

Sanmenxia multipurpose hydraulic project

Sanmenxia Yellow River Pearl (Group) Co., Ltd., Sinohydro Bureau 11 Co., Ltd.

ARTICLE INFO

Keywords

Sanmenxia
hydropower station
sediment-laden rivers
storing clear and discharging muddy
lesson and learn

ABSTRACT

Sanmenxia hydro-junction is the first sizable water conservation project constructed on the Yellow River's main stream during the socialist revolution and construction period following the foundation of new China. Due to lacking understanding and experience with sediment-laden water rivers, after the project was constructed in 1960, it was reconstructed and/or modified twice. This paper presents the case study of the Sanmenxia project.

1 Project profile

1.1 Engineering brief

Sanmenxia hydro-junction (Sanmen Gorge), also known as “the first dam of the Yellow River”, is the first sizable water conservation project constructed on the Yellow River's main stream following the foundation of new China. China commissioned the Leningrad Hydroelectric Design Branch of the former Soviet Union Hydroelectric Design Institute to design the Sanmenxia project, which was constructed by China Yellow River Sanmenxia Engineering Bureau. This project is situated approximately 14 km from Sanmenxia City and 1027 km from the Yellow River estuary in the lower middle reaches of the Yellow River, near the intersection of Sanmenxia in Henan Province and Pinglu in Shanxi Province. Sanmenxia hub controls 688,400 km² of the Yellow River basin, accounting for 91.5% of the total basin area, 89% of the Yellow River inflow, and 98% of the Yellow River sediment inflow. It is classified as a “Large (1)” reservoir with flood control and comprehensive utilization of ice prevention, irrigation, power generation and water supply, per China's national standard of *Standard for Classification and Flood Control of Water Recourses and Hydroelectric Project* (SL 252-2017). The dam was designed with a normal high water level at the elevation of 360.00 m. It is noted that the dam was initially constructed per the water storage level of 350.00 m, and the elevation of dam crest was 353.00 m (Dagu elevation system of 1902, the

same below). Due to the serious sediment deposition after impoundment, the dam was later modified. Currently, the height of the dam is 106.00 m, and the total storage capacity is roughly 5.89×10^9 m³. Seven generators are being operated with a total installed capacity of 450 MW. Engineering characteristics are displayed in Table 1.

1.2 Engineering complex layout and main buildings

Sanmenxia hydro-junction is composed of main dam, auxiliary dam, flood releasing structure, power plant building, and outdoor switch station. The layout diagram is shown in Fig. 1.

The main dam is a concrete gravity dam, with a length of 713.20 m, crest elevation of 353.00 m, and maximum dam height of 106.00 m. The non-overflow dam portion is on the left bank, followed by the overflow dam section, pier dam section, power station dam section, installation dam section, and non-overflow dam section on the right bank, in that order.

The auxiliary dam on the right bank is a reinforced concrete double-hinged core wall earth dam with a length of 144.00 m, crest elevation of 353.00 m, and dam height of 24.00 m.

The flood discharge structure includes 27 flood discharge holes (outlets and pipes), 12 deep holes, 12 bottom holes, 2 flood and sand discharge tunnels, and 1 sand discharge steel pipe. The surface holes in the original overflow dam section are no longer used because of the change of design water level. The depth

Citation: Sanmenxia Yellow River Pearl (Group) Co., Ltd., Sinohydro Bureau 11 Co., Ltd. Sanmenxia multipurpose hydraulic project. *J Intell Constr*, 2023, 1, 9180022.

© The Author(s) 2023. Published by Tsinghua University Press. The articles published in this open access journal are distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Table 1 Engineering characteristics of Sanmenxia hydro-junction

No.	Parameter	Unit	Quantity	No.	Parameter	Unit	Quantity
1	Name of project	Sanmenxia hydro-junction (Sanmen Gorge)		20 ²	Storage capacity at normal storage level	m ³	4.96 × 10 ⁸
2	Location	Sanmenxia City, Henan Province		21	Adjustment characteristics	Incomplete yearly regulation	21
3	Stream	Yellow River		22	Installed capacity	MW	22
4	Commencement date	April 1957		23	Guaranteed power	MW	—
5	Completion date	April 1961		24	Average annual energy output (2003–2018)	kW·h	1.495 × 10 ⁹
6	Engineering class (SL 252-2017)	Type I “Large (1)”		25	Annual use of hours (2003–2018)	h	3750.52
7	Dam classification level	Level 1		26	Type of dam	Concrete gravity dam	
8	Project investment	yuan	9.4 × 10 ⁸	27	Earthquake basic intensity/fortification intensity	degree/seismic acceleration	VIII/IX
9	Reservoir area	km ²	688,400	28	Dam height	m	106.00
10	Average annual runoff	m ³	4.267 × 10 ¹⁰	29	Crest length	m	713.20
11	Average flow	m ³ /s	1350	30	Number of overflow table holes	hole	—
12	Design standard flood flow ($P = 0.10\%$)	m ³ /s	40,000	31	Unit discharge	m ³ /(s·m)	—
13	Check standard flood flow ($P = 0.01\%$)	m ³ /s	52,300	32	Energy dissipating mode	—	
14	Average annual suspended sediment transport	t	1.6 × 10 ¹⁰	33	Number of bottom outlets/spillway tunnels	hole	24/2
15	Average bed load annual sediment transport	t	—	34	Single hole discharge	m ³ /s	1410
16	Checking flood level	m	340.00	35	Checking flood discharge	m ³ /s	15,346
17	Design flood level	m	335.00	36	Design flood discharge (335 m elevation)	m ³ /s	14,420
18 ¹	Normal water storage level/ice protection level	m	318.00/326.00	37	Casting volume of dam concrete	m ³	1.871,65 × 10 ⁷
19 ²	Aggregate storage capacity (335 m elevation)	m ³	5.89 × 10 ⁹	38	Earthwork volume of dam filling	m ³	2.1262 × 10 ⁶

Note: ¹No. 18 is the recent non-flood season water level; ²Nos. 19 and 20 are the current inventory data.

of the overflow dam and the cross-sectional view of the bottom outlet are shown in Fig. 2.

The power plant house is a downstream-surface type with a length of 223.88 m and a width of 26.20 m. Two outdoor switch stations of 110 and 220 kV, are arranged downstream on the right bank of the dam.

2 Exploration and design, engineering construction, and science and technology research

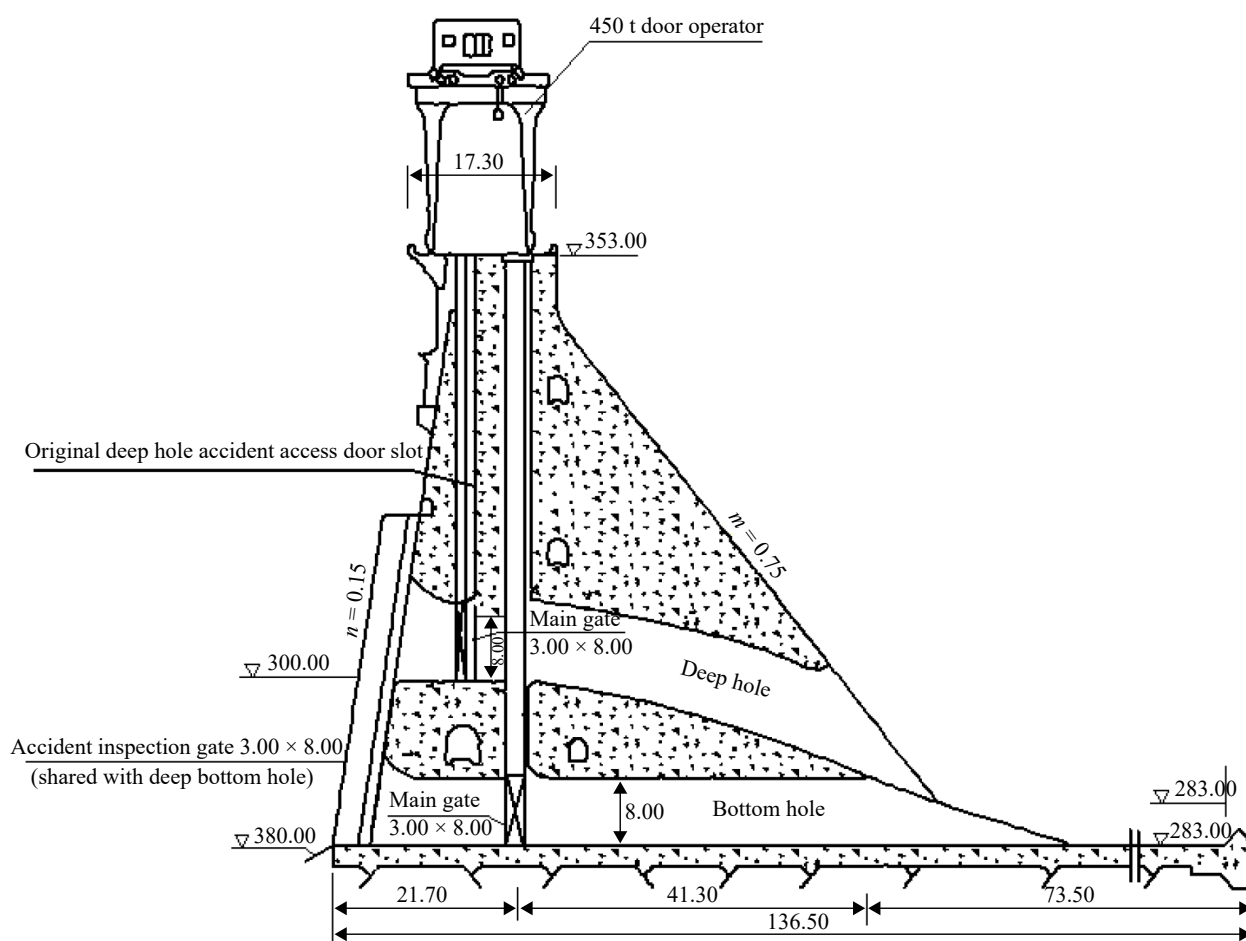
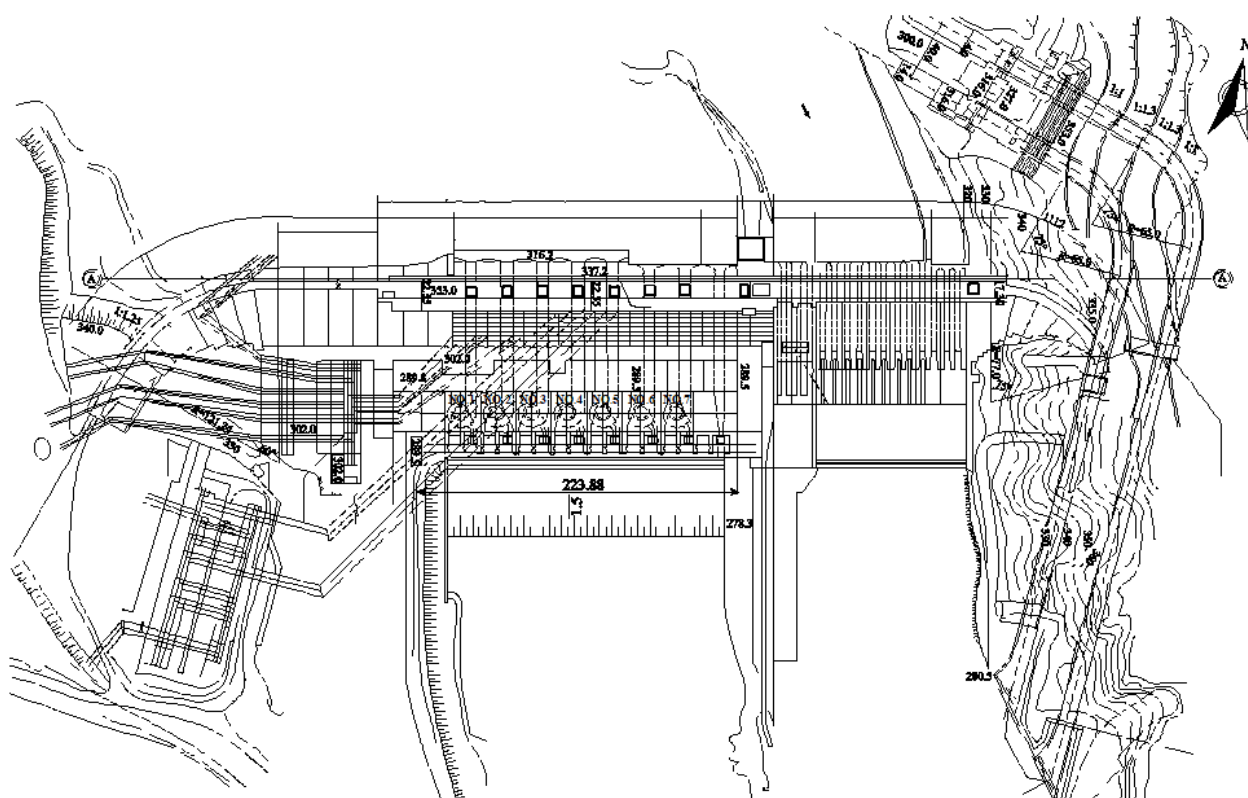
2.1 Exploration and design

Chairman Zedong Mao visited the Yellow River in October 1952 and instructed “to do well with the Yellow River”. In October 1954, *Technical and Economic Report of the Comprehensive Utilization Planning of the Yellow River* was compiled by the Yellow River Planning Commission, and Sanmenxia hydro-junction was selected as the first key national project. In July 1955, the second meeting of the First National People’s

Congress considered and adopted *Resolution on the Comprehensive Planning for the Root Control of the Yellow River Water Disasters and the Development of the Yellow River Water Conservancy*. In December 1955, the executive meeting of the State Council decided to establish the Sanmenxia Engineering Bureau of the Yellow River to undertake the construction task of the Sanmenxia hydro-junction.

The bedrock of the Sanmenxia dam is mainly diorite porphyrite. There are 48 structural fracture zones and 3 faults in the dam site area, and the products in the zone are mainly structural massive rocks. The diorite porphyrite in the foundation could be regarded as an impermeable layer, only a small amount of groundwater was contained along the upper (surface) fissures, the fissure seepage, and the Yellow River waterflow had no erosion. The dam foundation was grouted. The basic seismic intensity of the dam area is VIII, and the design intensity of the dam is IX.

The main sections of dam safety monitoring are No. 2 dam section of installation dam and No. 5 dam section



of overflow dam. The stress, strain, temperature, cracking of concrete, and bedrock, as well as the stress and temperature of steel bars and steel plates were monitored. The dam deformation monitoring adopted the methods of collimation method and geometric level measurement, dam foundation uplift pressure, and manual observation.

The seepage of the dam body is discharged through drainage ditches, drainage pipes, and shafts, and the seepage of the dam foundation is discharged through longitudinal deep drainage holes and auxiliary shallow drainage holes. Most of the seepage is collected into the water collecting wells at the elevation of 262.00 m in the dam section of the power station, and then pumped to the outside of the dam. A small part of the seepage flows through the embedded cast iron pipe to the outside of the dam. The seepage from the power house is also pumped to the outside of the dam.

The hydraulic model test of each building in the Sanmenxia water control project during the operation period was completed by the All-Soviet B. E. Vydenhuangev Research Institute to determine the overall layout of the project, the structural form of the overflow dam, and the cross-section of the tail water area of the hydropower station.

2.2 Construction management

The Sanmenxia hydro-junction project was carried out according to the project management mode under the planned economic conditions at that time. The project quality inspection was carried out under the first-level three-inspection system, and the first-level technical safety quality inspection office of the Sanmenxia Engineering Bureau of the Yellow River was responsible for the comprehensive quality inspection of the construction. The three-inspection system consisted of construction team leader self-inspection, construction technician review, and quality inspection station final inspection. Engineering construction and quality inspection and acceptance were based on *the Yellow River Sanmenxia Water Control Project Construction Code* and its supplementary provisions.

2.3 Dam construction

Sanmenxia hydro-junction officially commenced on April 13, 1957 (Fig. 3), the river was cut off in October 1958 (Fig. 4), the water storage was realized in September 1960, and the main dam project was basically completed in April 1961. The actual dam crest elevation was 353.00 m at that time.

2.3.1 Treatment of dam foundation

The excavation depth of fault and fracture zone was not less than its width, and the width was expanded by 0.5 m each side or until the good structure was excavated as massive rock. Before pouring concrete, it



Fig. 3 Commencement ceremony of Sanmenxia hydro-junction (provided by Sinohydro Bureau 11 Co., Ltd.).



Fig. 4 River cutoff for foundation pit (provided by Sinohydro Bureau 11 Co., Ltd.).

was necessary to remove weathered broken rock and wipe the bedrock surface with a clean white cloth after rinsing to check for compliance with cleaning requirements.

2.3.2 Diversion and cutoff

Open channel diversion was adopted. First, the open channel is excavated on the left bank. The channel bottom was at the elevation of the bottom holes and aprons of overflow dam section. When the water level in the river was at the bottom hole, the main stream of the Yellow River on the right bank was blocked.

2.3.3 Dam block and pouring

The dam body was poured by the block method of column, with a total of 163 pouring columns. Temperature joints and construction joints were set between the columns, and the free deformation of the column was permissible. When the concrete temperature reaches 15 °C, the longitudinal joint grouting was performed.

2.3.4 Dam cooling and heat dissipation

For small volume concrete, ice chips were added to cool the mixing water in summer, or heat dissipation was carried out by cooling wells (wide joints). For mass

concrete, metal serpentine pipes were embedded and cooled with cooling water circulation.

2.3.5 Anti-seepage treatment

Considering that the installation site and the non-overflow dam section on the right bank were relatively less affected by the water head upstream, the sediment deposition after reservoir impoundment would form a natural cover in front of the power station dam and the overflow dam, so the impervious curtain in front of the dam was not made. In order to reduce the uplift pressure of the dam foundation and improve the bearing capacity of the foundation rock in the fracture zone, shallow hole contact grouting was carried out near the upstream of the dam body, and deep hole grouting and consolidation grouting are carried out in the local fracture zone of the foundation.

In July 1960, the state organization's acceptance report of the Sanmenxia Hydro-junction Flood Control Acceptance Committee stated that "the engineering quality is good".

2.4 Engineering renovation

After the impoundment in 1960, sediment deposition in the reservoir area was serious. From 1965 to 1968, the first reconstruction of the junction (also known as the additional project) was carried out. Two flood discharge tunnels and four pressure steel pipes were added in the dam for flood discharge. The second reconstruction (also known as the reconstruction project) was carried out from 1969 to 1978. The diversion bottom holes Nos. 1–8 were opened as the permanent sediment discharge bottom holes, and five generators with 50 MW unit capacity were installed. From 1984 to 2003, the second phase reconstruction of the flood discharge project was carried out. Nos. 9 and 10 bottom holes were opened in 1989 and 1990. From 1998 to 2001, Nos. 11 and 12 bottom holes were opened, and energy dissipaters were added at Nos. 1, 2, and 3 outlets. After reconstruction, the discharge capacity of 315 m water level hub is 9701 m³/s (excluding generating unit discharge). As such, the reservoir basically reaches annual scouring and silting balance.

In order to further utilize water resources, the 75 MW No. 6 unit was installed from April 1991 to April 1994, and the 75 MW No. 7 unit was installed from May 1995 to March 1997. In order to solve the problems of aging of mechanical and electrical equipment, abrasion of overcurrent components, and blade cracks, the No. 1 unit was transformed from 50 to 60 MW from November 1999 to December 2000, and the Nos. 2–5 units were transformed from 50 to 60 MW from 2012 to October 2017. In order to solve the aging problem of lifting equipment, two 350 t gate machines were updated to 450 t from September 2007 to June 2011. The dam safety monitoring system was reformed for the first time from 1991 to 1994, and the automatic monitoring system was built.

2.5 Engineering features and technological innovation

Sanmenxia hydro-junction, in hydrological analysis and calculation, geological exploration survey, dam construction technology, mechanized construction, hydropower station construction, and other aspects, pioneered the use of modern science and technology in China to build large hydro junctions. After two reconstructions and three changes in reservoir operation mode, the balance of sediment erosion and out of the reservoir during the year and maintaining long-term effective storage capacity of the reservoir were explored successfully. Through the practice of hub engineering construction and management, achievements had been made in the governance and development of sediment-laden rivers, promoting the development of sediment mechanism research and local economics.

The main technological innovations of the Sanmenxia project are:

(1) Introduction, research, and development of water conservancy project construction technology and complete sets of equipment in China.

The Sanmenxia project is the first batch of mechanized construction water conservancy projects in new China. A large number of foreign complete sets of equipment were introduced and used for the first time in China. In 1957, dam cement with low heating, good durability, and frost resistance was successfully developed and applied. The application of fly ash in dam concrete was the first large-scale application in domestic hydraulic construction. This method improved the workability of concrete and reduced the early temperature rise of concrete, which was the first application in domestic and foreign water conservancy and hydropower projects. In the experiment of April 1959, the cold asphalt horseshoe grease was successfully obtained, which could be stored, used, and fetched, and could also be mechanized construction by spraying machine, which improved the working efficiency. In the reconstruction process, the Sanmenxia was the early project that applied new technologies, such as glass blasting of guide shaft, expanding excavation shaft, steel formwork trolley, and anchor mortar fixed template, which improved the construction efficiency and quality. At the end of 1984, the special deepwater cofferdam was successfully deposited, which overcame the key technical issue of bottom hole reconstruction without affecting the normal operation of the station. In 1985, the project "Special Deepwater Cofferdam of Sanmenxia hydro-junction" won the first prize of national science and technology progress of China. The introduction and development of a series of technologies and complete sets of equipment in engineering construction promoted the progress of water conservancy technology in China.

(2) Scientific and technological solutions to sediment problems.

The practice of the Sanmenxia project shows that the sediment problem should be considered first in the construction of water conservancy projects on sediment-laden rivers. Whether the sediment problem is properly handled will detect the success or failure of the project. Sediment problems include reservoir sediment, hydraulic structure sediment, and hydropower station sediment. The reservoir sediment problem was solved by keeping enough discharge scale and adopting the method of “storing clear water and discharging muddy water and regulating water and sediment” in Sanmenxia. The sediment erosion problem of hydraulic construction was solved by applying suitable anti-erosion material and selecting suitable body type. The sediment problem of hydropower station was solved by adopting reservoir optimal operation and applying suitable anti-erosion material of hydraulic turbine. In particular, “storing clear water, and removing muddy water” makes full use of the reservoir’s water-saturated nature of low flow and low sediment content in non-flood seasons, but more floods, high flow, and high sediment content, and sediment concentrated in flood seasons. The differential utilization of incoming water in different periods and different characteristics is a scientific method for the comprehensive utilization of reservoirs in sediment-laden rivers. It has explored the successful way of the balance of sediment erosion and out of the reservoir during the year and maintaining long-term effective storage capacity of the reservoir. The Sanmenxia project made breakthrough achievements in sediment treatment, which provided rich experience and theoretical basis for reservoir construction on sediment-laden rivers, and is a great reference and promotion value.

(3) Succeeded in the flood season “muddy water power generation”.

Due to the erosion and wear of the flow components of turbine caused by sediment, it used to be an unfavorable condition for power generation in flood seasons on sediment-laden rivers. In order to make effective use of water resources in the flood seasons and solve the contradiction between water and sediment, the power generation test of the Sanmenxia project was carried out in flood seasons from 1989 to 1994. The application mode of “flood sediment discharge and plain water power generation” was put forward, which solved the contradiction between sediment discharge and power generation and broke through the unfavorable condition of power generation in flood seasons on sediment-laden rivers. In 1995, the test task won the first prize for scientific and technological progress of the Ministry of Water Resources of China. This test provided valuable experience for the construction, management, and operation of hydropower stations on sediment-laden rivers. In addition, in the transformation of Nos. 1–5 units, the introduction of German global units, spraying

tungsten carbide, and other advanced technology, achieved good results.

(4) Successful development of integrated decontamination technology and equipment for hydropower stations.

Due to the low water level operation of the Sanmenxia reservoir in flood season, reeds, weeds, crop straws, and other pollutants accumulated upfront of the dam during flood season, resulting in congestion of trash racks and threatening the safe operation of generators. Since 1980s, the pollution control of Sanmenxia hub has been explored, and the source, composition, and spatial-temporal distribution of pollution have been studied. The measures of grabbing grass, pushing grass by boat, discharging sewage through outlet, building trestle to change the transportation of pollution, and reforming the structure of trash rack have been taken. The integrated pollution cleaning technology and complete set of equipment of “blocking, discharging, grasping, pushing, and fishing” have been developed, which greatly improves the efficiency and safety of pollution cleaning, and plays a great role in cooperating with the power generation work in the flood seasons.

3 Condition at operation

3.1 Operation of reservoir

The operation modes of the Sanmenxia reservoir experienced three stages, namely, “water storage and sediment retention” (September 1960–March 1962), “flood retention and sediment discharge” (March 1962–October 1973), and “emotional storage and muddy discharge” (from October 1973 to the present). The highest water level in front of the dam reached 332.58 m (February 9, 1961) during the operation of “water storage and sediment detention”, and the return water exceeded Tongguan City, resulting in serious sedimentation in the reservoir. The water elevation monitored at Tongguan was 4.30 m higher in March 1962 than that in March 1960. After the Sanmenxia reservoir was replaced by “flood detention and sediment discharge”, the reservoir was emptied as far as possible before flood seasons come, and the flood level was controlled at 335.00 m in the flood seasons, the sedimentation in the reservoir slowed down. However, due to the insufficient discharge scale, when a large flood occurs, the reservoir is still dominated by backwater and sediment discharge, resulting in sedimentation. Therefore, during this period, the Sanmenxia project has been reconstructed twice. At the end of 1973, the Sanmenxia reservoir began to use the control of “storing clear water and discharging muddy water”, that is, in the non-flood season with less sand, water storage and ice prevention, spring irrigation, and power generation take place (ice prevention at water

level of 326.00 m, spring irrigation at water level of 324.00 m). In the flood season, the water level is reduced to prevent flood and sediment discharge, and the reservoir sedimentation is mitigated obviously. The prototype test of Sanmenxia reservoir was carried out after the flood season in 2002. The control water level was 318.00 m in the non-flood season, and the reservoir was exposed in the flood season. During this period, the reservoir was used to discharge sediment in the flood season based on “storing clear and discharging muddy water”. In the flood season, the reservoir was used to discharge sediment instead of the previous control of a certain water level, and the sediment discharge capacity of the reservoir was fully developed.

3.2 Dam operation condition

The special construction history of the Sanmenxia dam yielded in the high dam design and low water level application in the reservoir. At present, the main dam monitoring includes dam deformation and dam foundation uplift pressures. The observation data show that the dam runs normally.

3.3 Problems and reinforcement of dam

The main existing problems of the Sanmenxia project are erosion and damage of high sediment flow to drainage structures, concrete carbonization of dam and ancillary buildings, aging of mechanical and electrical equipment, etc. In order to ensure the safe operation of the project, the reinforcement treatments were carried out.

In view of the erosion and damage of the lower sidewall, bottom plate, and metal structure of the overflow building caused by high sediment flow, maintenance and reinforcement are carried out every year. In view of the hollowing out of the left and right bank revetments at the downstream of the dam, the right bank revetment was reinforced in 1996 and 2008, and the left bank revetment was reinforced in 1999 and 2017. The foundation of Zhanggong Island was reinforced in 1984, 1986, and 2005 due to foundation brushing. For the collapse of the rock mass at the exit of the No. 2 tunnel and the bank slope of the left bank, from May 1994 to May 1996, the method of stepped concrete slope protection and piling was used to reinforce the collapse.

3.4 Engineering benefits

3.4.1 Flood control and ice prevention

The joint operation of Sanmenxia, Xiaolangdi, Guxian, and Luhun reservoirs on the Yellow River can prevent the flood in the millennium, reduce or eliminate the flood threat in the lower reaches, and ensure the safety of the levees in the lower reaches of the Yellow River. The threat of ice flood in the lower reaches of the Yellow River can be reduced or eliminated by storing water

before and during the ice period, controlling discharge and river water.

3.4.2 Irrigation

The Sanmenxia reservoir uses the Ling flood season and the Tao flood season to store water every year, maintaining a water storage capacity of $1.4 \times 10^9 \text{ m}^3$ for the downstream spring irrigation, and providing convenience for the upstream use of the reservoir water storage to divert the Yellow River for irrigation.

3.4.3 Power generation

The cumulative output value of the Sanmenxia project has exceeded the national investment in the power station. Its power generation undertakes part of the peak load capacity in the power grid, reduces the coal consumption of thermal power, and achieves remarkable economic benefits.

3.4.4 Water supply

The ice prevention and spring irrigation of Sanmenxia reservoir provide water to cities along the Yellow River, such as Zhengzhou City and Jinan City, as well as regions like Shengli oilfield and Zhongyuan oilfield. It is a reliable source of water for the downstream regions along the Yellow River, which has played a significant role in changing the appearance of the communities along the Yellow River and achieved remarkable social benefits.

3.4.5 Reducing silt

After the use of “storing clear and discharging muddy” water and sediment regulation, the sediment transport capacity of the lower reaches of the Yellow River is improved, the proportion of sediment discharge into the sea is increased, and the sediment deposition in the lower reaches of the Yellow River is effectively reduced.

3.4.6 Improving the ecological environment

The Sanmenxia reservoir area formed the largest wetland in Henan Province, where rare animals, such as white swans, live. It improves the environment of the reservoir and promotes the development of the local economy in Sanmenxia City.

3.4.7 Promoting the construction and development of Sanmenxia City

Sanmenxia City is an emerging city built with the construction of Sanmenxia water control project. The project has made outstanding contributions to the local water supply, improving the ecological environment, developing tourism, and promoting economic development.

3.5 Influence of Sanmenxia project in dam construction

Sanmenxia water control project is one of the backbone

projects of the main stream of the Yellow River determined by the *Outline of the Yellow River Management and Development Plan*, and is an important part of the “upper block and lower row” system of the flood control project in the middle and lower reaches of the Yellow River. The Sanmenxia project is an explorer of Yellow River management and development in new China, which is known as “the first dam of Yellow River” and has a unique position in the dam industry.

A series of scientific research aiming at the problems of the Sanmenxia project provided a good educational and experimental base of sediment-laden rivers. It accumulates positive and negative experience for the treatment and development of sediment-laden rivers. It gave people great enlightenment in the aspects of river control thought, Yellow River control planning, sediment science, engineering construction, and engineering management, and is a milestone in the history of water conservancy in China.

4 Engineering pictures (Figs. 5–9)



Fig. 5 Sediment removal in foundation pit (provided by Sinohydro Bureau 11 Co., Ltd.).



Fig. 6 Rock excavation for dam foundation (provided by Sinohydro Bureau 11 Co., Ltd.).

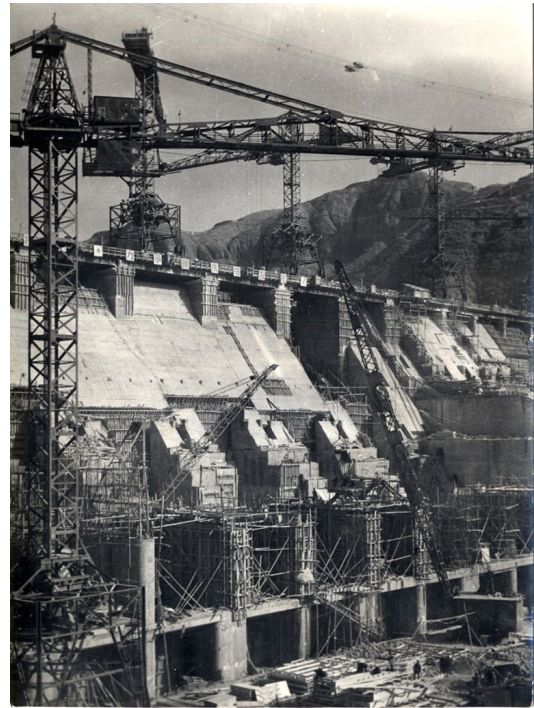


Fig. 7 Concrete casting of the Sanmenxia dam (provided by Sinohydro Bureau 11 Co., Ltd.).



Fig. 8 Bird's eye view of Sanmenxia hydro-junction.



Fig. 9 Discharge view of Sanmenxia hydro-junction.