. The whole dam is made of normal low-heat cement concrete, with a crack-resistant safety factor of more than 2.0. The dam body is provided with 6 surface holes and 7 deep holes, with a maximum discharge of 30098 m^3/s. Behind the dam, energy dissipation is carried out through the water cushion pond with the “compound trapezoidal section with inverted arch bottom plate” and the concrete gravity subsidiary dam. Three 2170–2317-meter non-pressure straight spillway tunnels are arranged on the left bank, which are composed of the entrance gate section, the upper flat section, the tailgate section and the flip

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Fig. 1 Panorama of Baihetan Hydropower Station.

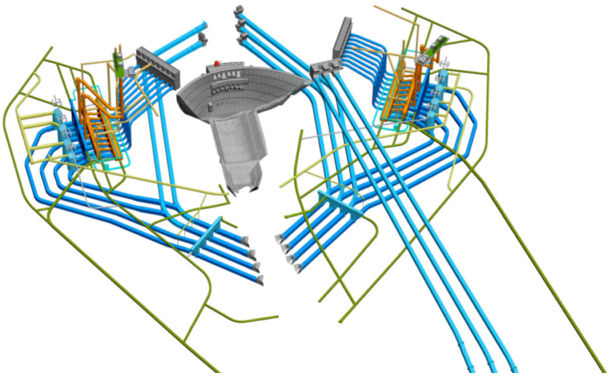

Fig. 2 Building layout of Baihetan Hydropower Station hub.

bucket, with maximum discharge arriving at 12250 m^3/s, which can withstand the once-in-ten thousand years flood in combination with the dam orifice. The underground powerhouses on both banks adopt the first development layout plan, and the two banks are basically symmetrically arranged. The excavation size of the main powerhouse is 438 m × 34 m × 88.7 m, the excavation radius of cylindrical impedance tailrace surge chamber is 43–48 m, and the height is 112.1–128 m. The tailrace tunnel in front of the tailrace surge chamber is arranged with one machine in one tunnel, while the rear of the surge chamber is arranged with two machines in one tunnel. There are more than 400 permanent tunnels, construction tunnels and various vertical shafts in total; various caverns are complex, with a total excavation length of about 217 km and a total excavation volume of about 25 million m^3. The powerhouses on the left and right banks are respectively equipped with 8 water turbine generator units with a unit capacity of 1 million kW, with the height of a single water turbine generator unit being 50 m and the weight being more than 8000 t, all of which are domestic manufactured.

3 Technical innovations

The Baihetan Hydropower Station Project is large in scale with complex geological conditions, making its technical difficulties ranking first among similar projects. In the face of numerous difficulties and obstacles, the world-class technical problems such as the excavation of the columnar jointed basalt dam foundation, the temperature controlled crack prevention of the 300 m super-high arch dam, and the stability of the surrounding rock of the excavation of huge underground cavern group have been conquered, and a number of advanced construction methods such as the "defect-free" construction of concrete for the high-velocity spillway tunnel have been formed. The comprehensive research and application of intelligent construction technology has promoted the transformation from traditional hydropower construction to intelligent construction. The comprehensive localization of the million-kilowatt water-turbine generator unit marks the fact that China's hydropower equipment development has entered the "unmanned zone". The Baihetan Hydropower Station Project has reached the world's leading level in planning and design, equipment manufacturing, material science, construction technology and intelligent construction, which is a landmark project for hydropower project construction in China and even the world.

3.1 Key technologies for excavation of columnar jointed basalt dam foundation

The geological conditions of Baihetan arch dam are complicated: The rock mass of the dam foundation is mainly composed of massive basalt, columnar jointed basalt, breccia lava, etc., and the interlayer and intralayer dislocation zones are developed; excavation may cause relaxation of the columnar jointed basalt dam foundation and deformation of the gently inclined staggered zone, and destroy the thin layer of breccia lava in the river bed, which brings about difficulty in comprehensive technology. To solve the above problems, a large amount of exploration work has been carried out before the commencement of the project: The number of exploratory drilling holes reached 4500 (with a length of 200000 m), and the number of exploratory adits arrived at 440 (with a length of 55000 m), the exploration workload of which is incredibly heavy. After detailed geological exploration, multi-method and multi-scale test and detection, theory-simulation-monitoring inversion, and other studies, the mechanical characteristics and relaxation evolution law of basalt rock mass have been mastered, and technical innovations in the basalt engineering rock mass deformation modulus, comprehensive utilization of strength and time-dependent deformation control have been realized, thus the column jointed basalt is used as the foundation of the 300 m super-high arch dam for the first time. Furthermore, on the basis of mastering the mechanism of mechanical properties of columnar jointed basalt, a new comprehensive treatment method of dam foundation, including active protection, fine excavation, rapid support, and combined treatment of relaxation and deformation limitation, was proposed, and innovative technologies such as zonal and graded excavation of double protective layers, heavy consolidation and grouting of rock cover, composite energy dissipation blasting, and deep rapid anchoring were developed. A complete set of foundation surface excavation protection treatment methods and comprehensive treatment measures for dam foundation excavation have been developed to ensure the good quality of dam foundation excavation.

3.2 Key technologies for safe, high-quality and efficient construction of super-high arch dam

In view of the difficulties in safe, efficient and high-quality construction of 300 m super-high arch dam, the "3 + 4" double-layer translational multi-cable crane transportation system has been constructed; the high-low line concrete production system and the feeding platform have been arranged; and the difficulty in cable crane group occupation and efficient allocation has been solved so as to realize simultaneous casting of multiple silos, providing the basic conditions for the rapid construction of arch dam. With innovative research and development and use of hydraulic climbing formwork, special formwork for waterstop setting, flexible variable-diameter pipe drawing, self-climbing turntable, gallery setting formwork and trolley and other formwork technologies, high-quality construction of concrete with accurate shape has been realized. Intelligent equipment for concrete construction such as intelligent leveling, intelligent vibration and intelligent roughening has been developed to improve the technical level of high-quality concrete construction. Based on the multi-dimensional coupling construction schedule simulation theory, the intelligent monitoring system for the whole links of concrete production, transportation and casting has been developed, and a series of complete technologies for rapid construction of key lines and key parts have been formed. The 289 m high dam has been completed in 50 months, creating the highest record among similar projects in terms of the maximum casting of 273000 m^3 in a single month, a casting of above 2 million m^3 for three consecutive years, and a yearly peak casting of 2.7 million m^3.

3.3 Key technologies of temperature controlled crack prevention for concrete of super-high arch dam

To solve the technical problems of temperature controlled crack prevention of mass concrete, the application of low-heat cement concrete in the whole dam is realized through the research method of "experimental research + numerical simulation + experimental verification + application optimization" based on the experience of partial application of low-heat cement in the Three Gorges Power Station and other projects, as well as the characteristics of Baihetan limestone aggregate and the dry and windy climate of the dry and hot valley in the dam area. The formulation of technical standards for low-heat cement and rules for production supervision ensures the excellent quality of low-heat cement from the source. Through a series of basic tests, such as temperature stress test, fracture performance test and negative surface capillary pressure test, of low-heat cement concrete, the basic properties of low-heat cement are mastered. Based on the application concept of "large aggregate, multistage mixing and low slump", the ingredient proportion of low-heat cement concrete is optimized. Moreover, the construction method and temperature control strategy corresponding to low-heat cement concrete have been explored and formed based on the application of low-heat cement in the whole dam through on-site vibration test, roughing test, setting time test, early strength test and other construction tests. Specifically, the temperature control concept of "small temperature difference, slow cooling, early insulation, long curing" has been put forward, and a series of standardized temperature control processes such as concrete precooling, thermally-insulated dump truck transportation, and intelligent spray cooling have been implemented. With the comprehensive application of the intelligent water supply system, the whole process of concrete water supply and cooling can be precisely controlled, thus the difficulty in temperature controlled crack prevention of mass concrete has been solved. The concrete structure with more than 8 million m^3 of the Baihetan dam has not been found even one temperature crack, building a real "seamless dam" (Fig. 3), and breaking the spell of "no dam without crack" in the world's dam industry.

Fig. 3 Seamless dam.

3.4 Key technologies for safe and efficient construction of huge underground caverns

Baihetan underground cavern group has a large scale and complex geological conditions, which is characterized by high ground stress, distributed interlayer (internal) dislocation zone and hard and brittle basalt, and the problem of excavation fracture relaxation is prominent, with a risk of catastrophic instability of high side wall and cavern collapse. To address the above problems, firstly, multi-level mechanical characteristics of rock mass, discontinuous deformation characteristics, and spatiotemporal joint deformation and damage effects have been comprehensively revealed through advanced means such as large-scale simulation test tunnel, in-situ seepage deformation test, high-precision acoustic wave test, and fiber grating monitoring, so as to establish the optimization method of space-time excavation sequence of giant underground caverns with complex geological conditions. Secondly, with the complete set of deformation and stability control technologies such as “pre-anchoring, pre-positioning and dynamic optimization” and the feedback control and prevention technology for discontinuous deformation of long and large staggered zones, safety risks encountered in the construction process have been eliminated. Thirdly, through the research on the disturbance mechanism and response characteristics of the excavation blasting of the large-span underground cavern group under high ground stress, a complete set of refined excavation blasting technologies for underground powerhouse, including the excavation technology of the large-span roof arch layer, the forming technology of the rock wall crane beam, the stability control technology of the high side wall, and the construction technology of the intersection and connecting parts, has been developed, effectively reducing the excavation disturbance and the linkage effect of the cavern group. Finally, a complete set of construction equipment consisting of new vertical shaft transportation system, rock anchor beam construction trolley and top arch mobile operating platform has been developed, and the once-forming construction technologies of pilot shaft and normal shaft of shaft raise boring rig with diameter of 600 m under complex geological conditions have been innovated, which not only improve the efficiency but also ensure the safety and quality compared with traditional equipment and measures.

3.5 Key technologies of mirror concrete construction of high-flow-rate and large-discharge spillway tunnel

The spillway tunnel of Baihetan Hydropower Station is the largest non-pressure spillway tunnel group in the world, with the characteristics of high water head, large flow, high velocity and complex shape; the high velocity brings a series of problems such as cavitation, erosion and wear. In order to meet the requirements of long-term safe and stable operation of the project, a high-performance lining concrete with “low-heat cement, low slump, no silica fume, low content of cementitious materials and high strength grade” has been developed to settle the contradiction between high strength and crack resistance of the lining concrete of the spillway tunnel. Meanwhile, the construction equipment such as automatic concrete conveying equipment with large slope and low slump, and liftable full-cover multifunctional special trolley with large section, variable slope and special-shaped structure that can complete casting and formation at one time has been invented, breaking through the conventional tunnel concrete construction technology and providing precise control of full-section shape and high-quality, safe and efficient construction of overflow surface concrete. Furthermore, the construction methods such as five-step construction of “rolling, filling, rubbing, plastering and closing” of the bottom slab lining concrete and the smooth connection of construction joints have been created to achieve the purpose of accurate, smooth and high-quality construction of the overflow surface of the spillway tunnel, so that the concrete surface can present a “mirror” effect (Fig. 4).

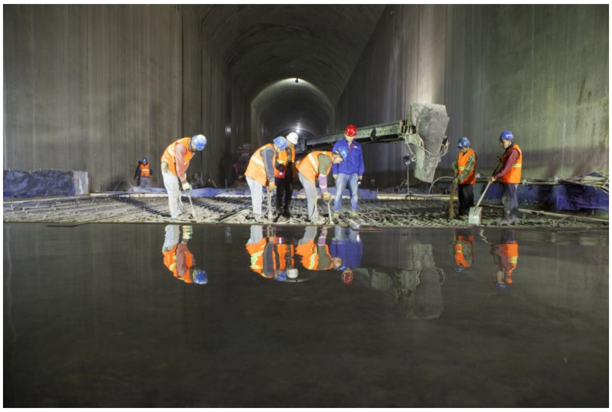

Fig. 4 Concrete “mirror” effect.

3.6 Key technologies of million-kilowatt units

The design, manufacturing and installation technologies of the million-kilowatt water-turbine generator of Baihetan Hydropower Station (Fig. 5) are all firstly proposed in the world, whose difficulty is far greater than that of the previous giant units. New technologies, new processes and new methods have been widely used in the million-kilowatt water-turbine generator units, and major breakthroughs have been made in the overall design, hydraulic development, structural design, ventilation performance, insulation technology and other aspects of the units.

The maximum water head of the water turbine is 243.1 m, and the rated output is 1015 MW. Through calculation and simulation, real machine model test, etc., the key parameters of the water turbine are continuously optimized, and its maximum efficiency arrives at 96.67%, reaching the world’s leading level. During the manufacturing of water turbine, a new world record of 346 t runner of the left bank unit and 338.1 t runner of the right bank unit processed on site with zero counterweight was finally made by optimizing the processing technology,

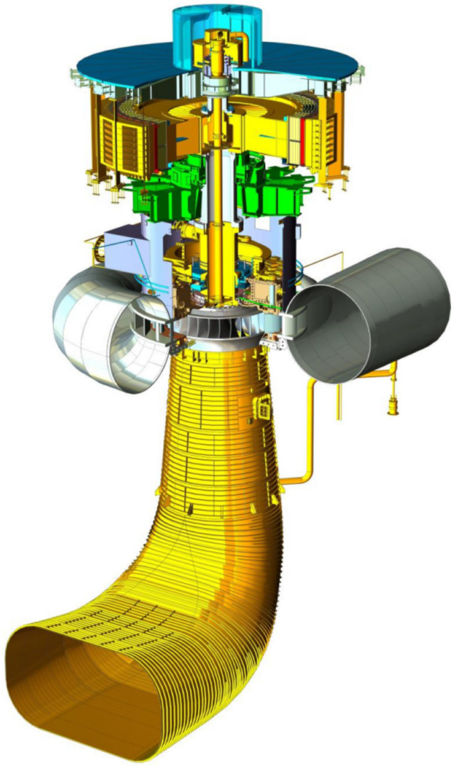

Fig. 5 Structure diagram of million-kilowatt unit.

welding method, process conversion, etc.

The rated voltage of the stator is 24 kV, which proves to be the highest voltage level in the world in the field of hydropower. Through the research of insulation materials and the optimization of the anti-corona structure of the bar, the problem of bar insulation has been solved. Through the research on the anti-corona technology of the bar, the optimization of the transposition angle of the copper wire, the optimization of the insulation winding process, etc., the technical problems such as the high potential difference of the bar slot and the high-potential corona discharge have been solved. The innovative research, development and design of stator and rotor structures have provided efficient cooling of stator and rotor under the low air volume, and solved the problem of ventilation and heat dissipation under the large-capacity full-air cooling mode.

In terms of raw materials of equipment, high voltage electrical equipment, control system, etc., their localized manufacturing has been fully realized. The technical research on key materials such as 750 MPa magnetic yoke steel plate, 800 MPa steel plate of spiral case, and 500 and 550 high-strength ultra-thick steel plate has been conducted, breaking through the material bottlenecks, improving the technical level of special steel for engineering, and achieving the grand goal of localization of the entire industrial chain of China's hydropower equipment.

Furthermore, the installation quality standards have been systematically studied and improved, and the key process of unit installation has been optimized, forming the key technologies for installation of stator and rotor. 3D laser mapping technology has been popularized to ensure the accuracy of unit axis adjustment. For the first time, the dust-free bar manufacturing workshop has been employed on a large scale, the micro-positive temperature and micro-positive pressure tooling for stator winding has been innovatively developed, and the welding process of electrical connector of stator has been optimized, ensuring the stator insulation strength and the bar flow area. A number of new industrial records have been set in manufacturing, installation and commissioning, and a number of industry-leading core installation technologies have been mastered. After the unit is put into operation for power generation, the operation indicators such as vibration, swing, temperature and pressure pulsation prove to be excellent, far superior to the requirements of national and industrial standards.

3.7 Key technologies of intelligent construction information management

Faced with the construction demand of high standards and high quality, Baihetan Hydropower Station employs the advanced technology to effectively integrate the construction of hydropower projects with the modern information technology with big data and Internet of Things as the core, and combines the intelligent management concept of comprehensive perception, real analysis and dynamic regulation to build an intelligent construction system covering the whole life cycle of the project construction. During the construction of the dam, nearly 10000 sensors are installed to comprehensively grasp the information such as dam construction progress, internal temperature, stress, and surrounding environment changes. An intelligent construction information management platform for ultra-high arch dam has been developed to manage and analyze various data online in real time during the construction and operation period of the project, thus the in-depth application of intelligent control technology, Building Information Modeling platform and comprehensive monitoring technology in the field of hydropower construction can be realized. A series of intelligent construction technologies, such as intelligent water supply, intelligent grouting system, intelligent sprayer, and intelligent monitoring of cable crane and leveling and vibrating equipment, have been developed and applied to monitor in real time, analyze and regulate the whole process of dam construction, realizing dynamic control of the whole construction process, providing objective and real data support for on-site construction management, effectively realizing automatic control of quality and safety, and improving the level of project management. Besides, a multi-dimensional, multi-site and multi-element life-cycle safety and work performance evaluation of the project has been conducted based on the site problems and construction needs, and the site construction has been guided by dynamic feedback through dynamic tracking simulation analysis, early warning of risks and optimization of measures for the work performance during the dam construction period.

4 Conclusions

The social, economic and environmental benefits of Baihetan Hydropower Station are prominent. Besides huge power generation benefits, it also presents comprehensive benefits such as flood control, promoting local economic development and improving navigation. After completion, the installed capacity of thermal power in the electricity-receiving area can be reduced, and the coal consumption in the electricity-receiving area can be cut accordingly, with about 19.68 million tons of standard coal saved each year. Meanwhile, the greenhouse gas emissions can be reduced, with the annual emission of carbon dioxide reduced by about 51.6 million tons, sulfur dioxide by about 170000 t and nitrogen oxide by about 150000 t, and the annual emission of soot can be lowered by about 220000 t. This can effectively alleviate the energy shortage in the electricity-receiving area, improve the power structure of the power grid, relieve the burden of coal mining and transportation, and reduce the pollution of the environment and haze in the electricity-receiving area. The construction of Baihetan Hydropower Station is expected to stimulate the development of the relevant industries and the regional economy, significantly improve the infrastructure conditions of transportation, electricity and communication in the surrounding areas of the project, promote the construction of new urbanization, increase employment and local financial income, and speed up the poverty alleviation and prosperity of migrant people. As an important measure to promote the development of the Yangtze River Economic Belt, and achieve the purpose of stabilizing growth, adjusting structure and benefiting the people’s livelihood, this project has practical significance on promoting the sustainable development of regional economy.