Chapter

Hydropower Development in China: A Leapfrog Development Secured by Technological Progress of Dam Construction

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Abstract

It has been over 110 years since China's first hydropower station, Shilongba Hydropower Station, was built in 1910. With the support of advanced dam construction technology, the Chinese installed capacity keeps rising rapid growth, hitting around 356 GW nationwide by the end of 2019, and the annual electricity production exceeds 10,000 TWh. At present, China contributes to 25% of global installed hydropower capacity, ranking first in the world for 20 consecutive years since 2001 and surpassing the combined of the 4 countries ranking second to fifth. This paper reviews China's progress in the context of global hydropower development and examines the role of technological advance in supporting China's hydropower projects, especially dam construction technology. China is currently actively promoting the "integration of wind, solar, hydro, and coal power generation and energy storage" and building a smart grid of multi-energy complementary power generation. New technologies and new concepts are expected to continue to lead the world's hydropower development trends.

Keywords: China, hydropower, super hydropower project, installed hydropower capacity, dam construction technology, high dam and large reservoir

1. Introduction

Hydropower is a clean and renewable energy source among conventional energy sources and has the advantages of low operating cost, simple electromechanical equipment, and operational flexibility [1–5]. Hydropower development has thus emerged as a priority option in most developed countries [6–8]. The utilization rate of hydropower resources in developed countries such as France and Switzerland already hit 97% in the late 1980s. In developing countries, the process of water resource development was slow in the past with a low degree of hydropower development due to political, economic, and other reasons. There has been an evidently rapid increase in the pace and rate of hydropower development and utilization in the recent four decades, especially since the mid-1980s. By the end of 2020, the total installed hydropower capacity in the world has reached 1330 GW, and the installed hydropower capacity in 2020 will increase by 1.6%. The global hydropower generation accounts for 16% of the total global power generation, which is lower than coal-fired power generation and gas-fired power generation, ranking third in the world. Among them, East Asia and the Pacific have the most hydropower generation, accounting for 37.6% of the global total. Major contributors to the added installed capacity are China, Laos, Pakistan in Asia, Brazil in South America, Angola, Uganda, and Ethiopia in Africa, and Turkey in Europe.

Dam is the principal structure for hydropower generation, so the number of dams speaks for the activity level of hydropower development in a country. A large dam is defined by the International Commission on Large Dams (ICOLD) as any dam above 15 m in height (measured from the lowest point of foundation to top of dam) or any dam between 10 m and 15 m in height impounding more than 3 million m^3. According to this definition, there were 58,713 large dams worldwide in 2020. China embraces 23,841 large dams, the most among all countries and more than the combined of the following United States (9263), India (4407), and Japan (3130) [9]. It ranks the world's first with a share of more than 40%. In fact, in addition to storing water for power generation, dams can alter natural runoff through reservoir regulation to render functions such as water supply from upstream reservoirs, downstream navigation, and river ecological flow maintenance. This helps alleviate the plague associated with flood, drought, electricity shortage, and water environmental degradation. In particular, hydropower development avoids greenhouse gas (GHG) emissions of thermal power generation. In view of this, the United States has incorporated hydropower in many targets of the 17 Sustainable Development Goals (SDGs) published in September 2015 [10]. More than 100 countries have so far made it clear that they will continue to build dams and vigorous develop hydropower. It is estimated that by 2035, global installed hydropower capacity will add by about 480 GW to reach 1750 GW, with annual electricity generation of 6100 TWh and hydropower exploitation rate of 38.6%; and by 2050, global installed hydropower capacity will further grow by 300 GW to reach 2050 GW.

China has set an example for global hydropower development. At the end of 2019, China's installed hydropower capacity hit 356 GW with an electricity output of 1300 TWh, accounting for 27.2% and 30.8% of the global total, respectively (**Table 1**). Such a scale is more than three times that of the United States, and larger than the combined of countries ranking second to fifth. China has grown into a veritable hydroelectricity powerhouse based on many super large dams and reservoirs. Next, China's course and

Year	China's hydropower generation TWh	China		World	
		Electricity generation/TWh	%	Hydropower production/TWh	%
2020	1322	7779.1	17.0	4296.8	30.8
2019	1269.7	7503.4	16.8	4222.2	30.1
2018	1202.4	7111.8	16.9	4193.1	28.7
2017	1155.8	6495.1	17.8	4059.9	28.5
2016	1051.8	5911.1	17.8	4138.4	25.4
2015	1180.7	5810.5	20.3	4032.1	29.3
2014	1111.7	5649.6	19.7	3970.5	28.0
2013	920.3	5397.6	17.1	3847.0	23.9
2012	855.6	4986.5	17.2	3765.3	22.7
2011	668.1	4730.6	14.1	3407.2	19.6

Table 1.
Share of hydropower in China's electricity generation and global hydropower generation.

achievements in hydropower development will be reviewed, and potential challenges to China's sustainable hydropower development will be analyzed [11].

2. China's course of hydropower development

It has been completely 110 years since China's first hydropower station, Shilongba Hydropower Station, was constructed in 1910 [12–16]. At of the end of 2019, there were 46,758 hydropower stations nationwide, with a total installed capacity of 332.89 GW. Among them, 22,190 above the designated size provide 327.3 GW and 24,568 below the designated size provide 5.59 GW. Besides, 11 of the world's top 20 hydropower stations are located in China (**Table 2**), and all the super hydropower stations built after 1990 come from China without exception.

World ranking	Name	Country	Installed capacity	Annual production	Date of start of operation	River
			10 MW	100 GWH		
1	Three Gorges Dam	China	2250	847	2003	Yangtze River
2	Itaipu	Brazil/ Paraguay	1400	900	1983	Parana River
3	Xiluodu	China	1386	571	2014	Jinsha River
4	Baihetan	China	1250	640	2018	Jinsha River
5	Wudongde	China	1020	387	2020	Jinsha River
6	Guri	Venezuela	910	510	1968	Rio Caroni
7	Tucurui	Brazil	837	324	1984	Tocantins River
8	Xiangjiaba	China	775	307	2012	Jinsha River
9	La GrandeII	Canada	732	358	1979	La Grande
10	Grand Coulee	America	649	203	1942	Columbia River
11	Sayano-Shushenskaya	Russia	640	235	1978	Yenisei
12	Longtan Dam	China	630	187	2007	Hongshui River
13	Krasnoyarsk	Russia	600	204	1967	Yenisei
14	Nuozhadu	China	585	239	2012	Lancang River
15	Churchill Falls	Canada	542	345	1972	Churchill River
16	Jinping-II	China	480	242	1967	Yalong River
17	Bratsk	Russia	450	226	1967	Angara River
18	Xiaowan Dam	China	420	185	2009	Lancang River
19	Laxiwa	China	420	102	2009	Yellow River
20	Ertan Dam	China	330	170	1998	Yalong River

Table 2.
World's top 20 hydropower stations.

Those Chinese hydropower stations are at the forefront of the world in terms of technology, representing important milestones in China and even the World's hydropower development. **Figure 1** shows the time points of project construction for China's super hydropower stations and their locations in China are as shown in **Figure 2**.

Shilongba Hydropower Station, the first hydropower station in China, was constructed in 1910 and commissioned in 1912. Its installed capacity was 480 kW upon completion and rose to 360 MW in 1949 when New China was founded. Sanmenxia Hydropower Station, the first large-scale hydropower station built in New China, started construction in April 1957 and operation in April 1961, with an installed capacity of 1160 MW. The multi-year average annual output stands at 6 TWh. It contains a concrete gravity dam with a maximum height of 106 m.

Xin'anjiang Hydropower Station was built at the same time as Sanmenxia Hydropower Station and officially put into operation 1 year earlier. This concrete gravity dam, 105 m tall with a crest length of 466.5 m, enables an installed capacity of 662.5 MW, based on 40,000 tons of metal structures and electromechanical equipment, after 5.8592 million m^3 of earth was moved and 1.755 million m^3 of

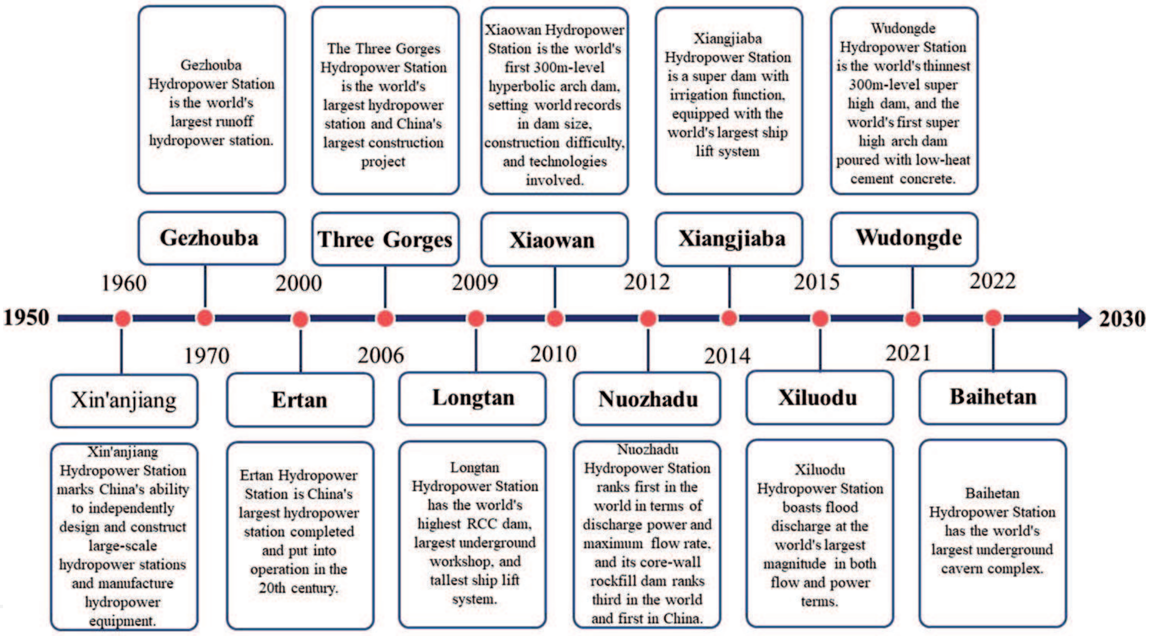

Figure 1.
Time points of project construction for China's super hydropower stations.

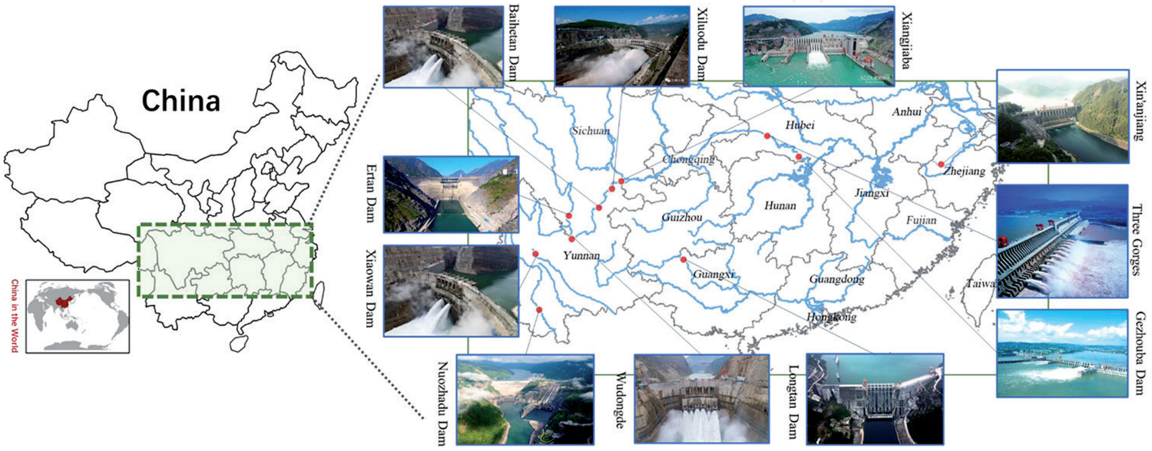

Figure 2.
Location map of China's super hydropower projects stations.

concrete poured. Xin'anjiang is a milestone in China's hydropower development that marks China has become able to independently design and construct large-scale hydropower stations and manufacture hydropower equipment.

Gezhouba Hydropower Station is the world's largest runoff hydropower station. The construction of the Gezhouba Water Control Project spanned from December 1970 to late 1988, with Phase I completed in 1981 and Phase II starting in 1982. The project consists of ship locks, power stations, spillway sluices, scouring sluices, and auxiliary dams. The dam is a gate dam with a maximum height of 47 m. Two riverbed power stations are located in Erjiang and Dajiang. The former has an installed capacity of 965 MW sourced from two sets of 170 MW generating units and five sets of 125 MW generating units. The latter is equipped with 14 sets of 125-MW hydropower generator units to form an installed capacity of 1750 MW. They make Gezhouba's installed capacity total 2715 MW. The 170 MW generating units of the Erjiang Power Station have a turbine diameter of 11.3 m and a stator outer diameter of 17.6 m.

Ertan Hydropower Station is China's largest power station built and commissioned in the twentieth century. The construction began in September 1991 and ended in 2000, and the first generating unit started operation in July 1998. Ertan Hydropower Station is located at the junction of Yanbian and Miyi counties, Panzhihua City, southwest border of Sichuan Province, China. Ertan Dam, with a maximum height of 240 m, sits on the lower Yalong River, 33 km away from the intersection of the Yalong River and the Jinsha River and 46 km from Panzhihua City. Ertan is the first of cascade hydropower stations developed in the Yalong River Hydropower Base, with Guandi in the upstream and Tongzilin in the downstream. Given a normal pool level of 1200 m above sea level, the reservoir impounds 5.8 km^3 of water, including a regulated storage capacity of 3.37 km^3. The installed capacity totals 3.3 GW with a guaranteed output of 1 GW, and the annual electricity production averages 17 TWh. The project involving 28.6 billion yuan in investment renders comprehensive benefits in addition to power generation.

The Three Gorges Hydropower Station is the world's largest hydropower station and China's largest construction project. It secures an installed capacity of 22.4 GW with an average annual output of 90 TWh by installing 32 sets of 700-MW generating units. The construction started in 1994 and was officially finished in 2006 [17]. The concrete gravity dam, the world's largest of its kind, is 2335 m long, 115 m wide at the bottom and 40 m wide at the top, and 185 m above sea level, with normal storage level of 175 m. It can withstand floods so severe they come only once in 10,000 years owning to the designed maximum outflow of 100,000 m^3 per second. The whole project moved about 134 million m^3 of earth and stone and used about 28 million m^3 of concrete and 593,000 tons of steel. The reservoir is over 600 km in length and 1.1 km in width on average, making a surface area of 1084 km^2. It impounds 39.3 billion m^3 of water, including 22.15 billion m^3 for flood control in a seasonal manner. Totally, 32 sets of 700-MW generating units are deployed on the back of the dam, with 14 sets on the left bank, 12 sets on the right bank, and 6 sets underground, and in addition two sets of 50-kW power supply units form an installed capacity of 22.5 GW, ranking second in the world and far exceeding that of Brazil's Itaipu Hydropower Station. By 24 o'clock, December 31, 2014, the Three Gorges Hydropower Station generated 98.8 TWh of electricity throughout the year, a new world record that secures its first position in terms of annual output. This is equivalent to a reduction of nearly 100 million tons of carbon dioxide (CO_2) emissions from over 49 million tons of raw coal consumption.

Longtan Hydropower Station started construction on July 1, 2001 and was completed and commissioned at the end of 2009. With a designed storage level of 400 m, the 216.5 m high and 836 m long dam has a storage capacity of 27.3 billion m^3, an installed capacity of 6.3 GW, and an annual output of 18.7 TWh. This dam sets three new world records: the highest roller-compacted concrete (RCC) dam (with a maximum height of 216.5 m, a crest length of 832 m, and a concrete volume of 7.36 million m^3); the largest underground workshop (385 m long, 28.5 m wide, and 74.4 m high); and the tallest ship lift system (with a full length of over 1800 m and a maximum lifting height of 156 m by two steps).

Xiaowan Hydropower Station is built primarily for power generation but also performs functions in flood control, irrigation, and water transportation. With a maximum height of 294.5 m, the world's tallest arch dam also ranks first in key indicators of arch dam construction such as peak ground acceleration, crest length, and water thrust. Construction started on January 1, 2002. River closure was achieved on October 25, 2004, a year ahead of schedule, and concrete pouring for the first dam warehouse began on December 12, 2005. The diversion tunnel was closed for water storage on December 16, 2008. Pouring and capping across the board was completed on March 8, 2010, marking the birth of the world's tallest 300-m-level hyperbolic arch dam. All the six generating units with a combined capacity of 4.2 GW were commissioned on August 22, 2010. Xiaowan Reservoir, the first reservoir of cascade power stations, impounds about 15 billion m^3 of water, including nearly 10 billion m^3 for multi-year regulation. The power station is equipped with six mixed-flow generators with a unit capacity of 700 MW and thus forms a total installed capacity of 4200 MW with a guaranteed output of 1854 MW. The average annual electricity production reaches 19.06 TWh.

Xiangjiaba Hydropower Station is a super dam with irrigation function, equipped with the world's largest ship lift system. It is only 1500 m away from Shuifu City, located on the lower Jinsha River at the junction of Shuifu City, Yunnan Province and Xuzhou District, Yibin City, Sichuan Province. The construction was formally kicked off in November 2006, and the station was fully put into operation in July 2014. The installed capacity reaches 7.75 GW with an average annual output of 30.7 TWh, including eight sets of 800-MW rectangular turbines and three sets of 450-MW large turbines.

The core-wall rockfill dam of Nuozhadu Hydropower Station is a classic case of China's successful application of gravelly clay core wall to effectively improve the strength of earth-rock dams. It is of great significance as the first successful case. The construction started in January 2006 and ended after final acceptance in May 2016, with the first generating units put into operation in August 2012. The normal storage level of the reservoir is 812 m and the maximum height of the dam is 261.5 m, ranking third in the world and first in China among similar dams. The open spillway is 1445 m long and 151.5 m wide, the largest in Asia. Flood discharge can reach a magnitude of 55.86 GW with a maximum flow rate of 52 m per second, ranking first in the world in both terms. The stratified water intake scheme adopted by Nuozhadu Hydropower Station created a precedent for environmentally friendly design of hydropower generation in China. The project involving an investment of about 61.1 billion yuan realizes an average annual electricity production of 23.912 TWh based on 4088 utilization hours, which is equivalent to saving 9.56 million tons of coal equivalent and reducing CO_2 emissions by 18.77 million tons each year.

Construction of Wudongde Hydropower Station was kicked off in 2015. Concrete was poured for dam construction in 2017. The first generating units were commissioned in June 2020, and all the generating units were officially put into operation in June 2021. A concrete hyperbolic arch dam with a crest elevation of 988 m, a maximum height of 270 m, and a base thickness of 51 m is used as the water-retaining structure. The thickness to height ratio of only 0.19 makes it the world's thinnest 300-m-level super high dam. Wudongde Dam is also the world's first super high arch dam poured with low-heat cement concrete. Twelve generating units with a unit capacity of 850 MW have been installed in the power station, making a total of 1.02 GW, the fourth largest in China and the seventh largest in the world.

Xiluodu Hydropower Station focuses on power generation but also contributes to flood control, sand retention, improvement of upstream shipping conditions, and cascade compensation for downstream power stations. It is located on the Jinsha River at the junction of Sichuan and Yunnan. The construction started in June 2004 and fully ended in 2015. A total of 18 sets of 770-MW generating units have been installed, forming an installed capacity of 13.86 GW that supports an average annual output of 57.1 TWh. Flood discharge is a major highlight of Xiluodu Dam, with the flow and power of discharge far exceeding the highest level of arch dams in the world. In European and American countries that have led the world in dam construction, arch dams generally do not have drainage holes out of consideration of stability, such as the famous Hoover Dam. In contrast, a large number of holes are opened in the Xiluodu Dam when the spillway tunnels on both sides of the dam are not enough to discharge all the floods. The Xiluodu Hydropower Station project has the characteristics of narrow river valley, high arch dam, huge volume of discharge, multiple generating units, large cavern complex, and high seismic resistance capacity. It has outperformed existing projects in many key technologies, boasting world's highest level of comprehensive technical difficulty.

Baihetan Hydropower Station is designed primarily for power generation but also plays a role flood control, sand retention, improvement of downstream shipping conditions, and development of navigation in the reservoir area. Equipped with 16 sets of 1-GW Francis turbine generators, Baihetan ranks second in the world in terms of total installed capacity and first in terms of unit installed capacity. The project was officially kicked off in 2013 and is expected to be completed in 2022, with the first group of generating units formally put into operation in July 2021. The underground cavern complex has a total length of 217 km, the largest in the world. For the first time, the power station uses all Chinese-made GW-level turbine generators. This is another historic leap for China's major hydropower equipment after the localization of generating units in the Three Gorges Hydropower Station and 800-MW generating units in Xiangjiaba Hydropower Station.

3. Super technologies underpinning super projects

Taking into account the historical background of hydropower development, China's super hydropower projects are underpinned by its unique super dam construction technologies, as shown in **Figure 3**.

Since the founding of New China in 1949, substantial progress has been made in the construction of gravity dams [18–21], arch dams [21–24], and earth-rock dams [25–27].

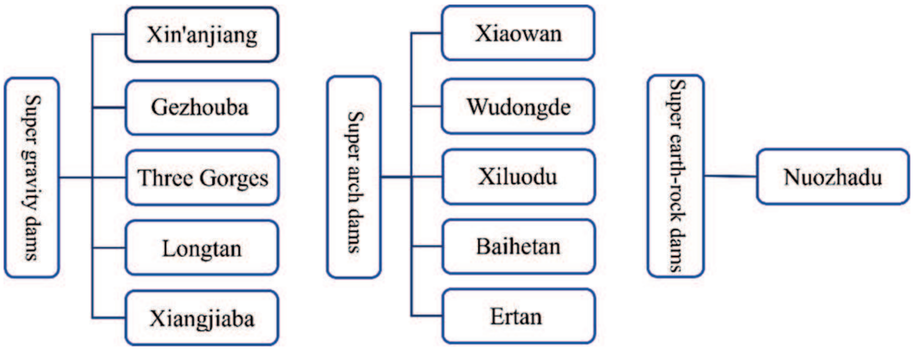

Figure 3.
China's super hydropower stations by world indicators.

Such advancement of dam construction technologies provides the basic guarantee for China's super hydropower projects.

3.1 Super gravity dams

Concrete gravity dams with simple structure and clear stress can integrate various spillway combinations to ensure high reliable resistance to flood hazards [28, 29]. They are well adapted to terrain and geological conditions by arranging flexibly various types of power plants. In the early 1930s, the 221-m high Hoover Dam was built on the Colorado River in the United States, marking the arrival of a rapid development period of dam construction. In the 1980s, a group of ultra-high gravity dams (higher than 200 m) embodying the dam construction technology of the twentieth century was commissioned to play an important role in river flow regulation, flood control, power generation, irrigation, and water supply. The 285-m high Grand Dixence Dam built in Switzerland in the early 1960s remains to be the world's tallest concrete gravity dam.

In China, the construction of gravity dams in the modern sense began after the founding of New China. In the 1950s, two slotted gravity dams, namely Xin'anjiang and Gutian-I, were constructed to meet the needs of economic and social development. In the 1960s, another two slotted gravity dams, i.e. Yunfeng and Danjiangkou, and two solid gravity dams, i.e. Liujiaxia and Sanmenxia, were added. Hunanzhen trapezoidal gravity dam was completed in the 1970s and Wujiangdu arch gravity dam in the early 1980s. There were over 20 gravity dams taller than 70 m in the country by the 1980s. In this stage, efforts were made to explore ways to reduce dam engineering volume and save project investment, which makes possible the design and construction of many new and lightweight gravity dams.

Dam construction technology, including concrete gravity dams, made notable progress after the 1980s. Following the gravity dam projects in Shuikou, Geheyan, Wuqiangxi, and Yantan, a number of high gravity dam projects such as the Three Gorges Dam, Longtan, Guangzhao, Jinanqiao, and Xiangjiaba were successively launched at the turn of the century, constantly setting records in terms of dam height and project scale. Longtan Dam on the Hongshui River is currently the highest gravity dam in China, with a designed height of 216.5 m and a concrete volume of 7.5 million m^3. In this stage, the height of concrete gravity dams in China grew from 100 m to 150 m and further to 200 m. The number of solid gravity dams also increased due to construction efficiency improvement because such simple structures are more suitable for mechanized construction. A series of new energy dissipation works were commissioned, solving the problem of high-head and large-flow flood discharge and energy dissipation. In addition, RCC gravity dams tend to gradually replace normal concrete gravity dams. China has technologically reached the international advanced level in the construction of high concrete gravity dams and high RCC gravity dams [30, 31]. The most representative examples are undoubtedly the Three Gorges Dam (normal concrete gravity dam) and Longtan Dam (RCC gravity dam).

The Three Gorges Dam is the most concrete incorporated gravity dam in the world. The dam with a height of 181 m and a crest length of 2309.47 m uses 16 million m^3 of concrete among the project total of 28 million m^3. Two famous dams comparable to the Three Gorges Dam are the 168 m high Great Coulee Dam on the Columbia River in the United States (with a concrete volume of 7.26 million m^3) and the 162 m high Guri Dam on the Caroni River in Venezuela (with a concrete volume of 6.71 million m^3). Longtan Dam as RCC gravity dam represents the highest level of RCC dam construction in the world. Built on the Hongshui River, the dam has a designed height of 216.5 m and a concrete volume of 7.5 million m^3. In order to solve the constraints of high temperature and rain and shorten the time of dam construction, China developed the world's most advanced technology of RCC construction under special climates. This technology effectively controls the initial setting time of concrete and realizes the quick coverage by improving concrete production and transportation capacity and silo capacity. It is integrated with unique interlayer treatment technology to enable construction in high temperature and rainy conditions. In addition, the pioneering anti-seepage scheme that combines second-grade RCC and distorted concrete also represents the world's highest level.

3.2 Super arch dams

Arch dams are water-retaining structures curving upstream on the plane, where water thrust is transmitted partially or fully through the arch to the bedrock on both sides of the river valley. The stability of arch dams is largely supported by the reaction of the bedrock of arch side to water pressure, rather than dam weight as in the case of gravity dams. Axial reaction force at the section of arch ring can take advantage of the strength of dam materials. Therefore, arch dams perform well in terms of economy and safety [32–34].

In the 1980s, RCC began to be applied to arch dams. In 1988, the world's first RCC arch dam, Knellpoort, was built in South Africa. In 1993, China completed its RCC gravity arch dam called Puding by using new dam construction technologies. Thereafter, a group of hydropower stations such as Longyangxia, Ertan, Xiaowan, Laxiwa, Jinping-I, and Xiluodu have been gradually put in place. Baihetan Hydropower Station is still under construction, expected to be completed in 2022. Longyangxia Hydropower Station is the first large-scale cascade power station on the upper Yellow River. It consists of barrage dam, waterproof structures, and powerhouse. The dam is 178 m high, 1226 m long (including the 396-m-long main dam), and 23 m wide. The project can not only block all the annual flow of 130,000 m^3 from the upper Yellow River but also forms an reservoir with a surface area of 383 m^2 and a storage capacity of 24.7 billion m^3.

Ertan Hydropower Station is the largest hydropower station built and commissioned in China in the twentieth century. The 240-m high dam, whose construction took 10 years, was the tallest arch dam in Asia at that time. The double-curvature arch dam, China's tallest dam, ranks third among dams of its kind in the world, topping in terms of crest length and flood discharge capacity. Laxiwa Hydropower Station is the largest hydropower station and clean energy base on the Yellow River. The dam is 250 m high, but only 49 m wide at the bottom. It is deemed as a thin dam as the ratio of width to height is 0.196, lower than the national standard 0.2. Nevertheless, it renders the largest installed capacity and electricity production in the Yellow River Basin, in addition to the highest dam. Xiaowan Dam with a maximum height of 294.5 m is the world's highest arch dam under construction. It outperforms in this category worldwide in key indicators such as peak ground acceleration, crest length, and water thrust.

Jinping-I Hydropower Station contains a double-curvature arch dam with a height of 305 m, the tallest of its kind in the world. Wudongde Hydropower Station features a super high arch dam, the world's thinnest at the 300 m level and the world's first poured with low-heat cement concrete throughout the whole dam.

The concrete double-curvature arch dam at Xiluodu Hydropower Station has a maximum height of 278 m, a crest elevation of 610 m, and an arc length of 698.07 m, which enables it to withstand 15 million tons of water thrust. The arch dam of Baihetan Hydropower Station has a crest elevation of 834 m and a maximum height of 289 m. The arch dam of Laxiwa Hydropower Station is 250 m high at the most.

3.3 Super earth-rock dams

Earth-rock dams refer in general to water-retaining structures built by dumping and compacting locally available earth, rock, or mixture. Earth dams are made up mostly of earth and gravel, and rockfill dams are made up mostly of gravel, pebbles, and crushed stones. Earth-rock dams as the oldest type of dams contain both two kinds of materials. Modern technology for earth-rock dams has been developed since the 1950s, which enables the construction of several high dams. Earth-rock dams are now among the most widely used and fastest-growing dam types in the world owning to strong adaptability to complex geological conditions, local availability of materials, and small investment [26, 35].

The United States, Canada, and the former Soviet Union has made rapid progress in earth-rock dams since early twentieth century. A number of 200 m–300 m-level high dams have been built, as Oroville (235 m high) in the United States, Boruca (267 m high) in Costa Rica, and Nurek (300 m high) in the former Soviet Union. China has seen rapid development of high earth-rock dams thought it started construction relatively late. It is now at the forefront of the world in terms of the number and height of high earth-rock dams (200 m level) built and under construction. Examples include Tianshengqiao, Xiaolangdi, and Nuozhadu with designed 300-m-level high dams, Shuangjiangkou (314 m high), Rumei (315 m high), and Lianghekou (295 m high). Earth-rock dam construction technology will make a huge breakthrough.

Tianshengqiao Hydropower Project was officially launched in April 1991, realized water diversion on December 25, 1994, and put into operation the first generator in December 1998. The dam has a maximum height of 178 m, a crest length of 1137 m, and a crest width of 12 m. The reservoir submerged 4539 hectares of arable land and relocated 44,300 people. Xiaolangdi Hydropower Project is huge with construction spanning 11 years. It adopts an inclined core-wall rockfill dam with a designed maximum height of 154 m, a crest length of 1667 m, a crest width of 15 m, and a maximum width of 864 m. Upon completion, it inundates an area of 272.3 km^2 and controls a drainage area of 69.4 km^2. Earth amounting to 518.500 m^3 is used, and 1.2 m thick and 80 m deep, concrete cut wall is built, both setting new records in China.

The earth-rock dam for Nuozhadu Hydropower Station is 261.5 m high, the tallest of its kind in China and the third tallest in the world. It replaces the 160-m high Xiaolangdi Dam to be China's tallest dam by crossing the line of 100 m in height. As the theory, technology, experience, and specifications for dam construction applicable at that time cannot meet the construction requirements, the project systematically proposed, for the first time, a complete set of technologies for super high core-wall rockfill dams, which uses artificial gravel mixed with earth, as well as soft rock for rockfill materials. This encompasses the static and dynamic constitutive model for rockfill materials, the method for measuring hydraulic fracturing and fractures, a complete set of design criteria, and a comprehensive safety evaluation system for super high core-wall rockfill dams. Nuozhadu Hydropower Station has made and applied a number of innovative results with China's independent intellectual property rights, bringing China's rockfill dam construction technology to a new level.

4. Discussion

Hydropower development at the river basin level contributes to green and harmonious development by way of efficient use of hydropower resources.

Multi-objective cascade hydropower development was first proposed in Tennessee river basin development plan in 1933. The model was then successively implemented in the rivers of Cumberland, Missouri, Columbia, Colorado, and Arkansas after Tennessee in the United States. At the same time (1931–1934), the former Soviet Union drew up and put into practice the cascade development plan for the Volga River. In the next 40 years, fast progress was made in cascade development of hydropower. Most developed countries highlighted hydropower in energy strategies and exploited the majority of superior hydropower resources. While developed countries moved toward a steady period of hydropower construction in the 1970s, an upsurge with rapid cascade development took place in some Latin American developing countries in the 1960s. In the 28 years from 1958 to 1986, Brazil carried out a series of cascade development projects on the Paraná River and its tributaries, which encompasses 17 cascade power stations with a total storage capacity of 17.922 billion m^3 and a total installed capacity of 39.58 GW. This raised its world ranking in hydropower to 5th from 12th in 1950 with a scale of 1.54 GW.

The continuous deployment of hydropower projects not only provides a steady stream of power to ease the pressure on power supply but also drives economic development. However, dam construction along with water conservancy and hydropower projects has aroused some controversies. On the one hand, dams make abundant water available for agricultural irrigation that facilitates people's lives. Flood regulation and control by dams is also very important to largely avoid the loss of life and property. But on the other hand, dams slow down water flow, which easily leads to water pollution. The United States has begun to demolish some early built dams, and many problems have arisen during the demolition process, including the impact on the river basin and on the topography and geology. China has about 98,000 reservoirs and dams, the most among all countries. As this number increases, the impact on river ecosystems has drawn growing social attention. Such impact is manifested in two aspects. First, the ecological environment of rivers is fragmented by cascade development. For instance, there are 11 hydropower stations built and under construction in the 1326-km mainstream section of the middle and lower Jinsha River, and 10 large hydropower stations sitting on the mainstream alone of the 1060-km long Dadu River. Impoundment of these reservoirs and dams has changed the natural runoff and sediment transportation process of rivers, and especially water temperature. Fish migration channels have been blocked, affecting the survival and development of aquatic ecosystems to varying degrees. Second, the minimum ecological flow of rivers cannot be guaranteed. Construction of dams and reservoirs on rivers inevitably sparks conflicts between economic water use for water supply and power generation and ecological water use within rivers. If the relationship between household, production, and ecological water use is not handled well, the excessive emphasis on water storage to secure household and production water supply will often compromise the ecological flow of rivers. For example, there are many small and medium hydropower stations early built on small- and medium-sized rivers in southern China. They typically do not contain spillway facilities to discharge ecological flow and thus are unable to ensure sufficient ecological flow during the dry season. Diversion hydropower stations have even more impact on the ecological flow of rivers. Flow of small- and medium-sized rivers is naturally limited except during the flood season and varies widely between high- and low-flow periods. As a result of water diversion for power generation, flow is frequently deprived of the section between the barrage and the power station, bringing obvious damage to river ecosystems.

The concept of circular economy provides a new path for the development of hydropower. The circular economy has the characteristics of saving resources, protecting the environment, and promoting economic development, which coincides with the concept of sustainable development of hydropower. Circular economy mainly affects the power industry in two aspects: one is that circular economy can improve the conversion efficiency of energy and reduce the waste of natural resources; pollution of the surrounding environment caused by electromagnetic fields. As a kind of clean energy, hydropower has relatively little pollution to the natural environment but has a great impact on the ecological environment of the river basin. Hydropower stations should not only consider the benefits of power generation, but also comprehensive benefits such as shipping, flood control, and irrigation. How to improve the current operation mode of hydropower station on the basis of circular economy, so as to achieve the state of nature-society virtuous circle, there is still a lot of research space.

After more than 140 years of development, hydropower has received attention in many countries in the world and has become an irreplaceable and important part of today's clean energy. With the increase of the dam's operating time, its hidden problems have gradually emerged. Due to the different geographical environments and policies of different countries, countries have different ways to deal with the problems arising from the construction of new dams and the operation of old dams. However, there are still some problems that have not yet found a good solution, which has become a common problem faced by hydropower construction in the world. China's hydropower construction is at the world's leading level, and its dam construction technology, management, and operation methods are of great reference value for dam construction and for solving problems in dam operation.

5. Conclusion

In fact, humans have harnessed water for thousands of years. Due to the late invention of electrical technology, it was not until 1878 that the world's first hydropower station was constructed in France. In the next 100 years, hydropower gradually became the second largest source for power generation after thermal power by virtue of low operating cost, simple electromechanical equipment, and operational flexibility. Super hydropower stations born after 1990 are all from China, in contrast to foreign ones built before 1990. In particular, 11 of the world's top 20 super hydropower stations and 4 of world's top 5 hydropower stations are located in China. The Grand Coulee hydropower station from the United States, the oldest in the ranking, was commissioned in 1942 with an initial installed capacity of 1.97 GW, the largest at that time. It was expanded in 1967 and completed in 1980. China's Jinsha River, originating from the Qinghai-Tibet Plateau, renders the strongest power generation capacity secured by four super hydropower stations. This is attributed to large height difference, water abundance, and perfect terrain with towering mountains on both sides.

Along with rapid economic and social development, household and production water use has squeezed the natural runoff of rivers. Therefore, ecological water requirements that guarantee and maintain the stability of river and lake ecosystems are essential to the sustainable development of human society. Ecological flow is related to the life of rivers and lakes and considered an important indicator to express the ecological water requirements of rivers and lakes. Hydropower development imposes huge negative impact on the ecological flow of rivers. While the United States has begun to dismantle some of the dams built in early days, power generation will be the top priority in the future because the use of electricity as an alternative to oil will be multiplied amid the growing trend of substitution. In recent years, hydropower construction is recovering worldwide. Not only China has started construction of more than a dozen large-scale power stations at the same time, but also Africa and the Americas are building large-scale power stations.

However, hydropower station construction is an extremely expensive project involving a series of environmental, geological, and ecological issues. Past dam construction plans largely place emphasize on construction and operation phases and pay little attention to potential problems related to demolition and reconstruction. As the vision of ecological civilization has been widely accepted, it is increasingly recognized in recent years that rivers are a vibrant community of life with biological resource attributes such as water quantity, water quality, shoreline, hydropower, and aquatic organisms. Hydropower developers must not only integrate the conservation of river ecosystems as an important task in the planning, design, and construction phases but also assume responsibility for improving the quality and stability of river ecosystems during the operation phase. In this sense, a major research topic of hydropower development is to minimize the adverse impact of dams on the environment through environment-friendly reservoir construction and operation, and meanwhile, to make full use of reservoirs to rebuild the environment toward a sound situation of ecological improvement featuring harmony between man and water.

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Conflict of interest

The authors declare no conflict of interest.

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