KEY TECHNOLOGIES AND ENGINEERING PRACTICE FOR TAIL DOWN SPILLWAY TUNNEL WITH HIGH FLOW RATE AND LARGE DISCHARGE CAPACITY

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Abstract: Recent years, a group of large water conservancy and hydropower projects developed and implemented in narrow valley areas in China. In terms of flood discharge, these projects feature high water head, large flow capacity, high flow rate and strong flood discharge power. Flood discharge and energy dissipation facilities are technologically challenged by layout, shape selection, design, construction, maintenance and operation, etc. Based on the construction practice of spillway tunnel project of Xiluodu Hydropower Station, this article mainly presents the problems addressed and successful experience summarized in the process of design and construction. From a perspective of case study, this article sets out achievements of large spillway tunnels in respect of layout and shapedesign, study on aeration for preventing cavitation erosion, new material and new technology application, construction technology innovation, and project management measures, etc. Practice show that, a series of technologies and management measures that have been adopted are successful, and have ensured spillway tunnels are completed smoothly and achieve the high-quality goal of excellent projects.

Key words: high-speed water flow; water conservancy & hydropower projects; key technologies; case study; spillway tunnel

IMPORTANCE OF FLOOD DISCHARGE AND ENERGY DISSIPATION OF HIGH DAMS AND LARGE RESERVOIRS

China’s reservoir dams rank first both in number and size. The safety of high dams and large reservoirs are closely related to the life and property safety of the
downstream people, the lifeblood of national economy, and even the ecological environment. Over the years, in spite of no dam break at medium- and large-sized hydropower stations in China, major engineering accidents have occurred several times[1]. China’s hydropower resources are mostly found in alpine and gorge areas in western part of the country. In recent years, a group of super-high dams close to and even exceeding 300m started construction one after another. For high dam flood discharge, such problems as energy dissipation and erosion control, atomization safety, and high-speed water flow cavitation damage are among the problems to be solved as a focus through engineering design.

High dam flood discharge takes three forms, namely dam discharge, bank side discharge, dam and bank side combined discharge, and in whatever form, there have been frequent flood releasing structure damage examples caused by high-speed water flow[2]. Therefore, the flood discharge and energy dissipation, and safe operation of high dams and large reservoirs have been a key concern in the field of water conservancy and hydropower projects.

1 FLOOD RELEASING STRUCTURES LAYOUT OF XILUODU STATION

Xiluodu Hydropower Station is located in the Xiluodu Gorge at the lower reach of Jinsha River. According to the measured data statistics for Pingshan Hydraulics Station which is 124km blew the Xiluodu Dam site from June 1939 to May 1998, runoff Eigen values are shown as Table 1.

<table>
<thead>
<tr>
<th>Multi-year Average Flow Rate</th>
<th>Multi-year Average Annual Runoff Volume</th>
<th>Max. Flow Rate Measured</th>
<th>Min. Flow Rate Measured</th>
<th>Historical Max. Flood Flow Rate Investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>4570 m³/s</td>
<td>144 billion m³</td>
<td>29000 m³/s</td>
<td>1060 m³/s</td>
<td>36900 m³/s</td>
</tr>
</tbody>
</table>

In terms of flood discharge and energy dissipation, Xiluodu Hydropower Station has high water head, large discharge capacity, narrow valley, and strong discharge power. To adopt a safe and reliable flood discharge manner, arrange flood releasing structures reasonably, and solve the downstream energy dissipation and cavitation erosion control problems is one of the key issues in the design. In accordance with the requirement of total discharge capacity of the Complex, combining the topographic and geologic conditions, hydraulic characteristics, reservoir regulating and operating mode and considering the river diversion in the middle and later periods, flood releasing structures are arranged in
the principle of “scattered flood discharge, energy dissipation in separate areas”, consisting of “7 surface outlets + 8 bottom outlets on the dam, and 2 spillway tunnel on each of the left and right banks” (Table 2). Discharge capacity is distributed across the flood releasing structure as follows: maximum discharge capacity of the dam is about 32300 m$^3$/s, or about 66% of the total discharge capacity; maximum discharge capacity of four spillway tunnels is about 16600 m$^3$/s, or about 34% of the total discharge capacity. The discharge capacity meets the designed flood requirements, and the needs of safe operation of the Complex can be met.

Table 2 Features of Spillway Facilities at the Complex$^3$

<table>
<thead>
<tr>
<th>Flood Releasing Structure</th>
<th>Dam Outlet</th>
<th>Spillway Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface Outlet</td>
<td>Bottom Outlet</td>
</tr>
<tr>
<td>Number of Outlets (Tunnels)</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Section Dimension (m×m)</td>
<td>12.5×13.5</td>
<td>6.0×6.7</td>
</tr>
<tr>
<td>Intake Height (m)</td>
<td>586.50</td>
<td>490.70~502.80</td>
</tr>
<tr>
<td>Single-outlet (tunnel) Discharge Capacity (m$^3$/s)</td>
<td>1326/2771</td>
<td>1545/1610</td>
</tr>
</tbody>
</table>

2 NATIONAL AND INTERNATIONAL SPILLWAY ENGINEERING PRACTICE AND FEATURES OF XILUODU SPILLWAY TUNNEL

For high dams, spillway tunnels tend to be important supplements to dam spillway facilities, and the overall layout of flood releasing structure often consist of dam spillway and bank side spillway. The vertical layout of spillway tunnel mainly falls into “head down” and “tail down” types. And there are also chute type, submerged orifice oblique/straight line type, and swirl shaft type. These various type of spillway tunnels are widely applied in national and international large hydropower stations$^{[4,5,6,7,8,9]}$. Specific form and shape of the spillway tunnel depend upon the layout, topographic and geologic conditions, and total discharge capacity of the Complex, etc.

It is noteworthy that, with the design of large “head down” type spillway tunnel such as Ertan Hydropower Station, relatively severe cavitation damage happened nearby the circle arc section of spillway tunnel in several projects, with the longest damage up to several hundred meters$^{[4]}$. This was due to the poor knowledge about cavitation and cavitation erosion caused by high-speed water flow, no
application of aerator or insufficient study on the shape of aerator in early projects.
In addition to aeration for preventing cavitation erosion, the “tail down” type layout adopted in recent years is also a better solution. Compared with the previously used “head down” type, most sections in a “tail down” spillway tunnel are flat tunnels with relatively gentle slope, and lower water flow rate; and the length of high-speed area of abrupt slope section is limited, which is convenient to arrange aerators in a concentrated way; and the positions most easily exposed to cavitation damage are located near the exit as possible as practical, and far from the dam and other buildings, thus the cavitation damage will not pose a threat on the safety of the whole tunnel and the dam, even though it occurs at the circle arc section. Therefore, the “tail down” shape is an innovation of design concept and summary of successful experience for the layout of spillway tunnels with large flow capacity and high flow rate during long-term engineering practice.

Xiluodu Hydropower Station lies in an alpine and gorge area, where the narrow river valley disables the arrangement of structures at the Complex, and the topographic features determines that only high arch dams can be arranged in the river valley; As dam outlets have limited flood discharge capacity, spillway tunnel has been one of the main flood discharge facilities for its flexible layout mode and adaptability to the landform of gorge. The project size, flood discharge power and technical difficulty of Xiluodu Spillway Tunnel come out top at home and abroad. The features of high water head, high flow rate, large discharge capacity pose extremely high requirements on design and construction quality, with main difficult problems to be solved as: (1) In terms of design, first, the spillway tunnel’s layout and shape problems shall be solved by considering all factors including topographic and geological conditions, distribution of structures at the Complex, and flood discharge capacity; second, the cavitation and cavitation erosion problems caused by high-speed water flow shall be solved through reasonable arrangement of aerators and study on appropriate shape. (2) In terms of construction, study is needed to adopt advanced and efficient construction solution and building materials with excellent performance, in order to solve the problems of large cave chamber excavation, concrete structure shape control, high-grade concrete construction as well as temperature control and crack prevention. (3) In terms of management, comprehensive management measures are needed in respect of technology, progress, quality, and safety, etc.
Construction objectives of the spillway tunnel project shall be achieved on schedule, which is guaranteed by technological measures and lean management, and preceded by ensuring quality and safety. This article focuses on the presenting the key technological problems solved in and successful management experience of Xiluodu Spillway Tunnel project from the foregoing aspects.

3 MAIN DESIGN CHALLENGES AND SOLUTIONS

3.1 Spillway tunnel layout, shape and relationship with the Complex

In the layout of a spillway tunnel, factors to be considered include topographic and geological conditions, requirement of flood discharge capacity, Orifice layout, design of lock gate structure, energy dissipation and erosion prevention at the outlet, and the like. And water flow in the tunnel shall be as “even, smooth, and straight” as possible to ensure smooth discharge. The Xiluodu Complex lies in the middle part of 4km straight watercourse, with precipitous gorges on banks. But there are moderately gentle slopes on left and right banks about 500m upstream the dam site at elevation of 535~640m, where are suitable for arranging spillway tunnel entrance. Combining the layout of the Complex, the spillway tunnel makes a horizontal turn by pressure flow section, bypassing the abutment of the arch dam, and connecting with straight free flow section; combining the topographic condition at the outlet, the “tail down ramp in the tunnel” type is used to concentrate about 70% of total water head difference at the tail end which accounts for 25% of the total tunnel length. This type of layout reduces the range of high-speed flow area and allows easier aeration for preventing cavitation erosion, and contributes to handle high-speed water flow problems in a concentrated way. The exit is located downstream the tailrace tunnel of the plant, far from other permanent buildings. Water flow enters the river bed through ski-jump energy dissipation, with better water flow coming into the channel. Spillway tunnels are roughly arranged symmetrically on left and right banks. Axes of tunnel on single bank are parallel, with center-to-center spacing of about 50m, and tunnel length ranging from about 1.4km to 1.8km (Fig.1). Hydraulic model verifies that, with the foregoing layout, the pressure flow section ensures smooth and steady flow regime in the tunnel, thus allows flexible and convenient entrance and exit layout, and shortens the tunnel line.
Four spillway tunnels have the same structural styles, consisting of intake tower, pressure flow section, underground service gate chamber, free flow section, tail down section, open channel and flip bucket, etc. (Fig. 2). (1) The intake tower lies between the plant’s water inlet and the dam, which includes contractive funnels on the top and two sides to ensure smooth and steady water flow regime. (2) The pressure flow section is a round section with lined diameter of 15m, bending radius of 200m, with its end connecting with the underground service gate chamber through “round to square” transition section. (3) The free flow section follows the arch-shaped service gate immediately, in a city gate shape with lined section dimension of 14m×19m (width×height), withfloor’s longitudinal slope of 2.3%. (4) The tail down section is complicated in shape, with the section dimension same as the free flow section, and consisting of the Ogee curve section, steepslope section, circle arc sectionandgentle slope section. Of which, the Ogee section is a parabola of the equation $Z=(X^2/400)+0.023X$, with maximum gradient of the steep slope section at 22.457°,circle arc section radius of 300m, and longitudinal slope ofgentle slope section at 8%. High-speed water flows often appear here, with the flow rate rising from 25m/s at the starting point of the Ogee section to nearly 50m/s at the end ofcircle arc section. To reduce and eliminate any cavitation damage to the lining structure, an air supply tunnel is constructed at the starting end of the Ogee section, which connects with the ground. And
3~4 aerators are provided for each high-flow-rate area according to their length. (5) The elevation of spillway tunnel exit is higher than the downstream water level. Considering the topographic and geologic conditions in the energy dissipation area in downstream watercourse, fall point of water jet, downstream water coming into channel, and other factors, it is cost-effective to apply diffused energy dissipation by diffused trajectory jet.

![Fig.2 Longitudinal Profile of the Spillway Tunnel](image)

### 3.2 Model test of high-speed water flow and aerator shape optimization

When the reservoir water level of Xiluodu Hydropower Station is higher than 580m, the number of most water flow cavitations at the tail down section decreases to 0.3 below. Thus, aeration measures must be taken to control cavitation erosion.

In the bidding design stage, totally 3 aerators were provided for the left-bank spillway tunnel and 4 aerators for the right-bank spillway tunnel in the high-speed flow area below the Ogee section, all in the form of bottom aeration through combined flip and falling buckets on the floor; and an air hole was provided on each of the left and right sides below the buckets to connect with the remaining space of the tunnel top via ventilation shafts in the sidewalls on both sides to supply air (Fig.3). According to the results of 1:45 model test conducted by China Institute of Water Resources and Hydropower Research (IWHR)\(^\text{[10]}\), in this manner of bottom aerator only, four aerators could all form stable aeration cavities when the reservoir water level is at 580m and the designed flood water level is at 600.63m. But there are still two problems: (1) after the first aerator, there’s certain backwater in the bottom cavity, with smaller air speed and ventilator capacity in the ventilation shaft, and poor aeration effect; (2) after the second aerator, aeration is not enough in the main flow area of side-walls in the bottom cavity, and
presence of clear water area is not good for preventing cavitation erosion when the flow rate reaches 36~38m/s in this area.

When in the implementation stage, in order to improve the aeration effect of water flow near the walls after the aerator, the shape of aerator needed further study and optimization. By referring to the Ertan Spillway Tunnel experiences, it was proposed to have additional side aeration model test for Xiluodu. For this purpose, research institutes conducted the left-bank 2# spillway tunnel 1:35 and right-bank 3# spillway tunnel 1:25 large-scale model tests on the basis of early-stage design and test study\[^{[11,12,13]}\], optimizing the design of aerator shape and comparing several solutions. After study and review at several expert meetings, the solution was finally determined as “3 aerators in the left-bank tail down section, with side aeration for first two aerators, 4 aerators in the left-bank tail down section, with side aeration for first three aerators.” In the model test, 6~9 different shapes were selected for comparative study for aerators 1 to 3 in the spillway tunnels on both banks. Based on the test results, the aerator shape was optimized as follows (Fig.4):

(1) Side-wall side aeration was added for left-bank aerators 1 to 3, right-bank aerators 1 to 2, as evenly contractive or trapezoid contractive side aerators. With side aeration added, stable bottom cavity and side cavity could be formed behind each aerator in different discharge conditions, with less back water in the bottom cavity, clear water belt behind aerator eliminated effectively; the side cavity was longer, with no obvious water wing, with clearly better effect of aeration near

![Fig. 3 Sketch Map of Aerator in Bidding Design Stage](image_url)
sidewalls than the result of test with bottom aeration only.

(2) The bottom aeration shape of some aerators was optimized. The gradient and height of floor flip bucket were adjusted, or the former continuous flip buckets were changed to combination of continuous flip buckets and trapezoid flip bucket. As additional side aeration has certain effect on the shape of bottom cavity and the back water flow, there might be more back water in the bottom cavity. Mixed water and aeration flow was inclined to sides, causing less aeration in the water flow in middle part. Therefore, proper adjustment to the bottom aeration leads to longer middle part of the bottom cavity, and better aeration effect of bottom water flow to some extent.

Fig. 4 Typical Shape of Bottom Aerator Optimized

Take the right-bank 3# spillway tunnel for example, with additional side aeration, the minimum floor aeration concentration of optimized shape was smaller slightly than that of feasibility study shape at different reservoir water levels, with small difference; and the minimum aeration concentration in left and right sidewalls rose sharply (Table 3). After several model tests, relatively desirable design of aerator shape of "bottom aeration + side aeration" was achieved, which effectively improved the aeration effect in high-speed flow area, especially of the sidewall water flow.

Table 3 Minimum Aeration Concentration (%) of Near-wall Water Flow after Each Aerator \(^{[12,13]}\)

<table>
<thead>
<tr>
<th>Reservoir Water</th>
<th>Location</th>
<th>Shape</th>
<th>Lower Reach of 1# Aerator</th>
<th>Lower Reach of 2# Aerator</th>
<th>Lower Reach of 3# Aerator</th>
<th>Lower Reach of 4# Aerator</th>
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4 MAIN CONSTRUCTION CHALLENGES AND SOLUTIONS

4.1 Shape and surface quality control of large-section high-speed flow-passing concrete surface

The tail down section of Xiluodu Spillway Tunnel has large section, abrupt slope, high flow rate, and complicated shape. High-speed water flow poses extremely high requirements for construction quality. The design requires to control the roughness within 3mm, the shape deviation bias within ±1cm. Reasonable placing tools, rigorous construction process, meticulous management measures are necessary to achieve the design objectives.

(1) For tail down section sidewalls, the large section made it difficult to pour and shape up at one time, control the shape deviation and planeness. An integral steel formworkjumbo was developed for sidewalls of tail down sections, in order to ensure the concrete placement shape and surface quality. The steel formworkjumbo's portal frame is a main load-bearing component for concrete placement, the anti-bending and torsion strength performance of which is essential to ensure the overall lining dimension. Therefore, H-shaped steel and I-shaped steel structure with strong strength and relatively small weight as well as
box beam structure were used in order to ensure the overall strength and stiffness of the formwork jumbo (Fig. 5a and 5b). The quality of panel directly determined the flatness and appearance quality after the concrete is shaped up. The panel was constructed with 10mm-thick steel plate, which used angle steel back ridges and horizontal waling on the back side to enhance the overall stiffness.

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(2) According to the features of floors in the tail down section and in the high-speed flow area at the exit, focused placing tools were adopted. Beyond the circle arc section, slopes were steep and the floor line shape varied sharply. So the construction was carried out with our own rail-hidden mould-towing formwork jumbo developed independently. The mould-towing formwork jumbo was, first, in a “rail-hidden” design, with rails embedded above the surface reinforcing mesh and under the floor placement section, as a supporting and traveling gear for the mould-towing formwork jumbo. After placement, the rails were embedded in concrete and would not be removed; second, it was in an “overhanging” design, with the die body hung over the tail of the travelling formwork jumbo instead of erecting directly on the rails. And the die body was designed to be horizontally adjustable in order to adapt to different line styles of the tail down section. These two improvements enabled steep-slope floor to be poured and formed at one time, with no hollow spot, opening or hole and exposure of embedded parts on the surface (Fig.6a and 6b).
For the gentle slope section, the construction methods of no cover mould, rail scraping process, manual smoothing and calendering were carried out. The shape and surface quality control points are: first, the installation and examination of scraping rails which were supported by height-adjustable screw support; Second, the surface plastering quality control which was ensured to be smooth, bright and clean through three steps: initial, second, and fine plastering.

(3) Elaborate process management measures were taken for aerator, flip bucket floor and other special sections in a complicated shape.

As the aerator has a complicated shape and special section, and it is impossible to use an integral steel formwork jumbo for placement, set-shaped steel formworks were assembled. Main measures included: first, the formwork supporting system was optimized and reinforced. Second, special management measures were developed to carry out whole-process strict control over the shape precision, surface evenness, edge joint closeness and supporting firmness of the formwork assembly (Fig. 7a).

The flip bucket floor has a warped surface. In the concrete placing for the whole floor surface, the shape of point, line and surface shall be controlled. This means to control the elevation of point, direction of scraping rail, and smooth degree of curved surface. No opening or hole is permitted on the flow surface. So the processes of combined steel formwork cover mould, manual opening formwork and smoothing surface were adopted. What should be controlled included: the assembly and location of formwork, the elevation control of scraping rail, the right occasion of formwork opening and concrete smoothing (Fig. 7b).
4.2 Measures for temperature control of lining concrete

Spillway tunnel projects need higher-grade strength of lining concrete, consume more demand, and produces much hydration heat. C\textsubscript{90}40F150W8 concrete is used for pressure flow section and free flow section, and C\textsubscript{90}60F150W8 anti-shock and wear-proof silica powder concrete for tail down section. Thus, there are high requirements for temperature control and crack prevention. In the whole process of construction, comprehensive and individualized temperature control measures were taken.

(1) Lower concrete hydration heat. Optimization was conducted through low-heat cement, design of mixture proportion, and normal concrete: ① Jiahua P.LH42.5 low-heat silicate cement was applied for the high-grade silica powder concrete in the tail down section, which has a maximum temperature of about some 3~5 °C lower than medium-heat cement. ② Comparative test of mix proportion was conduct to choose the best concrete mixture proportion and decrease the cement consumption. JM-PCA (Polycarboxylic acid) high-efficiency water reducer was mixed. Through test demonstration and expert consultation, the content of coal ash increased to 30%. ③ Normal concrete was placed for the invert of pressure flow section, the floor and sidewalls of free flow section, with 20kg cementitious material\textsubscript{s} saved per cubic meter than pump concrete.

(2) Lower concrete placing temperature. This was achieved mainly through lower exit temperature, reduced temperature rise during transportation, reduced
temperature rise during placement: ① Pre-cooled concrete was used. The exit temperature was controlled within 12~14°C through using air-cooled aggregate and adding ice in the concrete blending system. ② The concrete trucks were dispatched reasonably for quicker construction connection to reducing waiting time. ③ High-power air conditioner was installed on the steel formwork jumbo to deliver cool air into the block during high-temperature season, in order to improve the working environment and lower the ambient temperature.

(3) Enhanced surface heat rejection or thermal insulation. In summer, when formwork removal condition was available, it should be removed promptly, and immediately maintained with running water so as to cut down the concrete surface temperature and enhance the surface heat dissipation. In winter construction, thermal insulation door curtain should be hung at the tunnel entrance, in order to avoid cross ventilation, and prevent surface cracks caused by abrupt temperature decrease or too big temperature difference.

(4) Water cooling. PE cooling water pipes were embedded inside each block of concrete. Water pipe was cooled. Heat dissipation inside concrete was accelerated through continuous water supply, thus to control the maximum temperature inside concrete.

The above-mentioned temperature control measures brought outstanding effect of maximum temperature control inside concrete (Table 4). Compliance rate at different positions reached over 87%.

<table>
<thead>
<tr>
<th>Table 4Statistics on Temperature in Left and Right-bank Spillway Tunnels</th>
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</thead>
<tbody>
<tr>
<td><strong>Project Position</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>Left- bank</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Right- bank</td>
</tr>
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<td></td>
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</tbody>
</table>

4.3 Application of Low-heat Cement

Low-heat cement's greatest feature is gentle hydration heat release and low peak temperature. But it is not widely applied in water conservancy industry in China, mainly because it has lower early strength and slow and long heat release process, which may have an effect on subsequent temperature recovery inside
concrete after water cooling and other measures come to an end. High-grade C_{90}60 pump silica powder concrete was used for sidewalls in the tail down section of Xiluodu Spillway Tunnel, the mixture of which having high slumps, consuming large amount of cementitious materials, and having high hydration heat temperature rise. Thus low-heat cement was mainly used in the tail down section to ease the temperature control pressure.

To examine the applicability of low-heat cement, four research institutes include China Institute of Water Resources and Hydropower Research and Yangtze River Scientific Research Institute, and three construction companies of Xiluodu Spillway Tunnel project conducted indoor material test and outdoor process test of low-heat cement separately. Each of them got the basically same result. Low-heat cement has been massively promoted and applied in the tail down section of spillway tunnel. The result of tests and practices show that, for thin-wall lining structure like spillway tunnel, the application of low-heat cement contributes a lot to concrete construction quality control.

1. Effect on strength. For both normal and pump concrete, low-heat cement has lower strength at early stage, and stronger strength at later stage. Its compressive strength at 3d, 7d and 28d was slightly lower than medium-heat cement. And the compressive strength at 90d was basically the same as or slightly higher than medium-heat cement. Thus, the application of low-heat cement is helpful for reducing the early temperature rise of concrete, and helpful for crack prevention.

2. Effect on hydration heat. Indoor test showed that, hydration heat of low-heat cement at 1d~7d was some 15%~25% lower than that of medium-heat cement at the same age. Outdoor process test showed that, when comparing the medium- and low-heat cement concrete placed with the same cement consumption and same construction condition, the maximum temperature inside low-heat cement was 3.8°C ~ 8.0°C lower.


4. Effect on construction performance. Through comparing a great deal of
onsite constructions, during transportation, discharge and placing, the low- and medium-heat cement had the same construction performance, with no obvious difference in respect of concrete workability, slump loss, vibration for spreading, and bubble release, etc., and the same appearance quality after the formwork removal. Formwork removal was 3~4 hours later than medium-heat cement, which could meet the needs of site construction and progress.

(5) Effect on crack. Statistical results of Table 5 show that, low-heat cement could cut down the maximum temperature inside the concrete sharply, and an obviously smaller portion of blocks poured with low-heat cement experienced cracks than medium-heat cement.

Table 5 Statistics on Maximum Temperature inside Concrete and Cracks

<table>
<thead>
<tr>
<th>Project Location</th>
<th>Average Max. Temperature/℃</th>
<th>Statistics on Blocks with Crack</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Medium-heat Cement</td>
<td>Low-heat Cement</td>
</tr>
<tr>
<td></td>
<td>Total No. of Blocks</td>
<td>Blocks with Crack</td>
</tr>
<tr>
<td>Left-bank Tail Down Section</td>
<td>47.0</td>
<td>35.8</td>
</tr>
<tr>
<td>Right-bank Tail Down Section</td>
<td>38.5</td>
<td>36.8</td>
</tr>
</tbody>
</table>

5MAINE OBJECTIVES AND MEASURE OF THE SPILLWAY TUNNEL PROJECT MANAGEMENT

5.1 Technology Management

Due to the great construction difficulty, high quality requirement, and significant safety risk of spillway tunnel, a technology research group was formed by backbone construction companies to develop important technological plans and significant equipment R&D. A dozen of patents were awarded for the spillway tunnel construction technology and equipment research, with the main technological achievements including:

(1) The nationally pioneering normal concrete placing process was adopted for sidewalls in the free flow section. The automatic normal concrete conveying-belt-type formwork jumbo for sidewalls was developed, which was awarded national patent. Compared with pump concrete, such formwork jumbo consumed fewer cementitious materials, produced less hydration heat, reduced
(2) The steel formwork jumbo for lining of big-gradient inclined tail down tunnel was developed, weighing 270t, with maximum climbing ability of 31°, solving the main problem of “big-gradient climbing” of large-ton formwork jumbo in inclined tunnel.

(3) The rail-hidden mould-towing formwork jumbo for tail down section floor was designed independently, with a design of hidden rail, overhung formwork, with no hollow spot, opening or hole on the surface, thus subsequent mending avoided; floor between aerators could be poured at one time.

5.2 Quality Control

The spillway tunnel quality control aimed to “create a top-grade project”, focusing on the solidification, promotion and application of mature process, continuously studying and optimizing technical solutions, striving to achieve standardized process and lean management.

(1) The feature of spillway tunnel construction is flow process, with basically the same process in each block. Therefore, it is suitable for establishment and promotion of standardized process. Proven mature processes were solidified and formulated into standards and institutions. Empirical data were drawn from practice and quantified quality control standards were proposed. Totally more than 20 volumes of concrete construction process standards were prepared and promoted, which were applied throughout the spillway tunnel project.

(2) In accordance with the “PDCA” (plan-do-check-action) quality control concept, practical work was done in a manner of “pre-prevention and control, process supervision, post-summary and action” to carry out quality control properly, namely: the construction design and plan for concrete placing were reviewed carefully before construction; in the process of construction, site workers were supervised rigidly to carry out in strict accordance with process standards; after each block was completed, workshop was convened in good time to summarize experience; process standards were revised stepwise after a period of time of summary and exploration, in order to achieve the aim of continuous project quality improvement.

5.3 Safety Management

The construction of spillway tunnel project followed the “safety and
prevention first” principle. The focus was put on close monitoring of key source of danger. Especially, conspicuously safety problems existed in the steel formwork jumbo for large inclined tunnel. A series of special safety management measures were developed for the formwork jumbo:

(1) Expert consultation meeting and special safety acceptance were conducted to ensure compliance of design, manufacturing, installation and operation with requirements of safety regulations.

(2) For key equipment such as formwork jumbo and windlass, special management measures were developed, special safety checklist prepared and special person arranged to conduct daily check and maintenance for steel formwork jumbo, traction equipment and rails.

(3) The formwork jumbo was examined and approved level by level before travelling. Before travelling for each block, examination and approval was obtained from the construction site, equipment and safety departments of the construction company; before passing the aerator, three-party joint check and acceptance was required.

6 SUMMARY OF ACHIEVEMENTS

In July 2013, Xiluodu Spillway Tunnel project was completed fully and put into preliminary operation. For one year since its completion, flood flow passed 7 times, with maximum single-tunnel discharge capacity of about 1600m³/s, maximum flow rate of more than 40m/s, and longest operation time of 90-plus hours. The overall operation state of the spillway tunnel was within the predicted range of design. After the flood discharge, passageway was checked fully. Except for minor washout damage to a few construction joints, concrete at key positions especially the aerators and circle arc section were intact. However, currently the maximum single-tunnel discharge capacity was only 41.5% of the designed discharge capacity, which needs to be further tested in long-term operation.

As a representative of spillway tunnel with “high water head, large flow capacity, high flow rate, and large discharge power”, Xiluodu Hydropower Station spillway tunnel experienced solution of a series of technological problems during design and construction.

In terms of the spillway tunnel layout and shape design, lessons were learned from Ertan Hydropower Station. Topographic and geological conditions, discharge
volume requirement, exit energy dissipation and erosion prevention and other factors were considered comprehensively, bringing to the design of “tail down type” and exit energy dissipation by trajectory jet. Through three times of model test and comparison of several shapes, a 3D aeration pattern of “bottom aeration + side aeration” was finally adopted. In model test, it could be observed that, water flow could be aerated for total sections, and the floor and side walls were protected.

In terms of concrete placement, new construction equipment and low-heat cement was used fully for the C9060 high-grade silica powder concrete in the tail down section. It has been proven that the new equipment can greatly improve construction efficiency, and all performances of low-heat cement are suitable for the thin-wall lining structure of tunnel, which are very helpful for the construction quality control. Accompanied by comprehensive temperature control measures, it can significantly reduce the percentage of temperature cracks.

In terms of spillway tunnel project management, priority was given to technological innovation, either by independent development of new construction equipment, or by improvement to traditional construction method, or by application of mature technology to new fields. With advanced construction technologies and comprehensive management measures, Xiluodu spillway tunnel achieved the objective of high-quality lining concrete with “precise shape, glossy and smooth surface, abrasion and wear resistance, high strength and crack prevention”. Finally drove the overall improvement of hydraulic tunnel construction technology level in the process of pursuing innovation.

References:


