Engineering 2 (2016) 302–312

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Hydro Projects—Review

A Technical Review of Hydro-Project Development in China

Jinsheng Jia

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

ARTICLE INFO

Article history:
Received 13 April 2016
Revised form 15 August 2016
Accepted 22 August 2016
Available online 20 September 2016

Keywords:
Dam
River harnessing
Water diversion
Pumped storage power station
Underground cavern
Ecological protection

ABSTRACT

This paper summarizes the development of hydro-projects in China, blended with an international perspective. It expounds major technical progress toward ensuring the safe construction of high dams and river harnessing, and covers the theorization of uneven non-equilibrium sediment transport, inter-basin water diversion, giant hydro-generator units, pumped storage power stations, underground caverns, ecological protection, and so on.

1. The development of hydro-projects in China and a comparison with projects abroad

China is no stranger to recurrent floods and droughts. In the two millennia prior to1949, China suffered from a total of 1092 floods and 1056 droughts. In 1920, a severe drought in North China starved more than 500 000 people to death; in 1931, the Yangtze River flood rendered a death toll of 145 000 people. Since 1949, China has built numerous dams, inter-basin water diversion projects, pumped storage power stations, and more, in a bid to ensure flood control and water supply, and to increase the proportion of non-fossil energy sources. Water disasters now cost less than 2% of China's gross domestic product (GDP).

A dam is the most important indicator of water conservancy and hydropower development. While history does not record the construction of the earliest dam, it is acknowledged that China, India, Iran, and Egypt are the pioneer countries of dam construction. Records indicate that only three dams higher than 30 m existed before *anno Domini* (AD) 1000, among which the highest was the Fushan Weir earth dam in China (48 m in height). Before 1900, there were only 31 dams higher than 30 m, among which the highest was the Gouffre d'Enfer masonry gravity-arch dam in France (60 m in height).

The worldwide drive to build water conservancy and hydropower projects began around 1900. For its part, China went through four stages with this endeavor. In the first stage, from 1900 to 1949, China possessed only 21 dams higher than 30 m, with a total storage capacity of about 2.8×10^{10} m^3 and a total installed hydropower capacity of 540 MW. Water disasters remained a mortal malady, only varying in their severity based on the quantity of rainfall causing them. Technologies to combat water hazards were meager. In the second stage, from 1949 (when the People's Republic of China was founded) to 1978 (when China's reform and opening up began), China was the most active country in the world in building reservoirs and dams. The number of dams higher than 30 m increased from 21 to 3651, the total storage capacity increased to about 2.989×10^{11} m^3, and the total installed hydropower capacity increased to about 18 670 MW. These dams were constructed mainly for the purposes of flood control and irrigation. Despite these great achievements, China still lagged behind developed countries due to a lack of technology, investment, and similar aids. The third stage, from 1978 to 2000, was marked by the completion of huge dams such as the Ertan Dam. China achieved qualitative breakthroughs in water conservancy and hydropower development, and leaped from its former position as a late and weak arrival in the field to a new position as an internationally leading country in many aspects. Many projects stood the test of the major Yangtze River flood in

---

E-mail address: jiajsh@iwhr.com

http://dx.doi.org/10.1016/J.ENG.2016.03.008

1998 and the great Wenchuan earthquake in 2008. Projects constructed during this stage were characterized by quality design, speedy construction, and stringent safety, and generally fulfilled their purposes. In the 21st century, China entered the fourth stage of indigenous innovation and pioneering development, marked by the operation of the Three Gorges Project and the South-to-North Water Diversion Project. With the successive completion of Xiaowan, Longtan, Shuibuya, Jinping I, and other projects, China rewrote world records again and again. China began to pay more attention to the safety of mega projects and super-high dams, as well as to ecological protection. From a global perspective, China has marched fully into the international market, and now occupies over half of it.

As of 2014, China has built more than 98 000 reservoirs with a total storage capacity of 8.166×10^{11} m^3, accounting for 29% of the annual runoff of all rivers and streams in China. China's effectively irrigated farmland has reached up to 6.9×10^7 hm^2, accounting for 23% of global farmland; 6539 dams over 30 m high have been completed or are under construction, accounting for 43% of all such dams worldwide; total installed hydropower capacity has exceeded 300 GW, accounting for 27% of such capacity worldwide; the total installed hydropower capacity of pumped storage power stations has reached 22 110 MW, accounting for 12% of such capacity worldwide; the length of water delivery trunk canal has exceeded 13 800 km, and the length of hydraulic tunnel is over 10 000 km. China arguably owns the largest number of reservoirs and dams, the greatest farmland irrigation area, the biggest installed hydropower capacity, and the longest water diversion route in the world. Figs. 1 and 2 and Tables 1–3 provide international comparisons [1].

China owns the most water conservancy and hydropower projects in the world, and implements the strictest water resource management policies, under which water resources bearing capacity must be factored into the planning of cities and their industrial development. Nonetheless, project construction is still necessary, considering China's large population and uneven distribution of water resources in time and space. Figs. 3 and 4 compare the correlation between the degree of water resources development and the human development index (HDI), based on the data for 100 countries. The HDI is an important index for measuring comprehensive national strength. It can be concluded that developed countries generally achieve high HDI (involving life expectancy, educational level, and per capita GDP) and correspondingly command a high level of water resources development. In 2014, when the HDI in China was 0.727, China had developed 52% of its hydropower resources and its storage capacity per capita reached 600 m^3, basically approximating the indexes of relatively developed developing countries. It is clearly demonstrated that the development of reservoirs and hydropower projects in China is in line with the national economic and social growth on the whole.

2. Technologies for guaranteeing safety of high dams

The development of rockfill dams, gravity dams, arch dams, and cemented material dams in China has been elaborated in the literature [1–5]. Safety is treated as paramount when it comes to high dams, and various new technologies have been developed.

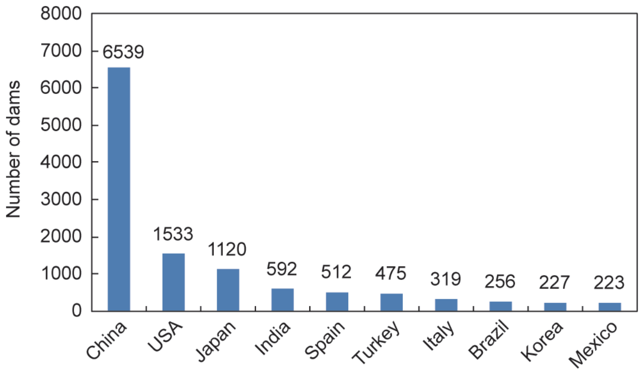

Fig. 1. Numbers of dams higher than 30 m in major countries.

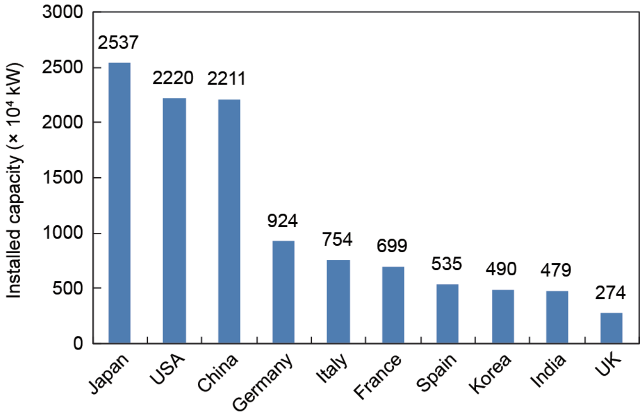

Fig. 2. Installed hydropower capacities of pumped storage stations in major countries.

Table 1
Top 10 highest dams in the world.

Rank	Dam name	Country	Dam type	Dam height (m)	Total storage capacity ($\times 10^8$ m^3)	Installed capacity (MW)	Year of completion
1	Jinping I	China	Arch dam	305.0	79.88	3 600	2014
2	Nurek	Tajikistan	Earth-rock dam	300.0	105.00	2 700	1980
3	Xiaowan	China	Arch dam	294.5	150.00	4 200	2012
4	Xiluodu	China	Arch dam	285.5	126.70	13 860	2015
5	Grande Dixence	Switzerland	Gravity dam	285.0	4.00	2 069	1962
6	Kambarata-I	Kyrgyzstan	Earth-rock dam	275.0	36.00	1 900	1996
7	Inguri	Georgia	Arch dam	271.5	11.00	1 320	1980
8	Vajont	Italy	Arch dam	262.0	1.69	—	1961
9	Nuozhadu	China	Earth-rock dam	261.5	237.03	5 850	2015
10	Chicoasén	Mexico	Earth-rock dam	261.0	16.80	2 430	1981

Table 2
Top 10 reservoirs with the largest storage capacity in the world.

Rank	Dam name	Country	Dam type	Dam height (m)	Total storage capacity (× 10^8 m^3)	Installed capacity (MW)	Year of completion
1	Owen Falls	Uganda	Gravity dam	31	2 048.0	180	1954
2	Kariba	Zambia/Zimbabwe	Arch dam	128	1 806.0	1 500	1976
3	Bratsk	Russia	Gravity dam	125	1 690.0	4 500	1964
4	Aswan	Egypt	Earth-rock dam	111	1 620.0	2 100	1970
5	Akosombo	Ghana	Earth-rock dam	134	1 500.0	1 020	1965
6	Daniel-Johnson	Canada	Arch dam	214	1 418.5	2 656	1968
7	Guri	Venezuela	Gravity dam	162	1 350.0	10 235	1986
8	Bennett	Canada	Earth-rock dam	183	743.0	2 730	1967
9	Krasnoyarsk	Russia	Gravity dam	124	733.0	6 000	1972
10	Zeya	Russia	Gravity dam	115	684.0	1 330	1978

The largest reservoir in China is the Three Gorges Reservoir with a storage capacity of 4.505 × 10^{10} m^3, ranked the 24th in the world.

Table 3
Top 10 projects with the largest installed capacity in the world.

Rank	Dam name	Country	Dam type	Dam height (m)	Total storage capacity (× 10^8 m^3)	Installed capacity (MW)	Year of completion
1	Three Gorges	China	Gravity dam	181.0	450.50	22 500	2010
2	Itaipu	Brazil/Paraguay	Gravity dam	196.0	290.00	14 000	1991
3	Xiluodu	China	Arch dam	285.5	126.70	13 860	2014
4	Guri	Venezuela	Gravity dam	162.0	1350.00	10 235	1986
5	Tucuruí	Brazil	Earth-rock dam	98.0	455.40	8 370	2002
6	Sayano-Shushenskaya	Russia	Arch dam	245.0	313.00	6 400	1989
7	Xiangjiaba	China	Gravity dam	162.0	51.63	6 400	2015
8	Krasnoyarsk	Russia	Gravity dam	124.0	733.00	6 000	1972
9	Nuozhadu	China	Earth-rock dam	261.5	237.03	5 850	2015
10	Longtan	China	Gravity dam	192.0	188.00	4 900	Phase I, 2009

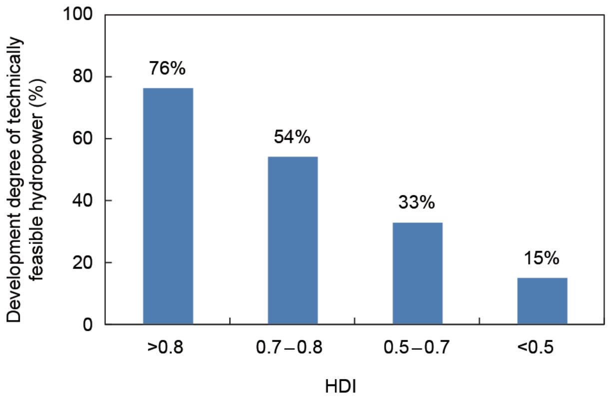

Fig. 3. Relationship between hydropower development degree and human development index (HDI).

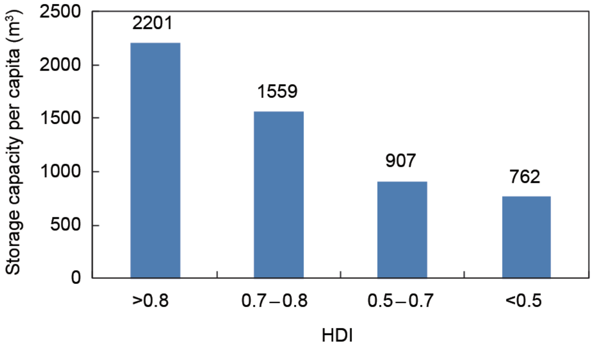

Fig. 4. Relationship between storage capacity per capita and HDI.

2.1. Behavior simulation, prevention of hydraulic fracture, and concrete-mix design for high concrete dams

The concrete dam is one of the main types of high dam around the world, accounting for more than 60% of dams over 200 m worldwide and 56% of dams over 200 m in China. More high concrete dams are to be built globally for the sake of developing water resources, hence high dam safety is of great significance.

The lessons learned from building high concrete dams in the last century have been mixed. Hoover Dam, Inguri Dam, Grande Dixence Dam, Itaipu Dam, and other high concrete dams were remarkable for their time; however, high dams such as Koelnbrein Dam in Austria (Fig. 5), Dworshak Dam in the US, and Sayano-Shushenskaya Dam in Russia had severe cracks and leakage, with tremendously high costs for repair and reinforcement. Malpasset Dam in France failed due to unstable abutment, rendering huge losses in life and property; there were also high concrete dams in China that severely cracked or suffered from other safety incidents such as hydraulic fracture. These incidents illustrate that traditional design methods and construction technologies fall short of the requirements for safety of high dams. More specifically, these shortages are manifested as follows: ① The stress, deformation, and stability calculated by traditional methods digress significantly from those in actuality, introducing large errors into the prediction of dam behaviors; ② the contradiction between high strength and high crack resistance of dam concrete is prominent, and it is difficult to balance both aspects with traditional methods; and ③ a high concrete dam has a high risk of hydraulic fracture with severe results.

In order to realize the proposed concept that *the more accurate the prediction of dam behavior, the more reliable the dam safety*, we have developed the finite element equivalent stress method and stress control standards that are applicable to extra-high dams around 300 m [1], based on an analysis of the stresses and cracking ranges of 15 domestic and overseas typical arch dams. There are major errors in dam behaviors predicted by traditional methods, in that the difference between the predicted displacement value and the observation value is generally greater than 30%; sometimes, the predicted stress state at the dam heel is contrary to the observation. Thus, it is difficult to accurately assess dam safety. Focusing on this problem, we have put forward an accurate temperature-rise model for the whole period for high concrete dams, and have developed the multi-joint dam efficient iterative model and other models. These models achieve the whole-process simulation of construction and operation for a concrete dam, from pouring, grouting, and impounding for operation, to aging and degradation, and significantly improve the precision of dam behavior prediction. For extra-high arch dams such as Xiaowan Dam, Jinping I Dam, and Dagangshan Dam, the errors between the maximum predicted deformation values and the monitored values are 0.9%, 0.1%, and 2.2%, respectively, from when the dam is impounded until the normal impounding level in the initial stage (three months). These are far less than the errors made by using traditional methods (36.6%, 76.1%, and 36.4%, respectively).

To prevent hydraulic fracture, we have invented the method and device for the hydraulic fracture simulation test on full-graded concrete; we have demonstrated that an extra-high gravity dam of over 200 m, designed in accordance with non-tensive stress criteria (in China) or compressive stress criteria (in the US), is subject to the risk of hydraulic fracture; and we have put forward a design method and criteria for preventing hydraulic fracture. A flexible seepage prevention structure and a dam-front self-reverse filter seepage prevention structure have been developed for the high concrete dam face; and a simulated test device has been developed to prove that hydraulic fracture can be prevented if the dam heel concrete crack is no greater than 8 mm under the action of the 300 m high water head. The proposed flexible seepage prevention and dam-front self-reverse filter structures are more reliable than the apron addition.

Hoover Dam in the US was constructed with low-heat Portland cement, which cost 1.3 times more than the concrete used for the Three Gorges Dam per unit cubic meter of concrete, rendering itself hardly affordable. To ensure safe construction of the "millennium plan"—that is, the Three Gorges Project and high concrete dams of over 200 m—we have discovered the close packing and synergistic cementitious effects of multi-component cementitious materials, and have put forward a new method for high dam concrete preparation. This new method solves the problem of balancing high strength with high crack resistance that is often encountered in traditional methods, and creates a precedent in the admixture of Class I fly ash and limestone powder being used in a large-scale high dam project. The new method was applied for the 4×10^6 m^3 of concrete for the Three Gorges Phase III, improving the anti-crack coefficient by 50% in some case. As shown in Fig. 6, if the content of micro fine powder (MF) reaches 20% to 40% of cementitious materials, the slurry water consumption will be reduced by 12%, significantly reducing the concrete water consumption and the cementitious materials consumption.

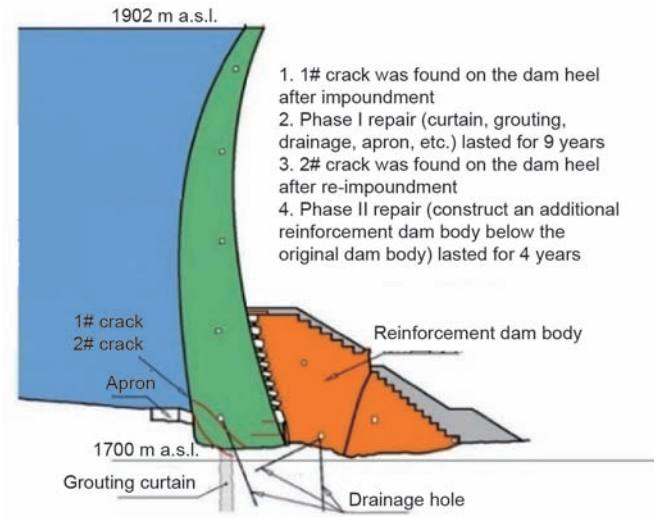

Fig. 5. Koelnbrein Dam accident and reinforcement.

2.2. Deformation compatibility control and dynamic stability design of water-stop for concrete-faced rockfill dams (CFRDs)

Modern concrete-faced rockfill dams (CFRDs) have been developed since 1965 [2]. Cooke (USA) [2] was representative expert to emphasize empirical design and thin-layer rolling construction with a small-tonnage vibrating roller. China began introducing modern CFRD technologies in the 1980s. Later, Chinese and Brazilian experts put forward the idea of dam deformation control and applied it in Shuibuya, Hongjiadu, and other CFRDs, achieving better control of structural cracks on the concrete face. In addition, China put forward stricter control indexes for porosity, with the aim of controlling the porosity of rockfill material within the range of 19%–20%, and controlling the maximum dam settlement within 1% of the dam height by using rolling equipment with greater weight (see Table 4 for details). Pinto (Brazil) [2] believed that the most efficient way to reduce compressive strain of concrete face slab was to improve the rockfill compression modulus, E, and established the relationship between the rockfill deformation modulus, $E/(\gamma H)$, and the valley shape factor, A/H^2 (Fig. 7). The development of CFRDs has been strengthened by these ideas and practices.

Based on Fig. 7 originally drew by Pinto [2], 10 additional CFRDs, such as Shuibuya, are added in. It can be seen that CFRDs such as Shuibuya and Bakun do not conform to Pinto's conclusion but without face slab damage, which means that it is not always scientifically sound to individually control the rockfill deforma-

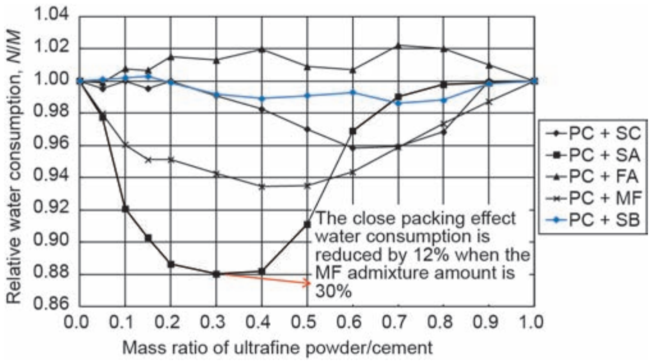

Fig. 6. Standard consistency relative water consumption test results. FA: fly ash; MF: micro fine powder; PC: Portland cement; SA: slag A; SB: slag B; SC: slag C; N stands for water requirement of standard consistency of the multi-component cementitious powders; M stands for weighted average of the water requirement of standard consistency of the multi-component cementitious powders.

Table 4
Statistics of typical high concrete-faced rockfill dams (CFRDs) at home and abroad.

Phase	Project	Dam height (m)	Settlement (cm)	Leakage (L·s^{-1})	Standard porosity of buildings rockfill		Construction parameters	Operation situations
					Main rockfill area (%)	Downstream rockfill area (%)		
Deformation compatibility	Bakun	203.5	227.5	170	20.0	20.0	25 t; rolling for 8 times	There is no structural crack or crushing failure in the face plate, and the dam operates in good condition
	Nam Ngum II	182.0	160.0	40	—	—	—	There is no structural crack or crushing failure in the face plate, and the dam operates in good condition
	Jiudianxia	136.5 + 56.0	138.0	65	17.3	19.1	25 t; rolling for 8 times	There are micro-cracks but no structural cracks or crushing failure in the face plate, and the dam operates in good condition
Deformation control	Shuibuya	233.0	255.5	40	19.6	20.7	25 t and below; rolling for 8 times	There is slight crushing failure but no structural cracks in the face plate
	Sanbanxi	185.5	175.1	300	19.3	19.5	20–25 t; rolling for 8–10 times	There are structural cracks and severe crushing failure in the face plate
Empirical design	Tianshengqiao I	178.0	354.0	150–70	22.0	22.0–24.0	18 t; rolling for 6 times	There are a lot of structural cracks and crushing failure in the face plate
	Aguamilpa	187.0	170.0	260	—	24.0	10 t; rolling for 4 times	There are structural cracks in the face plate. Infiltration is reduced by dump-filling
	Campos Novos	202.0	> 310.0	1400	22.0	—	9–12 t; rolling for 6 times	There are severe crushing failure, cracks, and fractures, as well as severe leakage in the face plate. The reservoir is fully discharged for overhauling
	Barra Grande	185.0	> 300.0	1284	22.0	—	9–12 t; rolling for 6 times	There are cracks, crushing failure, and severe leakage in the face plate

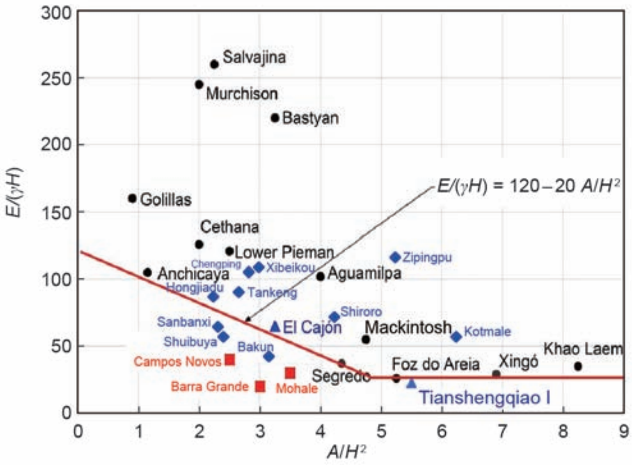

Fig. 7. Relation between rockfill dam deformation modulus and valley shape factor.

tion, and that both the total rockfill deformation amount and the deformation compatibility of each part must be controlled. With the construction of Bakun Dam and other CFRD projects, we have put forward a new design concept of deformation compatibility, and established the deformation compatibility criteria and judgment standard, as well as the design method. Table 4 shows the operation situations of typical projects designed according to new and old concepts.

The problem of damage and leakage at peripheral joints was common in the early developmental stage of CFRDs. In order to improve the safety of Shuibuya CFRD, we have put forward a new water-stop structure, and further proposed the dynamic stability design concept of water-stop. The basic requirement is that the water-stop structure must be able to bear three-directional-displacement action, and form a stable water-stop system through dynamic self-adjustment under the 300 m high water pressure. In other words, the new water-stop structure cannot only enable a dynamic stable water-stop under normal designed operating conditions, but also offset the defects of a water-stop system, with the new material having a flowing function under non-normal conditions. Table 5 compares projects that adopt the new water-stop design with those that use an overseas conventional water-stop design. The CFRD leakage evaluation method was established by using the comprehensive seepage coefficient method. Fig. 8 is based on monitoring data of 67 domestic and overseas CFRDs. Projects such as Shuibuya Dam and Hongjiadu Dam are located in the high-quality zone in Fig. 8.

2.3. Seismic safety of high dams

When designing Hoover Dam, the US Bureau of Reclamation (USBR) developed a trial-load method and adopted the pseudo-static method for seismic design with considering the seismic acceleration to be 0.1*g* (gravity acceleration, $g = 9.8\ \mathrm{m{\cdot}s^{-2}}$). Follow-up progress included analyses on the dynamic characteristics and dynamic response of the arch dam based on the trial-load method. For dams of over 200 m in highly seismic region of China, design seismic acceleration is generally set to a higher value. For example, the design seismic acceleration is 0.308*g* for the Xiaowan arch dam, 0.357*g* for the Xiluodu arch dam, and 0.5575*g* (the highest value assigned for concrete dams worldwide) for the Dagangshan arch dam. Teams led by academicians Houqun Chen, Chuhan Zhang, and Gao Lin [1,6] have developed and established a systemic analytical method for the seismic safety of concrete dams, which mainly involves seismic motion input, structural seismic response, and structural resistance analysis.

Chinese experts have taken the seismic motion input characteristics of a near-field large earthquake into consideration by the stochastic finite-fault method, in accordance with the process of surface rupture; used the effective peak acceleration (EPA) corresponding to the seismic motion acceleration response spectrum as the main seismic design parameter characterizing the

Table 5
Comparison of water-stop effects of dams at home and abroad.

Projects with dynamic stable water-stop design			Overseas projects with conventional water-stop design		
Dam name	Dam height (m)	Leakage ($L\cdot s^{-1}$)	Dam name	Dam height (m)	Leakage ($L\cdot s^{-1}$)
Shuibuya	233	40	Campos Novos	202	1400
Nam Ngum II	182	40	Barra Grande	185	1284
Hongjiadu	179.5	20	Alto Anchicaya	140	1800
Zipingpu	156	54	Shiroro	130	1800
Longshou II	146.5	76	Itá	125	1700
Gongboxia	132.2	10	Turimiquire	115	6000

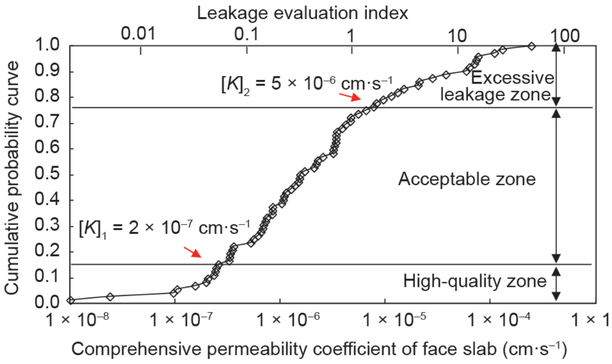

Fig. 8. Cumulative probability curve of comprehensive permeability coefficient of concrete face.

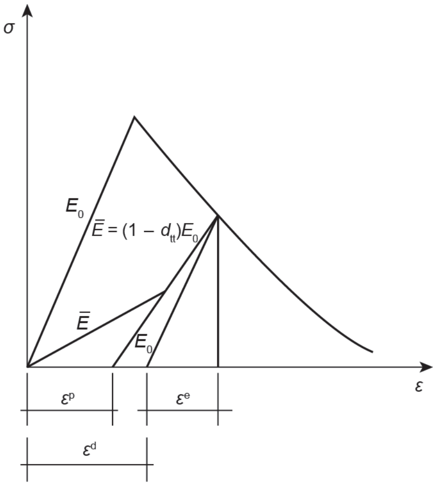

Fig. 9. Stress-strain relationship with apparent elastic modulus $\bar{E}$.

earthquake intensity; and combined the probability method and the deterministic method, so as to determine the design seismic response spectrum by scenario earthquake method.

The dynamic stability analysis method of a deformation body with the finite element method (FEM) has also been proposed. The improved dynamic contact force models are used to simulate the nonlinear mechanics behavior of each slip surface opening, adhering, and slipping of the dam foundation rock mass under the static and dynamic forces. New quantitative evaluation criteria has been put forward and it means that the dam foundation rock will come to the critical state when the displacement of the control point has an inflection change after the cumulative deformation of the body during over-load seismic calculation from linear to non-linear condition. A new evaluation system on dam stability and dam limit seismic capacity has been established based on this method. Then a parallel computing technique for high dams was created and the corresponding parallel computing software was developed. A large three-dimensional vibration table with six degrees of freedom was established to conduct earthquake simulation tests for many actual dam projects.

Chinese experts have proposed the concrete damage models considering residual deformation and stiffness degradation simultaneously, introduced an "apparent elastic modulus" $\bar{E}$ (Fig. 9) and an "apparent damage factor" to establish the constitutive relation of concrete dynamic damage (Eq. (1)), and carried out the seismic regime inspection of the Shapai arch dam, which suffered from the Wenchuan earthquake.

$$\bar{E}=\left(1-d_{tt}\right)E_0,\ d_{tt}=1-\left(1-d_t\right)\left(\varepsilon_{max}-\varepsilon^p\right)/\varepsilon_{max} \qquad (1)$$

where, $\bar{E}$ is apparent elastic modulus; d_{tt} is apparent damage factor; E_0 is initial elastic modulus; d_t is damage factor; ε_{max} is maximum principal strain; and ε^p is unrecoverable residual strain.

During the 2008 Wenchuan earthquake, four dams of over 100 m high, including the Shapai arch dam and Zipingpu CFRD, withstood the strong seismic shock and maintained their stability.

2.4. Flood discharge and energy dissipation of high dams

Many high dams in China are located in narrow valleys with complex geological and topographical conditions, and have high water heads and large discharges. Among these, projects such as Xiaowan, Ertan, and Xiaolangdi rank top in the world in regard to hydraulic parameters such as water head, discharge volume, flood discharge power, and so on. The challenges of fulfilling flood discharge and energy dissipation are formidable.

To realize flood discharge, energy dissipation, and erosion prevention of high arch dams, a portfolio of measures have been developed in China, including [7]: multiple and decentralized facilities for flood discharge; multi-flow way in two layers in elevation for striking with each other; energy dissipation by zoning and slope protection on-demand. The Ertan hydropower station was the first case to successfully implement such measures. As dam technologies continued to develop, innovations were made in dam flood discharge and energy dissipation as listed in Table 6. All of these projects adopt the "Ertan mode"—integrating flow discharge through dam orifice, flow discharge through spillway tunnels, and energy dissipation in plunge pools. Results show that all of the completed projects are in sound operation.

Based on the principle of longitudinal diffusion and energy dissipation by friction in air, Chinese experts have developed the technology of narrow-slot energy dissipation, which meets the challenge of flood discharge and energy dissipation for a series of high dams featured by a *narrow river valley and large discharge capacity*. We have carried out systematic studies on the narrow-slot energy dissipater; put forward application conditions, design steps, and dissipation characteristics of the narrow-slot energy dissipater; and successfully applied them to various high dams such as Longyangxia and Laxiwa arch dams.

Table 6
Hydraulic parameters of flood discharge for domestic and overseas high arch dams.

Project name	Country	Dam height (m)	Fall (m)	Flow ($m^3 \cdot s^{-1}$)	Flood discharging power (MW)	Channel width (m)	Valley shape	Year of completion
Inguri	Georgia	271.5	230.0	2 500	5 040	25		1980
El Cajón	Honduras	234.0	184.0	8 590	15 500	100		1985
Mratinje	Yugoslavia	220.0	175.0	2 200	3 890	35		1976
Ertan	China	240.0	166.3	16 300	26 560	80–100	V	2000
Jinping I	China	305.0	225.0	10 074	22 210	80–100	V	2014
Xiaowan	China	294.5	225.5	15 600	34 600	80–100	V	2012
Xiluodu	China	285.5	189.5	31 496	58 490	70–100	U	2015
Baihetan	China	289.0	200.7	30 000	59 006	50–90	V	In progress

To resolve the challenge of flood discharge and energy dissipation caused by a high water head, large discharge per unit width, and low Froude number, the flaring-pier gate stilling-basin united energy dissipater has been invented, which has been applied to a lot of projects, such as Wuqiangxi and Jinghong. Jinghong, with a maximum dam height of 108 m and a maximum discharge per unit width of 331 $m^3 \cdot s^{-1}$, marks the height of the flaring-pier gate stilling-basin united energy dissipater. In addition, Chinese experts have developed the technology of the interior energy dissipater in multiple forms, such as the orifice energy dissipater and the swirling flow energy dissipater, which solve the problem of water flow connection in a case where the diversion tunnel is rebuilt for the spillway tunnel, and reduces the adverse impact to the environment of the atomized flow without a hydraulic jump. The technology has been successfully applied to projects including Xiaolangdi and Gongboxia projects.

Geological and topographical conditions in remote mountain canyon areas often bring difficulties to the layout of spillway tunnels. The proposed layout of the innovated spillway tunnel with the steep slope part near the downstream outlet, as well as the technology of scouring reduction by aeration [8], can significantly reduce the risk of cavitation erosion caused by high-velocity flow. This layout and technology have been successfully applied to Xiluodu, Jinping I, and other projects.

3. River harnessing and the theory of non-equilibrium transport for non-uniform sediment

The Yellow River and the Yangtze River in China are well-known throughout the world, but harnessing and controlling them are with extremely difficulties. The gradients of typical rivers around the world are shown in Fig. 10. Records show that before 1949, the Yellow River changed its course nearly every 100 years and busted its bank about twice in every three years, wreaking tremendous havoc. In addition, the river flow fluctuated greatly between seasons, the sediment concentration was high, leading to severe sedimentation problems of the reservoirs. The long-term annual sediment discharge of the Yellow River is 1.6×10^9 t, 1.8 times that of the Amazon River, which is 9×10^8 t. Its average sediment concentration has reached 35 $kg \cdot m^{-3}$, which is 210 times that of the Amazon River. A 1992 survey revealed that over 20% of reservoir storage in the Yellow River Basin had been lost due to sedimentation. Against such a background, the methods of *storing clear water and releasing muddy water* and *sediment sluicing by turbidity currents* are utilized to rid the Yellow River of accretion, breaching, set-off, and water quality deterioration.

As a result of its high sediment concentration and severe sedimentation, the Yellow River became a "suspended river" above the Huang-Huai-Hai Plain when it flowed downstream. In an attempt to find a breakthrough in harnessing the Yellow River, Hu et al. [9] developed a whole-river-view framework of spatial optimized allocation for sediment, and constructed supporting theories and models. Relevant administrative agencies also set up modes for water and sediment regulation. This work is based on single-reservoir regulation of Xiaolangdi Reservoir, coordinated control of water and sediment in the spatial scale, and multi-reservoir joint regulating of water and sediment in the main stream. A system of theories and indicators for water and sediment regulation has been achieved.

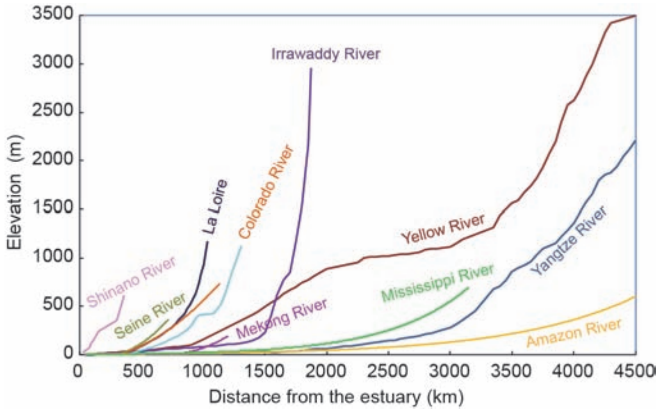

Fig. 10. Gradients of typical rivers around the world.

Han [10] created the theory of non-equilibrium transport for non-uniform sediment, elaborating the mechanism of non-uniform sediment movement and non-equilibrium sediment transport processes in rivers and reservoirs. As a result, problems such as the prediction of reservoir sedimentation and downstream channel erosion such as the Three Gorges Project on the Yangtze River and the Xiaolangdi Project on the Yellow River are resolved, and sediment movement cannot only be qualitatively described but also quantitatively simulated by the theory. This theory stands out in the following aspects: It sets up the expressions for non-uniform and non-equilibrium sediment transport, among which the change of non-uniform suspended sediment concentration along the river can be expressed by Eq. (2); it reveals and confirms that the exchange between coarse and fine sediments is universal for the channel evolution of alluvial rivers; it derives the expression of the recovery saturation coefficient in equilibrium and non-equilibrium conditions; it establishes a theoretical system for the statistics of theoretical sediment-carrying capacity; it derives the probability of relevant sediment transfer and status at different vertical and horizontal velocities; and it sets up the universal boundary conditions of the diffusion equation based on the intensity of sediment exchange on the channel bed. In recent years, the non-equilibrium transport for non-uniform sediment theory has been widely and successfully used in major models and projects at home and abroad.

$$S = S^* + \left(S_0 + \sum_{l=1}^{n} P_{4,l,0} \mathrm{e}^{-\frac{\alpha L}{\lambda_l}} - S_0^* \sum_{l=1}^{n} P_{4,l,0}^* \mathrm{e}^{-\frac{\alpha L}{\lambda_l}} \right) + \left[S_0^* \sum_{l=1}^{n} P_{4,l,0}^* \frac{\lambda_l}{\alpha L} \left(1 - \mathrm{e}^{-\frac{\alpha L}{\lambda_l}} \right) - S^* \sum_{l=1}^{n} P_{4,l}^* \frac{\lambda_l}{\alpha L} \left(1 - \mathrm{e}^{-\frac{\alpha L}{\lambda_l}} \right) \right] \tag{2}$$

where, S and S^* represent the total non-uniform sediment concentration and the total sediment-carrying capacity at the cross-section of the outlet, respectively; $\sum_{l=1}^{n}$ represents the sum of the sediment in $(1–n)$ groups; $P_{4,l}$ and $P^*_{4,l}$ respectively represent the grades of suspended sediment and the sediment-carrying capacity; α is the recovery saturation coefficient; L is the length of the channel segment; $\lambda_l = q/\omega_l$ is the settling distance of the sediment in group l, among which q is the discharge per unit width, and ω_l is the settling velocity of sediment; and the subscript 0 represents the corresponding value at the cross-section of the inlet.

4. Inter-basin water diversion project

To achieve sustainable development, long-distance inter-basin water diversion becomes an inevitable choice for solving water resource shortages and optimizing water resource allocation. Statistics show that 350 water diversion projects have been constructed in over 40 countries and regions. In China, nearly 50 large- and medium-sized water diversion projects have been constructed or are to be constructed, with an annual water diversion volume of more than 9×10^{10} m^3 [1]. The expected annual water diversion volume of the South-to-North Water Diversion Project (Fig. 11) is 4.48×10^{10} m^3, including 1.48×10^{10} m^3 on the east route, 1.3×10^{10} m^3 on the middle route, and 1.7×10^{10} m^3 on the west route. The length of the completed Phase I of the east route is 1467 km, and that of the completed Phase I of the middle route is 1432 km. The project features the longest diversion distance and the largest population affected in the world, along with tremendous engineering complexity, and a formidable safety control challenge .

The challenges for a long-distance water diversion project mainly include: ① water cycle simulation on different spatial and temporal scales and of different element processes; ② multi-water source, multi-objective and multi-agent grouping decision making and risk dispatching; and ③ hydraulic control for the safe and efficient operation of a complex mega system.

China has made a series of progresses in these aspects. A distributed hydrological model considering the influence of human activities has been developed; the adaptability of hydrological simulation to different climates underlying the surface conditions and human activities has been enhanced; economic characteristics of a reservoir system and the dispatching decision-making principle have been examined; three monotonicity-based improved dynamic programing algorithms have been developed, with the computational efficiency improved by one order of magnitude as compared with that of the traditional algorithm; and an optimization technology for the multi-objective grouping decision making of reservoir dispatching rules has been developed, with successful application to the Danjiangkou Reservoir in the middle route of the South-to-North Water Diversion Project [11].

In the multi-constraint, multiphase, and multi-process coupled simulation of the water-transfer system, the system identification model for key hydraulic parameters of water transportation open channels and the theoretical method for numerical simulations of complex multiphase flows of water-conveyance systems are proposed and successfully applied to the middle route of the South-to-North Water Diversion Project.

Chinese experts have proposed the formula for system identification of channel roughness (Eq. (3)), providing a theoretical basis for demonstrating the water-transfer capacity of a long-distance water-transfer project in China. The existing international Einstein's equations, Belokon-Sabaneev formula, and Larsen formula are special cases of comprehensive roughness formulas for freeze-up channels.

$$n = \frac{R^{1/6}}{22.9\lg(1020R)},\ n_{\mathrm{c}} = \frac{\left(n_{\mathrm{i}}^{3/2} + \beta a^{3/2} n^{3/2}\right)^{5/3}}{(1+\beta)^{2/3}\left(n_{\mathrm{i}}^{3/2} + \beta a^{5/2} n^{3/2}\right)} \tag{3}$$

where, n is channel bottom roughness; R is the hydraulic radius

Fig. 11. Overall layout of the South-to-North Water Diversion Project.

of the channel; n_c is the comprehensive roughness of the channel; n_i represents the ice cover roughness; β is the wetted perimeter ratio; and a represents the mean velocity ratio.

Chinese experts have developed a theory of frequency-domain analysis for the hydraulic regulation and control of a complex water-transfer system and an optimization control technology for a sluice group, put forward a distributed control mode for the sluice group of a long-distance complex water-conveyance system with the organic integration of *coarse control*, *fine tuning*, and *coordination* effects, and designed a sluice group control algorithm.

In the hydraulic control technology of the water diversion system under normal and emergency conditions, a new technology for the hydraulic control of a long-distance water diversion system has been developed to effectively solve the problem of hydraulic shock control for water-conveyance projects with medium-to-high head, long distance, and high-flow pressure pipelines. A technology for ice prediction, ice hazard prevention, and control and operational control during the ice time of a long-distance water-transfer system has been established and successfully applied to the water diversion project from the Yellow River to Tianjin Municipality, and the middle route of the South-to-North Water Diversion Project, and so on.

In long-distance water diversion, deeply buried long tunnels play an irreplaceable role in overcoming orographic barriers such as mountains and valleys, and shortening the spatial distance. According to incomplete statistics, there are 22 newly constructed and under-construction inter-basin water diversion tunnel projects with length greater than 5 km in China. Of these, a single water-transfer tunnel of Phase I of the Dahuofang water supply project is 85 km long, and is the longest constructed tunnel in the world by far. Currently, China's construction technology for deeply buried long tunnels, which has the New Austrian Tunneling Method (NATM) as its score, has reached the highest level in many aspects; and its advanced forecasting and control technology of geological disasters are mature. In particular, China has independently developed the full-face rock tunnel boring machine (TBM) (Fig. 12) with core technology and proprietary intellectual property rights, and the supporting process-oriented construction method, which have been developed and successfully applied in many projects, such as the Yellow River Crossing Tunnel in the middle route of the South-to-North Water Diversion Project, and the Qinling Tunnel in the Hanjiang-to-Weihe Water Transfer Project.

5. Giant hydropower units and pumped storage power stations

The full-on construction of giant hydropower stations in China has promoted the development of giant hydropower equipment. From 1949 to 1978, China's hydropower equipment industry developed significantly, with Francis, Kaplan, and Pelton hydro-generator units independently developed and manufactured. The hydropower equipment has advanced to a new level since 1978. The unit capacity reached 300 MW in Liujiaxia, Longyangxia, Yantan, and other hydropower stations; and 400 MW in Lijiaxia, 550 MW in Ertan. Under the guidance of development idea of *introduction, digestion, absorption, and re-innovation*, represented by the Three Gorges Project, the design and manufacturing capacity of the conventional hydro-generator unit in China's large-scale hydropower equipment manufacturing industry rapidly increased to 700 MW. There are more than 30 units in Three Gorges and Longtan with a unit capacity of 700 MW. Furthermore, in Xiluodu, Xiangjiaba, and projects under on-going construction, such as Baihetan and Wudongde, the unit capacity reaches the range between 700 MW to 1000 MW. In the process of developing hydropower units for the hydropower station on the right bank of the Three Gorges, Harbin Electric Corporation, through an optimization of the stator coil transposition mode and stator frame, rationally selecting stator iron core material and optimizing the design of the cooling system, had independently developed the fully air-cooled hydro-generator with a unit capacity of 840 MW—the biggest in the world at that time. Dongfang Electric Corporation has also developed the vapor-cooled hydro-generator unit for the Three Gorges underground power station, which has the world's top unit capacity of 840 MW and possesses the independent intellectual property right. Presently, the 800 MW-level hydro-generator units designed and manufactured by Chinese enterprises have been put into operation, and a 1000 MW-level unit is under development [1].

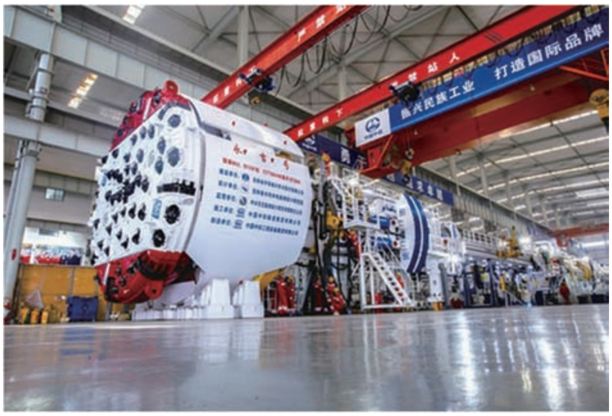
Fig. 12. The full-face rock tunnel boring machine (TBM), independently developed by China, with a diameter of 8.03 m.

The pace of localization of pumped storage unit equipment has been greatly speeded up by technologies introduced by the bidding for the manufacture of units for the Baoquan, Huizhou, and Bailianhe storage power stations, as well as by the combination with introduction of technology by trade of units for Heimifeng, Pushihe, and other pumped storage power stations. At present, China has possessed a set of core technology for 300 MW-level and higher-level pumped storage units. Since 2007, electromechanical equipment has been successively designed and manufactured for Xiangshuijian, Qingyuan, Xianyou, and other pumped storage power stations.

High-precision hydraulic machinery model test rigs have been built in China. Table 7 lists the parameters of test rigs of China and other countries. The construction of a test rig is the foundation for developing superior hydraulic machinery models. The contrast test between models for a large hydropower station and a pumped storage power station conducted on same test rig has provided a platform for scientific bid evaluation.

The construction of pumped storage power stations started late in China, but developed rapidly, with a huge potential for further expansion. The total installed capacity reached 2.211×10^7 kW by 2014, ranking third in the world, accounting for 2% of the total installed capacity of national electric power, still lower than the level of about 5% of developed countries. It is expected that by 2030, the installed capacity will reach 1.2×10^8 kW. In addition to technical progress in generator units, China has also gained innovative achievements in whole-reservoir anti-seepage lining, high-pressure diversion tunnel, powerhouse vibrating resistance, and more.

Following technologies have been successfully applied to the Tianhuangping and Hohhot pumped storage power stations and proved good results: a proposed quantitative concept for durability design of whole-reservoir anti-seepage lining with asphalt or concrete-faced slab; the establishment of the indoor and outdoor

Table 7
Comparison of test rig parameters.

Test rig name	Country	Maximum test water head (m)	Maximum test flow ($m^3 \cdot s^{-1}$)	Total uncertainty of efficiency measurement (%)
China Institute of Water Resources and Hydropower Research (IWHR)	China	150	2.20	0.20
Institute of Hydraulic Machines and Fluid Mécanique (IMHEF)	Switzerland	120	1.40	0.25
Voith	Germany	100	1.50	0.25
Voith	US	134	1.57	0.30
Alstom	France	120	1.50	0.25
Rainpower	Norway	150	1.50	0.30
VVATECH	Switzerland	120	1.10	0.25
Harbin Electric Corporation (HEC)	China	150	2.00	0.25
Dongfang Electric Corporation (DEC)	China	100	1.50	0.25

aging corresponding relationship; and development of modified asphalt with a frost-break temperature of −45 °C, which is the lowest in the world; a proposed design method for asphalt concrete in the impermeable layer with the characteristics of resisting frost-break at low temperatures and flowing at high temperatures; a proposed criteria for choice to use steel-liner or non-steel-liner water-conveyance tunnels at ultra-high pressure condition; new technology of grouting method developed at the ultra-high pressure of 15 MPa; a proposed dynamic modal analysis method for powerhouse vibrating resistance; and achieved dual control on resonant frequency and vibration displacement in the whole process.

6. Underground cavern

Since the 21st century, the hydro-rich southwest alpine valleys have become the main location of hydropower construction in China, and the number and size of underground hydropower stations grow exponentially. The main underground powerhouse caverns at the Three Gorges and Ertan hydropower station reach a depth-to-span ratio of 2.13–2.67, which is far larger than the general range (0.8–1.2) of shotcrete-supported underground cavern. The underground powerhouses of the Longtan, Xiluodu, and Xiangjiaba hydropower stations have spans of more than 30 m, with the largest single-unit capacity reaching 700–800 MW in general, and even approaching 1000 MW at the Baihetan hydropower station, which is under construction. The large-scale complex caverns entailed by these underground powerhouses pose a series of key technical problems to be addressed, in order to drive the fast development of design capacity and construction technologies of underground caverns in China.

The construction of underground caverns follows a dynamic design principle based on the NATM, and emphasizes the integration of design, construction, and monitoring. According to the feedback analysis of monitoring data, the excavation and support design parameters are optimized in a timely manner, and appropriate support measures are taken to ensure the stability and safety of surrounding rock during the construction period. Regarding construction technologies, integrated innovation is favored, covering all aspects of construction. For example: ① The advancement of measurement, precision drilling, and contour blasting technologies makes excavation near perfect; ② the excavation of large caverns under unfavorable geological conditions becomes more mature and stable, owning to the application of steel fibers and polypropylene micro acrylic fibers and to the development of the shotcrete geotechnical anchorage technique and the hierarchical block preference and pre-reinforcement technique; ③ inverted drillers, the open-perfect TBM, and improved sliding technology accelerate the construction of long inclined shafts and deep vertical shafts; ④ the ventilation and smoke dispersion of complex caverns is addressed through the introduction of efficient ventilators and ventilation methods; and ⑤ the widely used "multi-process, multi-layer" practice greatly speeds up the construction of underground caverns [1].

7. Ecological protection

China has paid more and more attention to the research and practice of eco-environmental protection in the process of water conservancy and hydropower development, and has reaped marked results by taking the most stringent measures, including ecological reservoir operation, stratified water intake, and rare fish protection.

Great progress, with fruitful results, has been made in the theoretical study and practical application of ecological reservoir operation in recent years [1]. The objective of ecological reservoir operation has expanded from only a single or a group of species to the whole ecosystem; the controlled object has expanded from the operation of a single reservoir to the integrated operation of a cascade of reservoirs; the affected area has grown from covering only sections and rivers to covering the whole basin; and the period of time has increased from the critical time of the protected target species to a whole year and even to mid-and-long term predictions. Based on the above achievements, academician Hao Wang has launched a study on eco-oriented comprehensive basin dispatchment, and has built a corresponding theoretical and technical system. Since 1999, comprehensive basin dispatchment has been conducted in the Yellow River Basin, in which the joint operation of the Sanmenxia, Xiaolangdi, and Wanjiazhai projects has been performed many times. This process ensures the basic ecological flow of the river and prevents the drying up of the mainstream, resulting in the ecological restoration of estuaries and lower reaches. In addition, with ecological reservoir operation, a number of emergency water-transfer cases have been successfully implemented to restore river ecosystems and maintain river health, such as a water transfer to stem the salty tide of the Pearl River, and a water transfer from Yuecheng Reservoir to Baiyangdian Lake.

With reference to multi-layer shaft-based water intake in the US and Japan, China built water stratification structures as early as the 1960s, in order to address the problem of low-temperature water discharge of a reservoir. In the 21st century, the multi-layer water intake technique, represented by the stop log, has been developed for the construction of high dams of 200 m and 300 m, in order to facilitate temperature control and the safe operation of inlets at high dams. The successful application of this technique can be seen at large hydropower stations, such as Jinping I, Xiluodu, Nuozhadu, and Guangzhao. Among them, the Jinping I Dam with 305 m in height has a range of operating water levels up to 80 m and a stand-alone water inflow of 350 $m^3·s^{-1}$, ranking top in the world in terms of operating water head and flow [12].

Centering on the conservation of natural and artificially bred Chinese sturgeons, Chinese experts have taken a considerable step forward in research on breeding techniques, species protection techniques, and natural population development and migratory movement. To date, a total of five million Chinese sturgeons have been released into the Yangtze River and the Pearl River, providing an important guarantee for the maintenance and conservation of the natural Chinese sturgeon population.

Hydro projects with the requirement of fish protection must be provided with facilities for fish to pass through dams. Chinese experts have studied and formulated the *Guideline for fishway in water conservancy and hydropower project (SL 609—2013)*. The current hydro projects under construction, such as Datengxia at the Pearl River, Xiajiang in Jiangxi, and Laluo in Tibet, are provided with fish ladders. In addition, in order to meet ecological demands for the downstream water, all the current hydro projects under design are specially set with ecological water drainage outlets to ensure that the projects are able to discharged own stream ecological flow during the whole process, from construction to operation.

8. Conclusions

The future playing field of water conservancy and hydropower development in China will be in the west region, where geological conditions are more complicated and the ecological environment is more fragile, and where greater challenges await. Nonetheless, we believe that, based on its existing achievements and continuous innovation, China's hydro poject construction technologies are bound to make new breakthroughs, contributing even more to global water conservancy and hydropower development.

Acknowledgements

This research was substantially supported by the National Key Basic Research Programs of China (2013CB035903, 2013CB036404, 2013BAB06B02, 2014BAB03B04, 2016YFC0401606, and 2016YFC0401609).

References

[1] Jia J, editor. Dam construction in China—a sixty-year review. Beijing: China Water & Power Press; 2015.
[2] Jia J, Li N, Xu Z, Li G, Hao J, Mi Z, et al. Study on key technology for the safety of high CFRDs. Beijing: China Water & Power Press; 2014. Chinese.
[3] Ma H, Chi F. Major technologies for safe construction of high earth-rockfill dams. Engineering 2016;2(4). Accepted.
[4] Niu X. Key technology of the hydraulic structures of the Three Gorges Project. Engineering 2016;2(3). In press. doi: 10.1016/J.ENG.2016.03.006.
[5] Wang R. Key technologies and practices in the construction of ultra-high arch dams of 300 m level. Engineering 2016;2(3). In press. doi: 10.1016/J.ENG.2016.03.012.
[6] Chen H. Anti-seismic research for high concrete dams. Beijing: Higher Education Press; 2011. Chinese.
[7] Xie S, Wu Y, Chen W. New technology and innovation on flood discharge and energy dissipation of high dams in China. J Hydraul Eng 2016,47(3):324–36. Chinese.
[8] Liu Z, Zhang D, Zhang H, Wu Y. Hydraulic characteristics of converse curvature section and aerator in high-head and large discharge spillway tunnel. Sci China Technol Sc 2011;54(Suppl 1):33–9.
[9] Hu C, An C, Chen J, Chen X. Optimum allocation of sediment in the Yellow River. Beijing: Science Press; 2012. Chinese.
[10] Han Q. Non-equilibrium transport of non-uniform suspended load. Beijing: Science Press; 2013. Chinese.
[11] Liu Z, Wu Y, Chen W. Study on key hydraulic issues for the Middle Route Project of South-to-North Water Diversion. Beijing: China Water & Power Press; 2010. Chinese.
[12] Wang H, Su Z, Xie X, Xie W, Xu H. Theory and practice on river basin ecological dispatchment. Beijing: China Water & Power Press; 2010. Chinese.