Front. Eng. Manag. 2017, 4(2): 231–237
DOI 10.15302/J-FEM-2017103

SUPERENGINEERING

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Technology improvements and management innovations in construction of Xiluodu hydropower station on Jinsha River

Keywords super-high arch dam, intelligent construction, mass concrete temperature control, structure behavior control, anti-erosion concrete, low-heat portland cement, large-discharge and high-velocity spillway tunnels, large scale underground powerhouse, green hydropower station, sustainable development, Xiluodu hydropower station

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Engineering management: China Three Gorges Projects Development Corporation (CTGPC)
Designer: Chengdu Engineering Corporation Co., Ltd., Power China
Construction contractors: Sinohydro Bureau 8 Co., Ltd., China Gezhouba Group Co., Ltd., Sinohydro Bureau 14 Co., Ltd., Sinohydro Bureau 7 Co., Ltd., CAPF Hydropower Force No. 6 Detachment etc.
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The Jinsha River is located in the upper stretches of the Yangtze River, and it contains a segment with abundant hydropower resources. The hydropower reserve in this stretch is as high as 1.12×10^8 kW, which is the highest among the thirteen planned hydropower bases in China. From Panzhihua to Yibin on the downstream of the Jinsha River, four giant hydropower stations have been planned. This includes, from upstream to downstream, Wudongde, Baihetan, Xiluodu and Xiangjiaba stations. The total installed capacity is 46,460 MW, equivalent to two Three Gorges projects. China Three Gorges Corporation is developing and constructing these projects. The Xiluodu hydropower station is the backbone of the West-East Electricity Transmission Project in China, which focuses on power generation with complimentary benefits such as flood control and navigation improvement. The Xiluodu station has a total installed capacity of 13,860 MW. This station ranks third in the world, following Three Gorges hydropower station and the Itaipu hydropower station among all constructed hydropower stations. The reservoir of Xiluodu station has a flood control capacity of 46.5×10^8 m^3 and is an important part of the Yangtze River basin flood control system. Preparation for the construction started in August 2003, construction initiated in December 2005, and river closure in November 2007. Water impoundment began in May, 2013 and the first batch of power generating units were commissioned in July 2013 as scheduled. Strictly following the reservoir dispatching regulations, Xiluodu station has been operating safely and stably ever since. Xiluodu project has received multiple awards both in China and across the world, such as the "FIDIC 2016 Outstanding Project".

The Xiluodu project consists of three main elements, which include the dam, water discharging structure, and power generation system. The dam is a concrete double curvature arch dam, with an elegantly curved transverse section and longitudinal section and a maximum dam height of 285.5 m. The water discharging section consists of seven crest outlets and eight bottom outlets in the dam, with a plunge pool and a secondary concrete gravity dam behind the arch dam, and two spillway tunnels in the mountain on each bank. The maximum flood discharge flow is 48,926 m^3/s; 32,278 m^3/s from the dam and 16,648 m^3/s from spillway tunnels respectively. These three indices rank first among all arch dams around the world. The power generation system is built in the mountains surrounding the river. Each generator is connected with one headrace tunnel. The underground cavern group comes with a compact layout, consisting of the main power house and main transformer chamber, the tailgate shaft, the tail surge shaft. Every two generators are connected with one tailrace tunnel. In an area of less than 1 km^2, there are almost one hundred interconnected chambers and tunnels;

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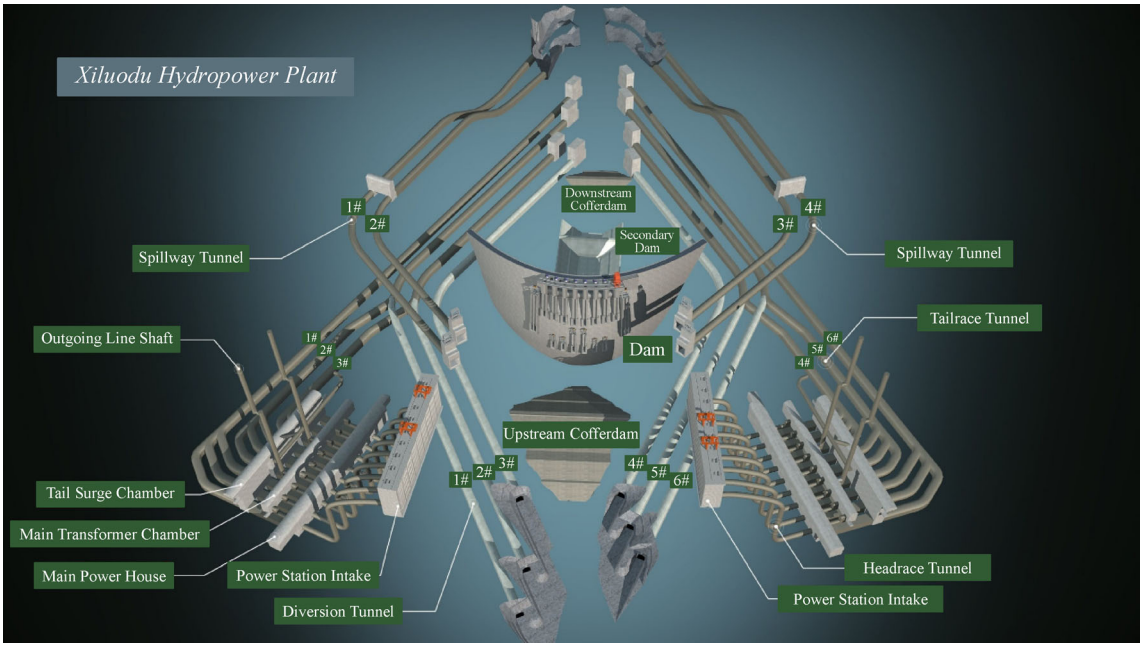
that forms an underground labyrinth. The main power houses on both banks are 31.9 m wide, 75.6 m high, and 439.7 m long and each power house is installed with 9 turbine generator units with an installed capacity of 770 MW each, making it the largest underground chamber group in the world. Xiluodu station sits at one valley in the mountainous southwest area of China and is a part of Hengduanshan Mountain with developed tectonic structure, intense erosion and complicated geological and seismic conditions. Therefore, Xiluodu project features a high arch dam, high side slopes, high flow velocity, high earthquake intensity as well as large flood discharging flow, large single unit capacity and a large underground chamber group. Multiple groundbreaking technologies have been developed during the project construction. Xiluodu is also the most challenging hydropower project after Three Gorges Project in China in terms of the scale and technological difficulties.

The Xiluodu dam is a 300 m super-high arch dam. The central arc length at the top of the dam is 681.51 m; the thicknesses of the top and foundation of the dam are 14 m and 60 m, respectively; the thickness-height ratio is 0.21; the total concrete volume is approximately 670×10^4 m^3. Compared with a gravity dam, the arch dam has a smaller dimension and thinner dam body, is safer and more economically viable, and has a more complex stress condition and structure. The Xiluodu arch dam has an overall hydraulic thrust of $1{,}400\times10^4$ t. To divert water after the closure of the diversion tunnels and for permanent discharging, 25 orifices are placed in four layers in the dam. These orifices further complicate the structure. Considering the interlayer staggered zone at the basaltic riverbed dam foundation, the dam foundation structure is expanded. The dam's concrete coarse aggregate is excavated basalt, which requires strict temperature control to prevent cracking. It is a challenge to coordinate such multi-work, multi-procedure and multi-objective construction and even more difficult to ensure the quality. To ensure the lifecycle safety of dam, key intelligent construction technologies are developed and applied to tackle technical challenges such as dam foundation consolidation treatment, concrete temperature control and dam structure behavior safety control during construction. Such technology development are under the guidance of close-loop control theory featuring all-around sensing, fact-based analysis and real-time controlling.

The project team overcame multiple key technical challenges, including precise blasting, digital grouting, intelligent concrete placing and intelligent water cooling through the development of corresponding control systems and equipment. In addition, the project team performed multi-factor coupling simulation analysis of construction progress and actual operation behavior. More particularly, a structure behavior safety control strategy is proposed to provide a precise forecast, instant feedback and real-time controlling during the construction cycle of the dam. An inclusive Dam Information Model (DIM) for the lifecycle was set up. A collaboration digital management platform (iDam) of multiple works to bring together all parties was also developed. Study and application of these key intelligent construction technologies transforms the arch dam construction from a conventional management model to an intelligent one, which guaranteed the integrity, balance, continuity and uniformity of the dam construction, and opens an intelligent era in China's hydropower station construction practice.



The Xiluodu hydropower station is located in a dry and hot valley. The dam concrete has inferior anti-crack performance because of the basalt coarse aggregate. This issue, along with the unique structure and shape of the dam, as well as the construction environments, creates a significant challenge to dam concrete temperature and cracking control. The Xiluodu hydropower station is the first project to develop and apply an intelligent water cooling system, a whole set of control equipment and simulation software. The project team implemented temperature sensing and real-time data transmission via wireless digital thermometers and optical fiber. Through an integrated water cooling flow and temperature controlling equipment, the concrete peak temperature, temperature drop rates and abnormal temperature can be pre-warned and controlled, to ensure that the concrete temperature stress is under control, especially at specific blocks of dam and during environment temperature abrupt drop or the change of seasons. With intelligent temperature control, real-time online customized temperature control is realized. Early cooling, slow cooling and smaller temperature difference between cooling water and concrete became realistic. In this way, the continuity, evenness and accuracy are ensured, both for the concrete temperature control in three phases with nine sub-sessions, and for the five layers vertical temperature gradient control of the block joint grouting. This system reduces the cooling water by 25% and the cost of temperature control by a large percentage. This innovation in the construction industry addresses the difficulties of precise, effective and reliable control of the temperature process for mass concrete.

To address the challenge of temperature control to prevent cracking in mass concrete and lining concrete, and to solve the anti-erosion difficulty with high velocity water flow, a comprehensive study on the characteristics of low heat Portland cement concrete for hydraulic structure is conducted to reveal its performance and evolution features. To meet the requirements of durability, anti-crack, and anti-erosion of hydraulic concrete, based on China's code for cement, namely, the mineral composition, chemical composition, specific surface area, heat of hydration and strength of the low heat Portland cement is refined with even stricter terms. Based on the composite cementitious material consisting of low-heat cement, low addition of ganister sand and high addition of fly ash, a construction-friendly concrete with high strength, greater anti-erosion, anti-cracking ability, is developed. This new concrete material was then successfully applied in the Xiluodu

spillway tunnel in order to solve the problem caused by concrete that is fragile to cracking and erosion. To fully leverage the advantages of low heat Portland cement such as low heat of hydration, gradual temperature rise, high-strength at a later stage and superior durability, this material was first applied to some sections of the Xiluodu arch dam. Moreover a construction technology matching early stage strength characteristics of this concrete was developed. All these methods and materials forms a new approach proven to be effective for dam temperature control and crack prevention.

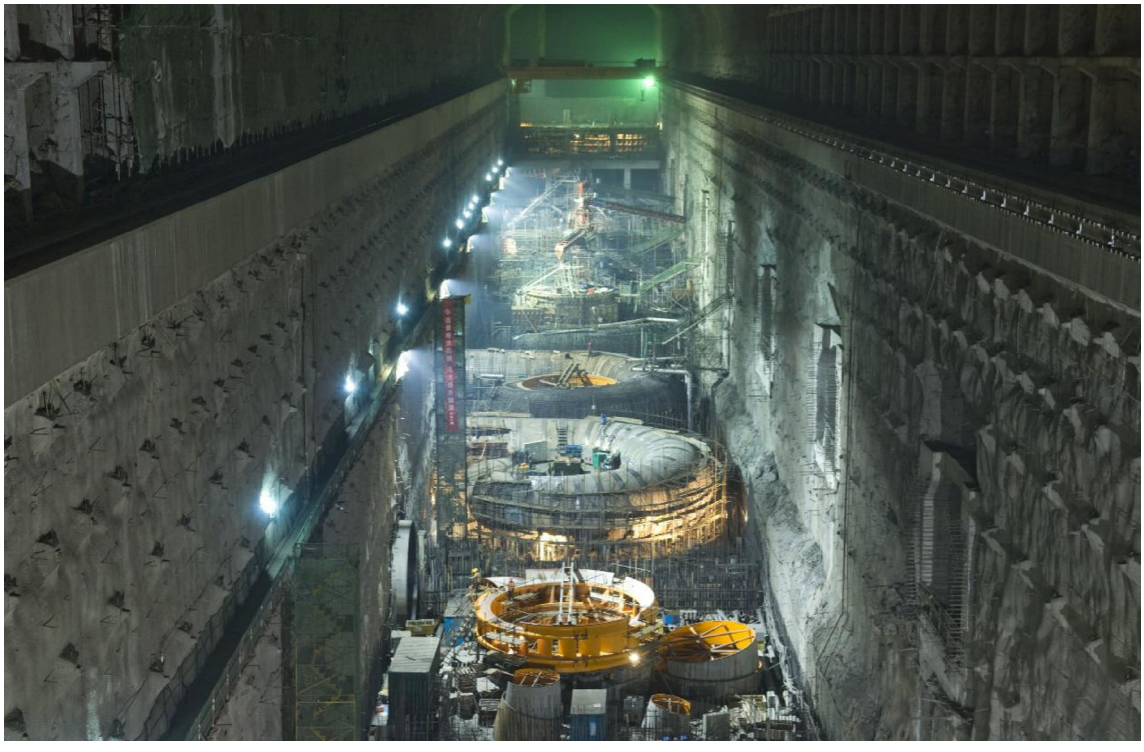
The spillway tunnels of Xiluodu hydropower station have the largest discharge capacity in the world. It has a peak discharge capacity of approximately 16,700 m^3/s and a peak flow velocity of 50 m/s. To ensure successful construction and safe operation of the spillway tunnel, key construction technologies regarding spillway tunnel lay-out, aeration facility, construction material, equipment manufacturing and process, are studied and applied. New technologies for the high water head and ultra-capacity spillway tunnel are adopted, including the design of a tail-drop tunnel, the technology of all-dimensional cross section aeration, technology of concrete protection in high velocity section and the dissipation technology of ski-jump plus underwater collision. These technologies have successfully solved challenges including spillway tunnel deployment along a straight river course, 50 m/s high speed water flow cavitation and energy dissipation and erosion control downstream of the dam. A new preparation formula for composite cementitious material has been developed, featuring low-heat Portland cement, low addition of ganister sand and high addition of fly ash. In this way, anti-erosion concrete with optimal performance has been created. A comprehensive technology is developed to build large scale lining concrete that is precise in dimension, wear and crack resistant with smooth surface. A complete construction equipment set of conventional concrete lining in a large cross section with varying gradient and multi-curve, is developed. Technology and construction procedures are developed to build smooth-surface concrete lining for high-speed water flow, which effectively improves the dimension precision and smoothness and prevents cavitation failure.

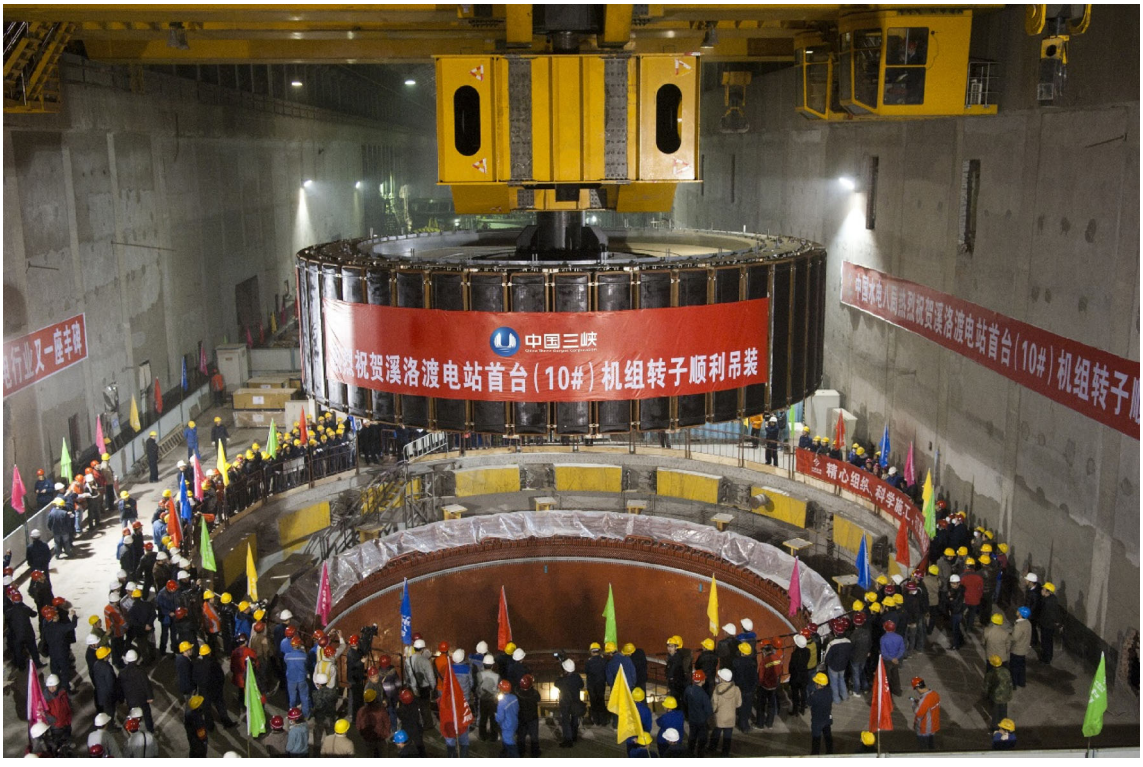
In the construction of Xiluodu underground power house, the project team is facing technical and managerial challenges because of its large scale, great number of chambers, large span, high side wall, compact layout and harsh working conditions and high safety risks. To address these issues, construction technology and management experiences summarized from other large scale underground plants in China are fully leveraged. Such technology and experience synthesis generated a range of technological breakthroughs including the technology of optimized mechanical and natural ventilation combination in complex chamber group, a series of technologies of a one-step finishing of excavation and supporting of large-scale powerhouse group, and the construction technology of deep vertical shaft with large cross section in thick overburden layer without pre-consolidation. The construction of such underground chamber group in complex

tectonic conditions has stringent requirements for safety, quality, environmental protection, energy saving and a very aggressive schedule. The powerhouse is constructed safely with high quality as scheduled under the guideline of "understanding, analyzing, utilizing, monitoring and feedback on surrounding rocks", and strictly followed the working procedures of "excavating one layer, reviewing one layer, accepting one layer and forecasting the next layers"— the physical and mechanical parameters of the surrounding rocks are collected, monitored and analyzed throughout excavation process and are indicators for following excavation and supporting work on a layer by layer basis. These challenges and engineering processes essentially drive the development of key construction technologies for complex projects. The maximum single unit capacity of the turbine generator in Xiluodu is 770 MW. All are designed and manufactured by Chinese companies. Major cast and forged pieces as well as critical material are also provided by Chinese manufacturers. The installation and testing of units are carried out with integrated mechanical and electrical working team committed to the first-rate standards, and to guarantee seamless handover with joint participation of construction and operation. In this way, a world record has been created: four turbine generators were put into operation in one month, twelve in six months and eighteen in twelve months. All generators were commissioned successfully, passed the pilot run and achieved stable operation during the first one hundred days without malfunction. This is a milestone indicating that design, manufacturing, installation capability, testing and operation quality of large scale hydro turbine generator in China has topped the world.

To construct a green hydropower station, construction of the entire Xiluodu project follows a sustainable development principle, which is people-oriented, eco-friendly and centers on intensive utilization of resources, environmental protection and social harmony. The project team developed various ecological protection technologies including dry and hot river valley slope restoration, waste water recycling, fish reproduction, release and habitat protection, cascade power station ecological dispatching, mitigation of accumulated effect of low temperature water via a layered stop log water intake. Reproduction and release stations for rare and endemic fish upstream of the Yangtze River are constructed. The aquatic ecosystem is monitored and evaluated continuously. The project design is optimized constantly to reduce the impact of the project on the environment. Environmental and water soil conservation measures are taken to achieve a harmonious relationship between human and nature.

During the project development on Jinsha River, to promote the overall development of the local community and the welfare of the resettled migrants while preserving environment where we are operation is the philosophy China Three Gorges Corporation has always been following. The management goal of zero quality defect and zero safety incident is followed strictly. By following the management requirements of standardized, orderly,

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coordinated and healthy project construction, six management goals including safety, quality, environmental protection, schedule, cost and construction area stability are achieved through technology development and management innovations to ensure the Xiluodu station a benchmark project in west China with remarkable construction achievements, excellent environmental protection, outstanding resettlement and good public security.

By the end of 2016, the Xiluodu hydropower station had been in sound operation for five years while comprehensive benefits being delivered in a sustainable way. The project has a cumulative investment of 838.63×10^8 CNY, which includes 12×10^8 CNY in environmental protection. The accumulated power generation has exceeded 1800×10^8 kWh, providing a large amount of clean energy to Zhejiang and Guangdong and other areas in east China. Its reservoir flood control capacity significantly mitigates the flooding threats to cities including Yibin, Luzhou and Chongqing. This dam, in joint operation with the Three Gorges project, significantly releases the flood control pressure in the middle and downstream of Yangtze River. Economy development in the reservoir region has been boosted while having more than 370 km roads been built in the reservoir region to provide more convenient and safe transportation to the local residents. Thirteen new towns were built and 60,000 resettled residents' living standards have been improved significantly. Artificial green areas in the project region cover 120×10^4 m^2 with 42% vegetation coverage, and the project well fits into the natural landscape where it sits. Rare and endemic fish reproduction and release stations are in operation and more than 120×10^4 fish fries have been bred and released. In brief, eco-friendly operation of this dam is implemented to ensure that the project is in harmony with environment.