Information about Xiangjiaba Hydropower Project for Applying for the International Milestone Project Award

China Three Gorges Construction Engineering (Group) Co., Ltd.
June 2021
# Basic Information

<table>
<thead>
<tr>
<th>Project name</th>
<th>Xiangjiaba Hydropower Project</th>
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<tbody>
<tr>
<td>Location</td>
<td>On the lower reaches of the Jinsha River, at the border between Yibing City of Sichan Province and Shuifu City of Yunnan Province</td>
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<tr>
<td>Purposes</td>
<td>Primarily for power generation, concurrently with benefits of navigation improvement, flood control, irrigation, sediment retention, and reregulation to Xiluodu Hydropower Station</td>
</tr>
<tr>
<td>Total reservoir capacity (10^9 \text{ m}^3)</td>
<td>5.163</td>
</tr>
</tbody>
</table>

### Participating units

| Employer | China Three Gorges Corporation  
| China Three Gorges Construction Engineering (Group) Co., Ltd. |
| Design firm | Powerchina Zhongnan Engineering Corporation Limited |
| Construction units | China Gezhouba Group Co., Ltd.  
| Sinohydro Engineering Bureau 3 Co., Ltd.  
| Sinohydro Engineering Bureau 4 Co., Ltd.  
| Sinohydro Engineering Bureau 7 Co., Ltd.  
| Sinohydro Engineering Bureau 8 Co., Ltd. |
| Supervision units | China Northwest Water Conservancy and Hydropower Construction Consulting Company  
| TGDC  
| Changwei Engineering Construction Supervision (Yichang) Co., Ltd |
| Equipment manufacture and installation units | Harbin Electric Machinery Company Limited  
| Tianjin ALSTOM Hydro Co., Ltd.  
| CSSC Wuhan Shipbuilding Industry Co., Ltd |

### Concrete dam

| Dam type | □ High concrete gravity dam  
| □ High concrete arch dam |
| Dam height (m) | 162.0 |
| Dam crest/ base width (m) | 12.0/166.0 |
| Dam crest length (m) | 896.26 |
| Concrete placing volume \(10^6 \text{ m}^3\) | 9.01 |
| Design flood | 500-year return period flood for normal operation,  
| 5,000-year return period flood for exceptional operation |
| Flood release structure | Type: Flood release through dam  
| Discharge capacity \(\text{m}^3/\text{s}\) | 41,200/48,660 |
| Energy Dissipation Pattern | hydraulic jump energy dissipation with alternated arrangement of high-level outlets and surface bays + high- and low-level flip buckets + stilling basin |

### Power plant

| Type | Dam toe powerhouse on left bank + underground powerhouse on right bank |
| Dimensions \(\text{L} \times \text{W} \times \text{H}, \text{ m}\) | 226.95 × 39.5 × 81.75 for dam toe powerhouse on left bank,  
| 255.0 × 31.0 × 85.5 for underground powerhouse on right bank |
| Installed capacity (MW) | 6,400 |
| Annual power generation (TWh) | 30.88 |

### Construction

<p>| Date of commencement | Nov. 26, 2006 |</p>
<table>
<thead>
<tr>
<th>Performance</th>
<th>Date of gate closure for initial impoundment</th>
<th>Oct. 10, 2012</th>
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<tr>
<td></td>
<td>Date of completion</td>
<td>May 26, 2018 (The shiplift was commissioned)</td>
</tr>
<tr>
<td></td>
<td>Max. daily concrete placing intensity (m³/d)</td>
<td>26,000</td>
</tr>
<tr>
<td></td>
<td>Max. monthly concrete placing intensity (m³/m)</td>
<td>542,000</td>
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<tr>
<td>Normal storage level (m)</td>
<td></td>
<td>380</td>
</tr>
<tr>
<td>Date of initial impoundment to the normal high level</td>
<td></td>
<td>Sept. 12, 2013</td>
</tr>
<tr>
<td>Max. level since commissioning (m)</td>
<td></td>
<td>379.98</td>
</tr>
<tr>
<td>Dam crest displacement at the latest normal storage level (mm)</td>
<td></td>
<td>12.14</td>
</tr>
<tr>
<td>Seepage (total, L/s)</td>
<td></td>
<td>52</td>
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</table>
II  Technical Features

(I) General Description of the Dam Works

Xiangjiaba Hydropower Project, the utmost downstream project of the cascade development on the Jinsha River, is the backbone power source of the National West to East Electric Power Transmission Program. It is developed primarily for power generation, concurrently with multipurpose benefits of navigation improvement, flood control, irrigation, sediment retention, and reregulation for the Xiluodu Hydropower Station. It is the only project on the Jinsha River that boasts huge farmland irrigation and high navigation capacity. It can play an important role in safeguarding the national energy security, improving the efficiency of water resources utilization in the river basin, promoting the connection of Southwest China with Central China and East China by waterway, boosting the regional socio-economic development, and advancing the environmental protection. The project has a normal storage level of 380 m, a total reservoir capacity of 5.163 billion m$^3$, a total installed capacity of 6,400 MW (8 × 800 MW), a mean annual power generation of 30.88 TWh, a firm output of 2,009 MW, an irrigated area of 353,330 ha, and a total investment of 54.165 billion Chinese Yuan as per the cost estimate at the feasibility study stage.

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<tr>
<th>No.</th>
<th>Main technical indicators</th>
<th>Rankings</th>
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<tr>
<td>1</td>
<td>A 162 m-high gravity dam is founded on 60 m-thick Class IV to V soft fractured rocks</td>
<td>Unprecedented in terms of technological difficulty</td>
</tr>
<tr>
<td>2</td>
<td>The design max. discharge power of flood release structure by hydraulic jump energy dissipation is 40,575 MW, and the max. unit width discharge power in the stilling basin is 187.6 MW/m.</td>
<td>The largest of its kind in the world in terms of max. discharge power, and the largest in China in terms of max. unit width discharge power</td>
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<tr>
<td>3</td>
<td>The unit capacity of turbine is 800 MW; the underground powerhouse has a span of 31.0 m, a height of 85.5 m, and an excavation span above the rock-bolted crane girder of 33.4 m; the tailrace tunnel shared by two units and having different roof elevations has a max. excavation cross section of 24.3 m × 38.2 m.</td>
<td>The then largest unit capacity in the world; the then largest-span and highest underground powerhouse in the world; the largest tailrace tunnel with different roof elevations in the world</td>
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<tr>
<td>4</td>
<td>The shiplift has a lift of 114.2m.</td>
<td>The highest single-stage lift in the world</td>
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<tr>
<td>5</td>
<td>The annual concrete volume for building the dam is 4.27 million m$^3$ and the monthly max. concrete volume is 0.54 million m$^3$.</td>
<td>World record for concrete placing for dam in gorgeous valley</td>
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<tr>
<td>6</td>
<td>The two-level flood release structure has a discharge capacity of 32,000 m$^3$/s.</td>
<td>The largest in the world</td>
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<tr>
<td>7</td>
<td>The aggregate processing system has a design capacity of 3,200 t/h; the belt conveyor for transporting aggregate has a max. unit length of 8.3 km and a total length of 31.1 km.</td>
<td>The largest design capacity of an aggregate processing system for hydropower project in China; the longest belt conveyor for hydropower project in China</td>
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Xiangjiaba Hydropower Project consists mainly of the water retaining structure, flood release and energy dissipation structure, sediment flushing structure, headrace and power generation system with dam toe powerhouse on the left bank, headrace and power generation system with underground powerhouse on the right bank, navigation structure, and irrigation water withdrawal structures on both banks. The dam is a concrete gravity one, with a max. height of 162.00 m, and a crest elevation of 384.00 m. The flood release structure in the dam consists of twelve 8.0 m × 26.0 m (W × H) surface bays and ten 6.0 m × 9.6 m (W × H) high-level outlets. For the headrace and power generation system on left bank, each turbine has a separate headrace and tailrace in arrangement, and the dam-toe powerhouse has dimensions of 226.95 m × 39.5 m × 81.75 m (L × W × H) and is installed with four sets of 800 MW generating units. For the headrace and power generation system on the right bank, each turbine has a separate headrace tunnel, two turbines share one tailrace tunnel, and the underground powerhouse has dimensions of 255.0 m × 31.0 m × 85.5 m (L × W × H). The navigation structure is a single-stage fully-balanced vertical shiplift with a max. lift of 114.2 m, which is designed for Grade IV navigable channel and can accommodate an individual ship of 1,000 t. Irrigation water withdrawal structures are respectively arranged at the dam section on left abutment and at the right side of the power intake of the underground powerhouse, and the design withdrawal discharges are 98.0 m³/s and 38.0 m³/s, respectively. A sediment flushing outlet and a sediment release tunnel are arranged on the left side of the intake of the dam toe powerhouse on left bank and beneath the intake of the underground powerhouse on the right bank, respectively.

**Figure 1** View of Xiangjiaba Hydropower Project
The concrete gravity dam has a max. height of 162.00 m, and a crest length of 896.26 m. Along the dam axis from left to right are the left abutment retaining section, left riverbed retaining section, sediment outlet section, shiplift section, dam-toe powerhouse section, flood release section, right riverbed retaining section, and right abutment retaining section. The left abutment retaining section has a front edge length of 199.922 m, consists of 12 monoliths, i.e., No.7 to No. 18, and has a foundation surface elevation of 262.00 m to 371.00 m and a max. height of 122.0 m. An irrigation water withdrawal structure is arranged at monolith No. 14. The monoliths No.7 to No.12 are of a circular arc in plane, with a central angle of 54° and a radius of 84.8m. The monoliths No.13 to No.18 are of a straight line in plane. The left riverbed retaining section has a front edge length of 115.0 m, consists of 6 monoliths, and has a foundation surface elevation of 222.00 m to 242.00 m and a max. height of 162.0 m. The sediment flushing outlet section is located on the right side of the left riverbed retaining section, with a front edge length of 30.0 m, a foundation surface elevation of 222.00 m, and a max. height of 162.0 m. The shiplift section is located on the left side of the powerhouse section, with a front edge width of 30.05 m, a length along the shiplift axis of 115.5 m, a crest width of 40.0 m. The dam-toe powerhouse section is located on the left side of the flood release section, with a front edge length of 148.35 m. The dam-toe powerhouse accommodates 4 generating units. Each unit has its own water conduit and the standard width of each unit section is 36.8 m. The flood release section is located at the center of the river channel and is slightly on the right side, with an alternated arrangement of surface bays and high-level outlets, and with high- and low-level flip buckets and energy dissipation by hydraulic jump. The flood release section has a front edge length of 248.0 m, consists of 13 monoliths, is arranged with 12 surface bays and 10 high-level outlets, and has a foundation surface elevation of 240.00 m, a base width of 166.0 m and a max. height of 144.0 m. The right riverbed water retaining section is located on the right side of the flood release section, has a front edge length of 60.934 m, consists of 5 monoliths, is of a circular arc in plane with a central angle of 52.50° and a radius of 66.5 m, and has a foundation surface elevation of 240.00 m to 268.00 m and a max. height of 144.0m. The right abutment water retaining section has a front edge length of 64.0 m and consists of 3 monoliths with a foundation surface elevation of 288.00 m to 351.00 m and a max. height of 96.0 m.

The dam site is located on the east plunge section of the anticline, with complex geological structure and a developed width up to 70 m. At the foundation of flood release section and the stilling basin, there exists a fractured zone of the deflecting anticline core, primarily of clastic sandstone. At the foundation of 16 monoliths, including the left abutment retaining section and powerhouse section, there exist gentle-dip squeezing zone and 24 soft interlayers mainly of mud and argillite. The soft
fractured rock is poor in property, with a permissible bearing capacity of 0.8 MPa to 2.0 MPa, a
deformation modulus of 0.3 GPa to 2.5 GPa, and a permissible seepage gradient of 2 to 5. To deal
with the problems of the dam foundation regarding sliding stability, bearing capacity, uneven
deformation and seepage stability, the dam foundation has been subjected to integrated treatment,
including foundation spreading, material replacement, three-dimensional force transmission, seepage
control, and handling unfavorable geological body. It is the first practice that a 162 m-high gravity
dam has been founded on a 60 m-thick soft, fractured rock mass.

The dam is built on a river with navigation requirements. A county seat and a large chemical
plant are on the right bank, only 400 m downstream of the dam. Due the constraints of bank stability,
atomization impact, environmental protection and navigation, the energy dissipation by hydraulic
jump has been finally selected. The max. flood discharge is 48,660 m³/s, and the max. flood
discharge power is 40,575 MW, which are the largest among the projects of its kind in the world. The
stilling basin has an inflow velocity of 40 m/s, a max. unit width discharge of 225 m³/s.m, and a max.
unit width discharge power of 187.6 MW/m, which are the largest in China. There is potential
deep-seated sliding in dam foundation, and the flood discharge and energy dissipation is also closely
related to the dam stability. Therefore, its dam safety concern is much higher than other similar
projects. With respect to the complex geological conditions and the flood discharge and energy
dissipation under high discharge power and rigorous environment, the energy dissipation by
hydraulic jump has been employed, including alternate arrangement of surface bays and high-level
outlets, high- and low-level flip buckets, and a stilling basin. As commented by Mr. Pan Jiazheng,
academician of both Chinese Academy of Engineering and Chinese Academy of Sciences, “the
challenges of Xiangjaba Hydropower Project in flood discharge and energy dissipation are
unprecedented, which may rank first in dam engineering in the world”.

The vertical shiplift has a max. lift of 114.2m, and a design seismic intensity of VII, which is the
highest among single-stage shiplifts and in design seismic intensity in the world. It poses high
requirements for the design, construction and operation of civil works and equipment. As the project
is located on a mountainous river with no reregulation reservoir downstream and high downstream
water level fluctuation, the navigation safety has stringent requirements for unsteady flow control
The rack and pinion vertical shiplift can ensure the levelness and stability of the ship chamber during
raising and lowering. It is the first practice to set an auxiliary lock chamber downstream the shiplift,
and the comprehensive control of non-steady flow, such as daily regulation operation control,
automatic flow compensation in unit changeover, and coordinated scheduling of flood discharge and
navigation, is proposed, achieving a good coordination among flood discharge, power generation and
navigation.

The dam is located on a river reach in gorgeous valley, the overburden is up to 45 m to 70 m thick, the design flood discharge for construction diversion is 32,000 m$^3$/s, the total concrete volume of the dam and its foundation treatment is 13.69 million m$^3$, and the design capacity of the aggregate processing system reached 3,200 t/h. All these indicate that the challenges of safe, efficient and green construction technology are far beyond the projects of its kind. The total concrete volume of the dam is 9.01 million m$^3$, including 5.0998 million m$^3$ of conventional concrete and 3.9106 million m$^3$ of roller compacted concrete. The intelligent construction technique of multiple levels in space and full cover in three dimensions is applied, realizing the use of roller compacted concrete and conventional concrete in an alternation manner in different zones and efficient and green construction. Both the conventional concrete and roller compacted concrete have a design strength at the 180 d. The flyash content in conventional concrete is up to 50%, the final adiabatic temperature rise of the conventional concrete and roller compacted concrete inside the dam does not exceed 30 ℃ (the difference in hydration heat between the two concrete in the later stage is controlled within 3 ℃), the difference in elasticity modulus is less than 20 %, and other properties are basically identical. The mean monthly concrete placing intensity is 336,000 m$^3$, and the max. dam rise in a construction year is 99 m.

![Figure 2  Full View of Dam Foundation Pit](image-url)
Figure 3  Xiangjiaba Hydropower Project under Construction

Figure 4  Xiangjiaba Hydropower Project under Construction

Figure 5  Xiangjiaba Hydropower Project upon Completion
Project Development History: Xiangjiaba Hydropower Project came into planning in 1950s, and underwent 40 years of preliminary survey and design. Totally 7 alternative dam sites were proposed on the planned 7.5 km-long river reach in gorge. Dam site VII at the exit of the gorge was finalized through a comprehensive analysis of dam site width, overburden thickness, engineering geological conditions, project layout, and investment. In July 2004, preparatory works was started; on November 26, 2006, construction was officially commenced; on December 28, 2008, river closure was realized; on October 10, 2012, gate closure for initial impoundment was realized; on October 16, 2012, initial impoundment level 354m was achieved; on November 5, 2012, the first generating unit in the underground powerhouse was commissioned; on April 12, 2013, the whole dam was concreted to its crest elevation 384 m; on July 5, 2013, the reservoir was filled to the minimum operating level 370 m; on September 12, 2013, the reservoir was filled to the normal storage level 380m ahead of schedule (the initial impoundment level was 354 m in 2013 as per the impoundment schedule in the feasibility study report); on July 7, 2014, the last generating unit was commissioned, one year ahead of the approved master construction schedule, i.e., June 2015; on May 26, 2018, the shiplift was commissioned. Then, Xiangjiaba Hydropower Project was fully completed according to the approved feasibility study report.

(II) Technological Innovations

The 162 m-gravity dam has been successfully founded on 60 m-thick soft fractured rock mass, which is unprecedented in terms of difficulty. The project is located on a river reach with navigation requirements and is very close to a county seat and a large chemical plant. The high-dam flood discharge and energy dissipation for the largest discharge power of its kind has been successfully addressed, which is probably the most difficult in the world for dam engineering (commented by academician Mr. Pan Jiazheng). High gravity dam is extremely rigorous in safe, efficient and green construction, and the alternated use of conventional concrete and roller compacted concrete in a large area is also unprecedented.

Technical Challenges: The large-scale deflecting core fractured zone is about 70 m wide at the dam site, and obliquely running through the flood release section and the stilling basin. Gentle-dip squeezing zone is exposed at 16 monoliths on the riverbed. At the dam foundation, there exist 24 soft gentle-dip interlayers. The fractured zone, squeezing zone or soft interlayers are all of Type IV or
Ⅴ rock mass, resulting in heavy challenges in sliding stability, bearing capacity, uneven deformation, and seepage stability. The max. flood discharge is 48,660 m$^3$/s, the max. flood discharge power is 40,575 MW, and the max. unit width flood discharge power in the stilling basin is 187.6 MW/m, which are all the largest of its kind in the world. The concrete volume for dam construction and foundation treatment is 13.69 million m$^3$, featuring tight schedule, stringent environmental requirements and high difficulty in safe, efficient and green construction. The heavy technical challenges can hardly be tackled with existing theory, codes and experience, and independent innovation is a must and the only solution. Through 50 plus years of tackling hard-nut problems in science and technology, a series of key technical breakthroughs have been made as below.

Innovation 1: Successfully deal with the problem in project layout, innovate the dam foundation treatment technology, and propose the integrated control technology in foundation sliding stability, seepage stability and base stress of the high gravity dam with complex geological conditions.

Study and propose the optimal project layout for the high multipurpose gravity dam on a river reach in gorge; propose the progressive failure pattern and multi-element safety criterion for the deep-seated sliding stability of gravity dam foundation; innovate the investigation and testing methods and means for dam foundation of hydropower project; propose the foundation deformation and stability treatment technology for high gravity dam with complex geological conditions, realizing the integrated control in foundation sliding stability, seepage stability and base stress of the dam, and successfully establishing the 162 m-high gravity dam on a 60 m-thick soft fractured rock mass. [With respect to the dam foundation stability analysis and assessment methods and theoretical research, the scientific and technological team published the papers “Failure Analysis of High-Concrete Gravity Dam Based on Strength Reserve Factor Method” in Computers and Geotechnics in 2008, “A Contact Model Based on the SQP Algorithm and Engineering Application” in Applied Mathematics and Computation in 2008, and “Formulations of Displacement Discontinuity Method for Crack Problem Based on Boundary Element Method” in Engineering Analysis with Boundary Elements in 2020, and discussed about the dam foundation sliding stability analysis and assessment methods, which has attracted the attention of the hydropower industry and has been highly complimented by
Successfully deal with the challenge in project layout to arrange the high multipurpose gravity dam on a river reach in gorge. In the project layout, considerations have been given to the multipurpose requirements of flood discharge, power generation, navigation, irrigation, sediment flushing and construction diversion. With respect to high discharge at the dam site, multiple generating units, limited front edge width of the dam in gorge, staged construction diversion on deep overburden, special geological conditions, and stringent environmental protection requirements due to being very close to the county seat, an elaborate project layout scheme has been proposed, i.e., based on the typical layout of a conventional gravity dam, the left and right abutment water retaining sections are of the reverse arc to avoid the coal mining goaf areas, the dam-toe powerhouse and underground powerhouse are arranged on the left and right banks, respectively, the flood discharge surface bays and high-level outlets are arranged alternately, the shiplift aqueduct crosses over the dam-toe powerhouse spatially to save the front edge width, and the construction diversion structures are designed for both temporary and permanent purposes, which has successfully overcome the challenge in project layout and achieved the coordination among multiple purposes.

Disclose the progressive failure mechanism of deep-seated sliding stability in dam foundation, and propose the progressive failure pattern and multi-element safety criterion for deep-seated sliding stability of gravity dams. Systematic research on the deep-seated sliding failure mechanism has been conducted for the gravity dam; the progressive failure pattern and multi-element safety criterion, including the curtain deformation stability criterion, abrupt displacement change criterion of representative point of tailrock, and connection criterion for upstream and downstream plastic yield zones, has been proposed for the deep-seated sliding stability of the gravity dam by the finite element method; the strength reserve coefficients for the three phases (abrupt change of deformation in curtain, abrupt change of displacement in tailrock resisting body, and connection of the upstream and downstream plastic yield zones) have been used for assessing the deep-seated sliding stability of the dam; the theoretical basis for analyzing and assessing the deep-seated sliding stability of the dam with complex geological conditions has been successfully solved. The above achievements have provided technical support for adding the finite element method in dam foundation stability analysis in NB/T 35026-2014, Design Code for Concrete Gravity
Dams.

(3) Innovate the investigation method for dam foundation with complex geological conditions and the foundation treatment technique of high dam, and achieve an overall balance among foundation sliding stability, seepage stability and base stress control of the dam. The digitalized investigation technology of 3D visualized geological model and quick digital geological television and logging system has been developed. Two unconventional exploratory adits, totally 641m long, have been arranged in the riverbed, and special tests, such as extra large load-bearing plate (0.5 m × 1.0 m) test, drillhole shear test, and extra heavy-duty dynamic penetration test, have been employed. The spatial distribution of soft fractured rock mass has been ascertained, and the engineering properties have been acquired. With respect to the lack of project example for sedimentary rock quality classification of dam foundation in the related code, based on the anisotropy of layered structure rock mass and its effect on the rock mass quality, the key factors such as layered structure feature, adit RQD and soft interlayer development degree have been determined for dam foundation rock mass classification, and the soft rock interlayer classification scheme, layered structure rock mass quality classification system of dam foundation, and indictor quantification standard have been proposed. The findings have been included in the latest edition of the code, enriching the dam foundation rock mass quality classification system for hydropower projects.

As an innovation, the integrated dam foundation treatment technique, including foundation spreading, material replacement, three-dimensional force transmission, seepage control, and handling unfavorable geological body, has been proposed for the high gravity dam with complex geological conditions. It is the first time to use the pumping and pressure relief technique, i.e., setting a valve at the dam foundation drainage hole + automatic monitoring + remote regulation, realizing the dynamic regulation of the dam foundation seepage control system. The max. discharge of drainage hole in the dam foundation has changed from initially 294 L/s to 52 L/s, and the uplift pressure in dam foundation is within the range of design value, with a considerable allowance. The research has revealed the deformation and stress characteristics of rigid gravity dam and flexible impervious wall, and a type of connection structure between the dam and the impervious wall has been invented. The high-pressure squeezing and grouting technique and equipment has been proposed for treating the
soft fractured zone. After grouting, the seepage through curtain is less than 0.1 Lu, and the seepage failure gradient is 100 and more. The monitoring data indicates that the dam foundation has a max. displacement to upstream or downstream of only 9.98 mm, the soft foundation has a settlement of only 11.4 mm after impoundment and is free from differential settlement, and the dam has satisfactory performance.

Innovation 2: It is the first time to considerably lower the hydraulic indicators on sidewalls of structures, and employ the high dam flood discharge technique that substantially improves the flood discharge safety and is friendly to the environment.

Break through the conventional hydraulic jump energy dissipation framework, propose the submerged jet theory and hydraulic design method for the new-type stilling basin based on the energy dissipation mechanism of three-dimensional submerged jet and spatial hydraulic jump, and develop the hydraulic jump energy dissipation design theory and technology for large discharge power of high dams. It is the first time to employ a new type of energy dissipation, i.e., high- and low-level flip buckets + stilling basin, which greatly lowers the hydraulic indicators on sidewalls of structures, substantially improves the flood discharge safety, and successfully controls the atomization. Develop the integral placement technology and operation monitoring and control devices for the flood release structures. The challenges of high dam flood discharge and energy dissipation, including the largest discharge power of its kind in the world, the largest unit-width discharge power in China, and in the near vicinity of a county seat and a large chemical plant, have been successfully tackled. With respect to the application of the new flood discharge and energy dissipation theory and technology, the scientific and technological research team has successively published the following papers: “Scale Effects of Air-Water Flows in Stilling Basin of Multi-Horizontal Submerged Jets” in Journal of Hydrodynamics in 2010, “Particle Image Velocimetry Measurements of Vortex Structures in Stilling Basin of Multi-Horizontal Submerged Jets” in Journal of Hydrodynamics in 2013, “Characteristics of Vortex Structure in Multi-Horizontal Submerged Jets Stilling Basin” in Water Management in 2014, “Characteristics of the Velocity Distribution in a Hydraulic Jump Stilling Basin with Five Parallel Offset Jets in a Twin-Layer Configuration” in Journal of Hydraulic Engineering in 2014, “Hydraulic Prediction of Near-Field Vibrations Induced by Releasing Flood” in Journal of Hydraulic Engineering in 2017. All
the research findings have been highly complimented by the editors-in-chief of the journals, and have attracted the extensive attention of the professionals at home and abroad, and have significance of guiding the hydropower industry.

(1) **With respect to the new energy dissipation type, i.e., multi-level and multi-stream submerged horizontal jets, the stilling basin vortex flow field theory and a complete set of hydraulic design method has been proposed, which brings the development in flood discharge and energy dissipation design theory and technology for high dams.** The stilling basin vortex flow field theory has been proposed, and the calculation formula for three-dimensional hydraulic jump energy dissipation theory has been established. The hydraulic characteristics and energy dissipation mechanism of multi-level and multi-stream submerged jets has been revealed, and the relationship between the shape parameters of energy dissipation structure and the flow structure and hydrodynamic characteristics has been obtained, which provides the theoretical basis for the research on and application of the flip bucket + hydraulic jump energy dissipation pattern.

(2) **It is the first time to propose the high- and low-level flip buckets + stilling basin energy dissipation technology, which greatly lowers the hydraulic indicators on the sidewalls of structure and successfully controls the atomization.** The high- and low-level flip buckets and stilling basin (dam height 162 m, and unit-width discharge of 225m³/s·m in stilling basin) can form two-level and multi-orifice submerged jets to dissipate the energy of discharge. Compared to the conventional flat–bottom stilling basin, the max. near-bottom velocity decreases by 65.4 % from 31.8 m/s to 11.5 m/s, the max. root mean square value of pulsating pressure on the stilling basin floor decreases by 51.7 % from 82 kPa to 39.6 kPa, the water surface fluctuation downstream of the end sill in case of frequent flood decreased by 67.9 % from 4.2 m to 1.6 m, and the energy dissipation rate increases by 42 % to 113 % from 40 % - 60 % to 70 % - 86 %. Therefore, the near-bottom velocity and pulsating pressure on the stilling basin floor are greatly decreased, the energy dissipation rate is high, the flow pattern is steady, and the outflow is smooth, which can improve the safety of flood release structures, and is conducive to the downstream navigation and bank safety. The atomization is slight and is limited to the area at the head of the stilling basin. The challenges in flood discharge and energy dissipation of high dam, including the largest flood discharge power of its kind in the world, the largest unit-width discharge power in the stilling basin in China, in the near
vicinity of the county seat and large chemical plan, have been successfully tackled, which relieves the project of major technical restraints.

(3) **Integral concrete placing and performance monitoring of the flood discharge and energy dissipation structures.** The integral forming and concrete placing technology has been developed. It is the first time to realize the integral concrete placing of the flow passage floor slab and sidewalls with the dam, which improves the structural integrity, avoids the damage to the weak zone at the sidewall bottom due to erosion of high-velocity flow, and ensures the structural safety under the action of high-velocity flow. The actual operation over the past 9 years from 2012 up to now shows that the floor slabs and sidewalls of 22 flow passages of surface bays and high-level outlets have performed satisfactorily. It is also the first time to develop and bury abrasion gauges to real time monitor the abrasion, cavitation and scour of the flood discharge and energy dissipation structures under high head and high sediment content flow.

**Innovation 3: Develop the safe, efficient and green construction technology and intelligent construction and management technologies for high gravity dams.**

It is the first time to employ the dam construction technology combining both conventional concrete and roller compacted concrete and develop an information and intelligent management platform to realize the efficient multi-level and 3D full-cover construction. Innovate the staged construction diversion technology featuring the world largest two-level flood release structures and super large caisson group in thick overburden. Innovate the artificial aggregate supply system featuring extra-long haul distance, high intensity, low energy consumption, environmental friendliness, and zero emission. It is the first time to practice the new hydropower development concept, i.e., build the hydropower station, boost the local economy, improve the local environment, and benefit the resettlers. The power plant has been commissioned at higher impoundment level ahead of schedule, and has produced an additional power of 13.971 TWh.

(1) **It is the first time to propose the dam construction technology with both conventional concrete and roller compacted concrete as well as the intelligent multi-level and 3D full-cover construction technology, which has created the world records in dam concrete placing intensity: annual concrete placing volume of 4.27 million m$^3$ and monthly concrete placing volume of**
0.54 million m³. Reveal the theoretical basis for the coordinated deformation and joint load bearing of conventional concrete and roller compacted concrete, innovate the alternated use of conventional concrete and roller compacted concrete for different levels, blocks and locations of the dam, develop the dam construction technology with both conventional concrete and roller compacted concrete, and develop the high dam design theory and method with construction materials of different properties. Innovate the dam construction technology based on informatization and intelligence, including the optimal configuration of equipment for multi-level and 3D full-cover construction, and the world record of monthly concrete placing volume of 121,700 m³ per tower crane, and achieve the efficient construction of the gravity dam. The research on and application of the dam construction with both conventional concrete with high flyash content and roller compacted concrete has attracted extensive attention of 850 experts and scholars from 30 plus countries and regions at the 2019 academic annual conference of China Commission on Large Dams and the eighth international symposium on roller compacted concrete dams. “The Conventional Concrete + Roller Compacted Concrete Dam Construction Planning of Xiangjiaba Hydropower Project” has been included in the 24th volume of 2019 China Hydropower Annals.

(2) Innovate the staged construction diversion technology for the world largest two-level flood discharge structures and super large caisson group in thick overburden. To deal with the staged construction diversion challenges, including the thick overburden 45 m to 70 m, high discharge 32,000 m³/s, high sediment content 24.2k g/m³ (measured max. value), high velocity (28.6 m/s) , and limited river channel width, the shape, construction and scour resistance of the two-level flood discharge structure with super high orifice rate 50 %, large unit-width discharge 278 m³/s.m, and super high abrasion and cavitation resistance performance has been innovated, and the world largest two-level flood discharge and construction diversion structure has been developed. It is the first time to systematically research the use of super large caisson group as the retaining wall in the initial stage, which has worked together with the roller compacted concrete as an composite cofferdam in the later stage, as well as the quick construction technique of the caisson group. Altogether 10 multipurpose super large caissons (17 m × 23 m each) have been arranged. It is the first practice to fill the caisson with riprap and self-compacted concrete, and the vertical excavation
of the 60 m-thick overburden in riverbed has been realized. The world highest caissons + roller compacted concrete composite cofferdam has been built, with a max. height of 94m. “The Research on the Design of Large Caisson Group and Key Construction Technology for Xiangjiaba Hydropower Project” has been included in the 13th volume of 2009 China Hydropower Annals.

(3) Innovate the artificial aggregate supply system featuring extra-long haul distance, high intensity, low energy consumption, environmental friendliness, and zero emission. With respect to the large artificial aggregate yard with extra-long haul distance and high-intensity supply requirements, the new concept on artificial aggregate processing and green transport design has been developed, and the largest aggregate processing system with a design capacity of 3200 t/h and the longest belt conveyor with a total length of 31.1 km and an individual length of 8.3 km have been built for hydropower project in China. The dynamic analysis technique of rubber belt conveyor and the composite technique of flexible drive and flexible brake have been developed, making full use of the terrain drop, and realizing the smooth transit of various transporting conditions. The measured unit energy consumption is only 0.06 kW·h/t·km, far lower than the internationally advanced level 0.11 kW·h/t·km, which meets the aggregate supply requirements and greatly lowers the energy consumption for the project. It is the first time to employ a large reservoir formed by tailing slag dam to treat the wastewater from aggregate processing, which has a wastewater treatment capacity of 4320 m³/h and consumes less energy. This innovation has been complimented by Mr. Tan Jinyi, Academician of the Academy of Engineering of China, as absolutely zero emission, and has been popularized to hydropower industry to obtain remarkable environmental benefits.

(4) It is the first time to practice the new hydropower development concept, i.e., build the hydropower station, boost the local economy, improve the local environment, and benefit the resettlers. In view of the Jinsha River bordering two provinces, practice the new hydropower development concept for the first time, establish such a hydropower development system that China Three Gorges Corporation holds the controlling interests and Yunnan and Sichuan Provincial Governments also participate in investment, innovate the scientific power source dispatch mode, improve the taxation system for the power station revenue, and establish the hydropower development benefits sharing system, i.e., property rights sharing, revenue and tax sharing, targeted public welfare.
Innovate and realize the “Three-Zero Management Objectives”, i.e., zero safety accident, zero quality accident, and zero environmental protection accident. Make a number of achievements, including the world record of “zero abnormal shutdown” of generating units, the award of National Ecological Civilization Project, and the rare fish breeding and releasing station as the National-Level Popular Science Base and the Patriotic Education Base.

Expand the Three Gorges Project Management System and develop several “Intelligent Management” subsystems. Inherit and expand the Three Gorges Project Management System, an integrated, collaborative work platform facilitating the designer, contractors, supervisors and employer to accomplish the project work. Make full use of modern information technology and develop a number of subsystems serving the project construction and management, including the anti-fake intelligent grouting system, the integrated dispatch and control systems of belt conveyor supply lines, and the automatic measuring and reporting system of dam instrumentation. Improve the intelligent management level for the construction of large projects. Realize the efficient multi-level and 3D full-cover construction through technological and process innovation. Create the world records in placement intensity of individual concrete system and in production intensity of individual equipment package.

In November 2017, the project design firm, Powerchina Zhongnan Engineering Corporation Limited, was invited to make a presentation at the 2017 academic annual conference of China Commission on Large Dams and the international symposium on dam safety. The topic was the Research on and Application of Key Technologies for Xiangjiaba Hydropower Project, which summarized the challenges in the project construction and the innovations and application of key technologies and attracted extensive attention of 700 plus academicians, experts and scholars from 20 plus countries and regions.

(III) Operation of the project

Xiangjiaba Hydropower Station has been completed in accordance with the approved design scale and scheme. The design of the main structures meets the requirements of the relevant standards and codes of China, the project quality management system is complete, the construction quality meets the requirements of the design and contract documents, the safety monitoring instruments and equipment have been installed and are in service as required, the performance of the
turbine-generator units and other main electromechanical equipment satisfies the power station operation requirements, and all the flood discharge and energy dissipation structures, sediment flushing and releasing structures and navigation structures meet the project safety requirements.

The reservoir was impounded to the initial filling level of 354 m in October 2012, to the minimum operating level of 370 m in July 2013, and to the normal pool level of 380 m in September 2013. The project was subjected to the operation test of 9 flood seasons (2012 to 2020). After the impoundment, the maximum reservoir inflow is 16,600 m$^3$/s, the maximum outflow is 16,900 m$^3$/s, and the water retaining structures, flood discharge and energy dissipation structures, 12 surface bays and 10 intermediate flood discharge outlets have withstood flood discharge test. During the operation period, through careful maintenance before and during flood season, the complex structures and flood discharge facilities operate normally, and the gates, hoists and other equipment operate safely, reliably, and highly stably. The monitoring over the electromechanical equipment show that the operation of the turbine-generator units and their auxiliaries, power equipment, control, protection and communication system, and hydraulic machinery ancillaries of the whole station is safe, reliable and stable.

The monitoring over Xiangjiaba Hydropower Station is comprehensive, and the main safety monitoring results are as follows:

(1) Dam foundation deformation: the deformation in the upstream and downstream direction is mainly towards the downstream, ranging from -0.25 mm to 9.98 mm; the deformation in the left and right bank direction is mainly towards the right bank, ranging from -3.91 mm to 0.63 mm; the vertical displacement is of settlement displacement at a maximum of 11.40 mm after impoundment, except that some measuring points in the left non-overflow monoliths indicate a slight uplift displacement.

(2) Dam deformation: the deformation in the upstream and downstream direction is mainly towards downstream, ranging from 3.95 mm to 11.50 mm; the deformation in the left and right bank direction is generally of displacement to the right bank ranging from -10.48 mm to 1.49 mm, except for Discharge Monolith No. 1 showing a slight displacement to the left bank; for the vertical displacement, except for the measuring points in some monoliths indicating a slight uplift...
displacement, the measuring points in other parts indicate settlement deformation, with the maximum settlement displacement of 14.82 mm; the settlement distribution indicated by the measuring points in galleries shows that the settlement is the largest at the riverbed and decreases gradually towards the monoliths on the bank slopes, the settlement of the lower gallery is greater than that of the higher gallery due to the dead load of concrete, and, following the completion of dam concreting and reservoir impoundment, the settlement at the measuring points is stabilized at present.

(3) Joint observation: currently most of the dam joints are in an open state, with the maximum opening of 3.65 mm. The joint opening mainly changes in initial installation, grouting and measurement interruption. Now the measurements of all kinds of joint meters are relatively stable, indicating there is no obvious tendency of opening or closing. The opening of the transverse joints varies with temperature, while that of the longitudinal joints does not.

(4) Dam foundation seepage pressure: the measurements of the piezometers for the dam foundation have been relatively stable since the impoundment, with a water level variation no more than 20 m at most measuring points; the seepage flow of dam foundation has been decreasing year by year since the impoundment in early 2012, and it is 52 L/s now.

(5) Dam foundation deep seepage pressure: the measurements of the piezometers for cutoff wall are relatively stable except for PFSQ-13, whose converted water level rises slightly and slowly. The average converted water level of the piezometers upstream of the cutoff wall is more than 60 m higher than that of the piezometers downstream of the wall. The water level measured by the piezometers upstream of the cutoff wall has a positive correlation with the upstream water level and fluctuates slightly, while the water level measured by the piezometers downstream of the cutoff wall is relatively stable. The measurements of the piezometers for dam foundation seepage holes are relatively stable and have no apparent correlation with the upstream water level.

(6) Stresses in the dam: all the calculated stresses are within the design concrete allowable strength range currently. Inside the dam body of each monolith, the concrete is mostly in a compressed state, the strain changes steadily and periodically with the seasons, and the change in temperature inside the dam lags behind the external water temperature and air temperature to a certain extent.
(7) Stresses in reinforcement: currently the reinforcement meters for the dam are mostly in a tensioned state, and the measurements of most reinforcement meters are within 50 MPa. The stress measured by the reinforcement meters has a negative correlation with the temperature and is generally stable with slight fluctuation.

(8) Dam body temperature: the historical measurements of bedrock thermometer show slight fluctuation only, and the current measured bedrock temperature is stable, varying between 15.7 °C and 24.8 °C. As measured by dam body thermometers, the change in temperature mainly occurs in the early concreting stage due to the influence of hydration heat, and the temperature has gradually stabilized in the later stage. The temperature measured by the dam surface thermometers at some locations changes greatly and periodically under the influence of ambient air temperature and reservoir water temperature. At present, the dam body temperature is between 13.4 °C and 23.0 °C.
Precise Level Graph of Dam Gallery at El. 260 m

Graph of Displacement Meter for Left Non-Overflow Monolith

Graph of Dam Seepage Flow (Drain Hole)

Converted Water Level of Bedrock Piezometer PB-1 – Upper Water Level Graph
After the impoundment in October, 2012, six earthquakes of ML 5.0 or above and one earthquake of ML 6.0 or above struck the area within 100 km around the dam site. Among them, the ML 6.0 earthquake occurred at 22:55 on June 17, 2019 at Changning County, Yibin City, Sichuan Province is the largest, with a focal depth of 16 km and an epicenter about 50 km away from Xiangjiaba Hydropower Station.

After the earthquake, the Owner organized intensified patrol inspection and observation with the
macroseismograph, plummets, and piezometers for the dam. In the patrol inspection, no abnormalities were found in the dam, galleries, and left and right bank slopes, and the complex structures operated normally. The intensified monitoring shows that the peak acceleration in all directions measured by the macroseismograph is within 35 gal, far less than the design horizontal peak acceleration of the bedrock 226.1 gal; the change in plummet displacement before and after the earthquake is small, ranging from -0.02 mm to 0.52 mm in the left and right bank direction and from -1.12 mm to 0.29 mm in the upstream and downstream direction; the measurements of dam foundation piezometers are stable with the converted water level ranging from -1.45 m to 2.49 m, and there is no abnormal change in dam foundation seepage flow.

In accordance with the requirements of the Administrative Measures for Safety Appraisal for Hydropower Projects issued by the National Energy Administration of the People’s Republic of China and following the principles of being independent, objective, scientific and standardized, the Owner entrusted a third party, China Water Resources and Hydropower Engineering Consulting Co., Ltd., to carry out the safety appraisal on the completion of the project complex. In April, 2016, Xiangjiaba Hydropower Station passed the safety appraisal on the completion of the project complex organized by China Water Resources and Hydropower Engineering Consulting Co., Ltd. The appraisal report draws the following conclusions: the layout of Xiangjiaba Hydropower Project is
reasonable, and the project design complies with the national and sector codes and standards; the project development procedures and construction management meet the relevant requirements, the project complex (except the shiplift) has been completed according to the approved design criteria, scale and scheme, and the construction, manufacturing and installation quality of the civil works, safety monitoring works, hydraulic steel structures and electromechanical works meet the requirements of the design and contract documents and relevant technical standards; the initial operation and safety monitoring results of the power station show that the complex structures and the slopes work normally, the reservoir bank slopes near the dam are stable, and the hydraulic steel structure equipment, turbine-generator units and their auxiliaries, power equipment, control, protection and communication system, and hydraulic machinery ancillaries of the whole station are in normal operation. In January, 2020, Xiangjiaba Hydropower Station passed the special safety appraisal for the navigability of the shiplift organized by China Water Resources and Hydropower Engineering Consulting Co., Ltd. The appraisal report draws the following conclusions: the design of the shiplift of Xiangjiaba Hydropower Station on the Jinsha River has passed the review and complies with the relevant laws, regulations, and national and sector technical standards; the construction quality of civil and safety monitoring works generally meets the design requirements or the stipulations of the contract documents; the design calculations and the trial navigation monitoring results show that the structural stability and deformation of the main structures of the shiplift such as the ship chamber pillars meet the design requirements and the main structures work normally. The test results and the 19-month trial navigation show that the performance of the main equipment and the systems generally meets the design and operation requirements.

(IV) Main Benefits, Achievements and Awards

1 Main Benefits

(1) Remarkable power generation benefits, continuous and stable supply of green and clean energy, and promotion of sustainable economic and social development

Since the first unit was put into operation in November 2012, Xiangjiaba Hydropower Station has achieved the operation goal of “zero abnormal shutdown” of all the eight units for consecutive four years, keeping the world record. From 2016 to 2020, the annual output for five consecutive
years exceeded 30,880 GWh (design index); by the end of May, 2021, the cumulative output exceeded 253,000 GWh and the single unit operation time exceeded 40,000 hours for all the units. The power station has provided stable and sustainable green and clean energy for the society, effectively mitigated the regional power supply and demand imbalance, optimized the energy mix, made the respective advantages of western resources and eastern economy complementary to each other, and greatly promoted the balanced development of regional economy. Huge amount of electric energy has been sent from Xiangjiaba Hydropower Station to East China by ±800 kV ultra-high voltage DC transmission line, which is a localization demonstration project.

The average annual output of the power station is over 30,000 GWh, which can replace a coal-fired power plant of the same scale, and reduce raw coal consumption by about 14 million tons and emission of carbon dioxide by about 25 million tons, nitrogen dioxide by about 170,000 tons and sulfur dioxide by about 300,000 tons, equivalent to planting 68,000 ha of broad-leaved forest. The power station can not only save coal resources, but also reduce coal pollution, making positive contributions to energy conservation, emission reduction, eco-environment protection and green development of the world.

(2) **Remarkable navigation benefits through improving the navigation conditions of the reservoir area and the lower reaches and boosting the development of the “Yangtze River Economic Belt”**

The construction and operation of the power station have effectively improved the navigation conditions of the reservoir area and the lower reaches, and greatly promoted the leap-forward development of navigation on the Jinsha River. After the completion of the power station, its backwater reaches the downstream of Xiluodu Dam all year round, forming a 156.6 km-long reservoir surface with a small water level variation (a drawdown of only 10 m). The reservoir, which flooded 84 navigation-hampering shoals, has made the reach of the reservoir area a safe deep-water navigable zone, improved the navigation conditions fundamentally, and upgraded the channel in the reservoir area upstream of the dam site from Grade V to Grade IV. Although the nature of the river channel downstream of the dam was not changed after the impoundment, the Navigation dispatching scheme for the shiplift operation period (initial stage) for Xiangjiaba Hydropower Station on the
**Jinsha River** was formulated through physical model test and mathematical model analysis of the downstream river channel, prototype observation and full-scale ship trial, and comprehensive study and analysis of the scientific law of the power station dispatching and joint dispatching with the upper cascade stations. After the shiplift was built, the channel upstream of the shiplift is upgraded from a seasonal channel suspended in flood and dry seasons to a high-quality all-year-round deep-water channel. Before the construction of the power station, the cargo throughput of the river reach was generally 200,000 t/year to 300,000 t/year; after the impoundment, the regional navigation increased rapidly, and the cargo crossing the dam reached the level of 8.5 million t/year (including the amount of trans-shipment crossing the dam) in 2020, achieving a leap-forward development. Due to the regulation of the power station, the minimum navigable flow of the downstream channel is increased from 1,100 m$^3$/s to 1,500 m$^3$/s, greatly improving the navigation conditions.

The power station has developed the function of water replenishment at unit shedding to deal with accident situations. Because the natural channel from Xiangjiaba Hydropower Station to Yibin City is relatively narrow, accidents or events occur to the power station or the grid, especially in the dry season, may lead to unit shutdown, sudden drop of reservoir outflow, formation of steep falling water wave in the downstream channel, and significant drop of water level, which will impede the passage of ships, and in serious cases, possibly cause marine accidents such as ship stranding and capsizing. Therefore, the power station was specifically designed with a function of water replenishment at unit shedding, i.e., to quickly open the flood gates according to the shed capacity to replenish water to the downstream channel to ensure its water level variation does not exceed 1.0 m/h and to ensure the ship navigation safety and the conformity with the ecological water replenishment requirements. In view of the specific conditions such as many flood gates and their complex operation combinations and different discharge capacities under different water heads, an optimized flood gate opening scheme will be put forward automatically when the reservoir outflow changes rapidly based on the power station operation data and real-time outflow data collected by the SCADA system, so as to realize automatic control and opening of the gates by the SCADA system. Through continuous optimization and improvement and actual operation test, the function of water replenishment at unit shedding has been further improved and become more effective.
The shiplift is the planned navigation facility for the power station. It can pass a single ship of 1,000 t class, with a design freight volume of 1.12 million t/year and a passenger capacity of 400,000 passengers/year. Before the construction of the shiplift, the annual freight volume at the dam site was generally 200,000 tons to 300,000 tons from 1994 to 2002. Since the shiplift was put into service in May, 2018, the careful operation and maintenance and the active technological and management innovation have ensured the safe and efficient operation of the shiplift and the orderly and smooth navigation of the river section. The joint navigation dispatching management mechanism has been improved gradually, and the ship traffic volume increased year by year. By the end of May, 2021, 7,778 ships passed the shiplift, carrying 3,016,900 tons of cargo. In 2020, the shiplift was navigable for 287 days and accomplished a freight volume of 1.3 million tons, exceeding the design index of 1.12 million tons/year.

(3) Significant flood control benefits through joint dispatching with the upstream cascade reservoirs to ensure the property safety of the downstream

Xiangjiaba Hydropower Station has a flood control capacity of 903 million m³, featuring in high flood control ratio and being close to flood protection objects. On the premise of ensuring the safety of the power stations, the joint operation of Xiluodu-Xiangjiaba cascade reservoirs has improved the flood control criterion of Yibin, Luzhou, Chongqing and other downstream coastal cities from being protected against the flood smaller than 20-year flood to against 50-year to 100-year flood. The joint flood control with the Three Gorges Project has further improved the flood control capacity of the Jingjiang reach, reduced flood diversion losses in the middle and lower reaches of the Yangtze River, and effectively ensured the flood safety of the Yangtze River Economic Belt, which covers 11 provinces and municipalities, with an area accounting for about one-fifth of China’s total area and a population and GDP exceeding 40% of the country.

The cascade reservoirs have significant flood control benefits and have successfully retained many extraordinary floods in the Jinsha River and the Yangtze River. Since the impoundment of Xiangjiaba reservoir, 13 floods have been retained, with a cumulative flood storage of 3.827 billion m³. In particular, from August 17 to 19, 2020, Xiangjiaba-Xiluodu joint dispatching successfully coped with the maximum flood peak occurred to Xiluodu reservoir since its establishment (the
maximum inflow of Xiangjiaba reservoir was 16,600 m$^3$/s) and had reduced the outflow of Xiangjiaba reservoir to 4,000 m$^3$/s for 42 hours continuously, effectively avoiding the occurrence of 100-year flood peak to the downstream tributaries and greatly reducing the flood losses. Through joint dispatching and operation, the cumulative flood volume retained and stored was up to 700 million m$^3$, and the peak water levels at Lizhuang, Luzhou, Zhutuo, and Cuntan gauging stations were reduced by about 3.2 m, 2.9 m, 3.3 m, and 3.0 m respectively.

(4) Remarkable irrigation benefits through rebuilding a Dujiangyan Irrigation System to effectively ensure the drinking water safety in urban and rural areas

Sichuan Basin is known as the “land of abundance”, where the famous world cultural heritage Dujiangyan Irrigation System has a long history and has been nurturing the fertile land in Sichuan Basin for more than 2,000 years. Xiangjiaba Hydropower Station and its supporting irrigation district works are equivalent to rebuilding a Dujiangyan Irrigation System and, after completion, can effectively solve the irrigation problem for 5.3 million mu of fertile land (the irrigation district starts from Da’an District of Zigong City in the north, Gongle Town of Xingwen County in the south, Xiangjiaba Hydropower Station in the west, and the Yangtze River and the Chishui River in the east), and thus effectively contribute to the world food security; help solve the water use problem for 2 cities, 143 towns (including 8 county towns) and more than 4 million rural people in the irrigation district, and supply industrial water to the surrounding towns and industrial parks; effectively guarantee the drinking water safety in the cities and rural areas, meet the water supply demand of some cities, improve the urban production, living and agricultural production conditions in the irrigation district, enhance the grain production capacity, accelerate the development of new socialist countryside, and promote the coordinated regional economic and social development. Xiangjiaba Irrigation District is developed in three phases and will be completed in 15 years. The first phase, North Main Canal, commenced in November 2018 officially, is under construction currently, and is planned to be put into service in 2023.
2 Scientific Research Achievements and Awards

Table 1  Awards to Xiangjiaba Hydropower Station

<table>
<thead>
<tr>
<th>S/N</th>
<th>Description</th>
<th>Awards</th>
<th>Year</th>
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<tbody>
<tr>
<td>1</td>
<td>Analysis theory, method and application study for deep-seated sliding stability for gravity dams</td>
<td>China Society for Hydropower Engineering First Prize</td>
<td>2012</td>
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<tr>
<td>2</td>
<td>Study and application of technology for fractured deep, thick and weak rock mass treatment for high gravity dam foundations</td>
<td>Hunan Science and Technology Progress Awards First Prize</td>
<td>2015</td>
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<tr>
<td>3</td>
<td>Study and application of new energy-dissipation technology for high-power flood discharge of high dams in complex environment</td>
<td>China Society for Hydropower Engineering First Prize</td>
<td>2015</td>
</tr>
<tr>
<td>4</td>
<td>Study and application of new energy-dissipation technology for high-power flood discharge of high dams in complex environment</td>
<td>China Association of Construction Enterprise Management First Prize</td>
<td>2015</td>
</tr>
<tr>
<td>5</td>
<td>Study and application of new energy-dissipation technology for high-power flood discharge of high dams in complex environment</td>
<td>Power Construction Corporation of China First Prize</td>
<td>2015</td>
</tr>
<tr>
<td>6</td>
<td>Study and application of energy-dissipation technology for high-power flood discharge of high dams in complex environment</td>
<td>Hunan Science and Technology Progress Awards First Prize</td>
<td>2018</td>
</tr>
<tr>
<td>7</td>
<td>Study and application of energy-dissipation technology for high-power flood discharge of high dams in complex environment</td>
<td>Chinese National Committee on Large Dams First Prize</td>
<td>2018</td>
</tr>
<tr>
<td>8</td>
<td>Study and application of new technology of dam building with high-fly-ash-content conventional concrete and RCC</td>
<td>China Association of Construction Enterprise</td>
<td>2019</td>
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(V) Environmental and Social Impacts and Contribution to Regional Development

During the construction of Xiangjiaba Hydropower Station, the Owner always adhered to the hydropower development idea of boosting the local economy, improving the local environment, and benefiting the resettlers while building the power station, insisted on the guideline of protection in development and development in protection, promoted eco-environment protection and soil and water conservation in all aspects, and simultaneously advanced the effective linking and organic combination of the power station planning and construction with the local economic and social development plan, forming a new situation in which economic benefits, social benefits and ecological benefits are harmoniously unified.

Good results have been achieved in the protection of rare and endemic fish in the area of Xiangjiaba and Xiluodu hydropower stations. The National Nature Reserve for Rare and Endemic Fish in the Upper Yangtze River is just downstream of Xiangjiaba Hydropower Station, with a total length of 1,162.61 km and a total area of 33,174.213 ha. The main protected objects are paddlefish,
sturgeon, myxocyprinus asiaticus and other rare and endemic fish in the upper Yangtze River and their spawning grounds, involving Yunnan, Guizhou, Chongqing and Sichuan, mainly including the 353.16 km Jinsha River reach and Yangtze River reach from the point 1.8 km downstream of Xiangjiaba Dam axis to Masangxi in Chongqing, the 90.1 km Minjiang River reach from Yuebo to its estuary, and the 628.23 km Chishui River from the source to the estuary. In order to effectively protect the rare and endemic fish in the area of Xiangjiaba and Xiluodu hydropower stations, a rare and endemic fish breeding and releasing station for Xiangjiaba and Xiluodu hydropower stations was built in 2008, mainly for artificial reproduction, cultivation and releasing of rare and endemic fish in the Jinsha River and the Minjiang River. It is one of the important breeding and releasing stations for the National Nature Reserve for Rare and Endemic Fish in the Upper Yangtze River, and was appraised by China Association for Science and Technology as the National Science Education Base for Production Facilities at the end of 2009. From 2008 to 2020, it made 26 releases, with a total of 2.013 million rare and endemic fish released. The submerged jet energy dissipation adopted by the power station has effectively reduced the air saturation of the downstream water flow and is beneficial to fish protection. The jet-flow atomization is limited to the first section of stilling basin, which avoids the influence on the surroundings such as neighboring county town and large chemical enterprises. During the operation period of the power station, the Owner carries out further studies on ex-situ conservation and breeding of endemic, rare and resource-type terrestrial plants in the impoundment-affected area, and is building the second phase works of the rare and endemic fish breeding and releasing station for Xiangjiaba and Xiluodu hydropower stations and a botanical garden for regional rare plants, so as to further strengthen the natural ecological protection.
Figure 9  National Nature Reserve for Rare and Endemic Fish in the Upper Yangtze River

The eco-environment protection and soil and water conservation for Xiangjiaba Hydropower Station are combined with the project construction, ecological landscaping and ecological leisure facility building, forming a perfect ecological measure system for environmental protection and soil and water conservation, reaching the goal of building a green hydropower project and an ecologically beautiful dam area. Xiangjiaba Hydropower Project won the title of “National Ecological Civilization Project for Soil and Water Conservation” in 2019 and has a demonstration effect for large-scale hydropower development. In the construction, the “three simultaneities” environmental protection system (i.e., the environmental protection works and the project are designed, constructed and operated simultaneously) was strictly implemented, and a series of effective measures for construction pollution control, water environment protection and eco-environment protection were adopted to control and reduce the construction wastewater, air and noise pollution, including wastewater treatment, recycling and up-to-standard discharge measures for aggregate processing and concrete mixing systems. On the one hand, optimization was made to some construction sites and auxiliary works such as quarries, borrow areas, and spoil areas, reducing the total land area by 311.19 ha; on the other hand, the new requirements for eco-environment protection
were strictly implemented, and the investment support was constantly increased. The total investment in environmental protection is up to 978 million yuan, an increase of 365 million yuan compared with that in the EIA stage. Before the impoundment, as a precondition, inspection and acceptance were conducted in terms of the environmental protection measures, reservoir basin clearing, old tree transplanting, cultural relics protection, environmental protection scheme for reservoir impoundment and operation, construction of the nature reserve, and rare and endemic fish breeding and releasing. Nowadays, Xiangjiaba Hydropower Station, with a beautiful environment full of flowers and trees, has become a water culture park with picturesque scenery and harmonious relationship between human and water and realized the harmony and unity of development and environmental protection. The project has played a positive demonstration and leading role and popularized science and culture to serve the society.

Figure 10  Ecological Restoration and Landscaping of Office and Living Quarter of Xiangjiaba Hydropower Station
The comprehensive social benefits of Xiangjiaba Hydropower Station have been brought into full play. Xiangjiaba Hydropower Station is a national key project and a model project in the Large-Scale Development of Western China and has many functions and great social benefits. It has provided green and clean energy for the society and made the respective advantages of western resources and eastern economy complementary to each other; it has brought the social benefits of flood control into full play through joint operation with cascade reservoirs and greatly mitigated the flood hazards and losses; it has fundamentally improved the navigation conditions in the reservoir area and the lower reaches and realized the leap-forward navigation development of the region. In addition to exerting huge comprehensive social benefits in power generation, flood control, navigation and irrigation, the power station also has such functions and social benefits as re-regulation for Xiluodu Hydropower Station, sediment retaining, ecological flow compensation and urban water supply. In addition, the power station’s design scheme and the local government’s regional economic and social development plan have been organically combined and connected for mutual promotion, which has further promoted the local economic and social development. Since the impoundment, the 150 km-long reservoir area has fostered the local tourism industry in sightseeing, leisure and vacation.
The development of Xiangjiaba Hydropower Station has greatly promoted the local economic and social development in the reservoir area. Pingshan, Leibo, Yongshan and Suijiang counties in the reservoir area, belonging to the extremely poor areas in Wumeng Mountain district, were national key poverty-stricken counties mostly. They had many ethnic groups and were very poor and marginalized in terms of location. **The first is to solve the problem of poverty.** Before the impoundment in 2012, the resettlers were helped get rid of poverty and become better off by utilizing the relocation policy for the reservoir area; and then, through making full use of the national precise poverty alleviation policy and giving play to the radiation and driving role of the large project, and thanks to that China Three Gorges Corporation actively fulfilled the social responsibility of state-owned enterprise, the local people were helped get rid of poverty and become better off through various channels. In 2019, all the poor people in all the reservoir area counties were lifted out of poverty, achieving the goal of the national poverty alleviation plan one year ahead of schedule. **The second is to comprehensively improve the social features of the reservoir area.** The urban living environment has been significantly improved. For example, the planned land area and the per capita area of the new county town of Suijiang are 393.60 ha and 102.3 m², more than 3 times and nearly
1.6 times that of the old county town, respectively; the planned land area and the per capita area of the new county town of Pingshan are about 273.62 ha and 103.14 m², more than 3 times and 2 times that of the old county town, respectively. The urbanization rate in the reservoir area has increased greatly. For instance, the urbanization rate of Pingshan County rose from 11.8 % before the relocation to 40 % in 2018. The infrastructure in the reservoir area has been significantly improved, with about 330 km of highway rebuilt and 17 wharfs rebuilt or built with subsidy. All the facilities in the reservoir area for community interest such as education and health care facilities were planned and constructed in accordance with the national standards, and 56 schools and kindergartens and 23 medical and health services were relocated or extended. The original functions before the inundation were not only restored, but also improved by leaps and bounds. **The third is to accelerate the economic development of the reservoir area in an all-round way.** As of the end of December 2020, the investment in resettlement for Xiangjiaba Hydropower Station was up to about 35.8 billion yuan. The huge investment has greatly promoted the development of the local economy. The GDP of Suijiang County on Yunnan side of the power station reached 2.405 billion yuan in 2018, 10.69 times that before the relocation (2002); the GDP of Pingshan County on Sichuan side reached 5.297 billion yuan in 2018, 5.43 times that before the relocation (2002), with a growth rate far higher than that of other non-relocation counties in the same region. In addition, China Three Gorges Corporation has allocated special funds to support local development in addition to the planned investment in resettlement, which has played a significant role in developing industries and improving people’s livelihood and infrastructure. It provided 23,000 jobs for local villagers, increased the income of local farmers, and promoted the coordinated and stable social and economic development. By the end of December 2020, Xiangjiaba Hydropower Station paid 14.089 billion yuan of taxes and fees, of which 6.900 billion yuan to Sichuan Province and 7.189 billion yuan to Yunnan Province, and became a stable and sustainable tax source for the local governments. The large amount of taxes and
fees were directly transformed into a drive for local economic development and played an important role in boosting local economic growth and promoting local people’s employment, creating good economic and social benefits. The fourth is to explore new ideas for the enterprise to help the resettlers in the reservoir area. Since 2013, China Three Gorges Corporation has drawn a certain amount of funds from the power generation revenues of Xiangjiaba Hydropower Station to set up Jinsha River Hydropower Fund for helping resettlers and protecting ecological environment, exploring new ideas to help resettlers, and establishing an enterprise assistance mechanism for the development of resettlers. By the end of December 2020, 126 resettler assistance projects, involving education, health care assistance, infrastructure improvement, industrial support, and skill training, had been implemented at Xiangjiaba Hydropower Station, helping the long-term development of the resettlers in the reservoir area.

Figure 13  Shaonyping Town, a New Town for Resettlers for Xiangjiaba Hydropower Station