



Technology and Market Outlook Paper

Smart hydropower

Executive summary

The intensifying global warming and energy crisis are speeding transformation of the world's power systems and energy structures toward low-carbon goals. However, severe challenges will certainly arise due to access of massive amounts of variable and renewable energy into power systems. Establishing a zero-carbon power system is essential to promote sustainable development and to achieve carbon neutrality. But that systematic process will be complicated. It is necessary for system designers to deliberate and balance a safe and steady power supply, acknowledging the rising proportion of new types of energy and keeping a reasonable cost for the entire power system.

As an integral part of a zero-carbon power system, hydropower will serve as a technically mature, widely applied, economical and flexibly regulated power source. Due to different levels of economic development and hydropower resources, countries around the world exhibit different trends in hydropower development. In developed regions like Europe and North America with their huge hydropower stocks, upgrading their systems is an urgent task. Developing countries in Latin America, Southeast Asia and Africa, meanwhile, are in an earlier stage of rapid development of hydropower.

With the global pursuit of carbon neutrality, a zero-carbon power system will have hydropower requirements for greater flexibility, reliability and safety. Hydropower is also facing new challenges brought by climate change, energy market changes and disaster risk on a global scale.

Looking to the future, global hydropower will become smarter. The development of technology, connectivity, and the integration of hydropower and advanced information technology have gradually given rise to a new field of smart hydropower

technology and industries. Smart hydropower will play a crucial role in promoting construction of zero-carbon power systems, and its development prospect is broad and significant. Smart hydropower expands the functions of traditional hydropower, carries forward its advantages and makes up for its shortcomings. It has the characteristics of optimization, comprehensive perception, real analysis, and intelligent control, which together can ensure safety of project construction and operation, improve the stability of the power system, promote an ecological environment, and increase the economic benefits of power generation.

Smart hydropower will provide more efficient and economical energy solutions for countries that rely on hydropower energy. More rational use of water resources and more effective ecological regulation will also promote development of agricultural and ecological economies of basin areas.

Smart hydropower encompasses many technology subfields, altogether covering the entire lifecycle of hydropower projects. Remarkable progress has been made in smart hydropower, with a large number of key technical achievements and a series of new applications for their use. However, smart hydropower still faces technical challenges, and it will be necessary to further improve the depth of integration with smart technology to find solutions.

Smart hydropower is aligned with long-term progressive goals of a sustainable global society: no poverty, zero hunger, gender equality, clean water and sanitation, affordable and clean energy, decent work and economic growth. These objectives, the UN's eight Sustainable Development Goals (SDGs), also encompass industry, innovation and Infrastructure, responsible

consumption and production, and climate action, all of which are closely linked. Smart hydropower can effectively contribute to achieving these SDGs.

Standards play an important role in promoting the development of smart hydropower. They can promote construction of a technical system framework, accelerate progress in various technical directions in the field of smart hydropower, and promote coordination and unification of technologies. Currently, the standardization of smart hydropower is in its infancy, and there is no global consensus on its concept and scope. The main work is still in basic research aspects, including technical framework research, identifying missing technical standards, and researching standard systems. Problems include uneven development of standardization in various technical directions and a lack of support from certain technical institutions in certain areas. Therefore, it is urgent to develop the standardization of smart hydropower and its related supporting fields, to drive rapid development of smart hydropower and its related industries, and to broaden the intelligent boundaries of the power industry.

This report is structured as follows:

- Section 1 reviews the current situation of global hydropower development and puts forward the definition and scope of smart hydropower.
- Section 2 outlines and analyzes the main driving forces for the development of smart hydropower from eight aspects.
- Section 3 summarizes the characteristics and functions of smart hydropower.
- Section 4 provides an overview of the key technologies and technical challenges in the various specialized areas covered by smart hydropower.
- Section 5 gives 17 representative application cases in the field of smart hydropower.

- Section 6 analyzes the standardization status and standardization demands of smart hydropower related fields.
- Section 7 summarizes the current situation of smart hydropower technology and the prospects for its development and standardization.

Hydropower will continue in the current stage of rapid development into the future, with the scale of project start-ups and production continuing to increase. In order to cope with global climate change and the energy crisis and build a zero-carbon power system, highly smart hydropower construction and upgrading has become the main development direction for the foreseeable future. Smart hydropower development has profound implications for all IEC stakeholders, from power suppliers to equipment manufacturers and service providers, to power system end-users. Understanding the definition and scope of smart hydropower, and of its key technologies and challenges, as well as the status and needs of standardization, as detailed in this report, will ensure that IEC remains at the forefront of the evolution now underway.

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List of abbreviations

Technical and scientific terms

AHP	analytic hierarchy process
AI	artificial intelligence
BESS	battery energy storage system
BIM	building information modelling
CAE	computer-aided engineering
CBM	condition-based maintenance
DIM	dam information model
DNN	deep neural network
E&M	electromechanical
FCEM	fuzzy comprehensive evaluation method
FM	facilities management
FSC	full size converter
GFS	Global Forecast System (NCEP)
GIS	geographic information system
GNSS	global navigation satellite system
GPS	global positioning system
GRAPES	Global/Regional Assimilation and Prediction System (China)
HSS	hydraulic steel structure
IFS	Integrated Forecasting System (ECMWF)
IoT	Internet of Things
IT	information technology
ITIL	information technology infrastructure library
ITSM	information technology service management
LCOE	levelized cost of energy
O&M	operation and maintenance
PID	proportional-integral-derivative (control)
PLC	programmable logic controller
PU learning	positive and unlabelled learning

PV	photovoltaic
QC	quality control
R&D	research and development
RCC	roller compacted concrete
ROV	remotely operated vehicle
SC	subcommittee
SDG	sustainable development goal (UN)
SLAM	simultaneous localization and mapping
TC	technical committee
TL	transmission line
UAV	unmanned aerial vehicle
UWB	ultra-wide band
WG	working group

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**Organizations,
institutions and
companies**

ACER	Agency for the Cooperation of Energy Regulators (EU)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ECMWF	European Center for Medium-Range Weather Forecast
IAHR	International Association for Hydro-Environment Engineering and Research
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IHA	International Hydropower Association
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCOLD	International Commission on Large Dams
MSB	Market Strategy Board (IEC)
NCEP	National Centers for Environmental Prediction (US)
NIBS	National Institute of Building Science (US)
WMO	World Meteorological Organization

Glossary

autocorrelation function

a mathematical tool used in signal processing and statistics to analyze the degree of similarity between a given time series and a lagged version of itself over successive time intervals

basin-level cascaded reservoirs

a series of reservoirs constructed along a river flow within a basin, connected by their geographical and hydrological links, forming a cascaded or sequential system

Dempster-Shafer Evidence Theory

also referred to as theory of belief functions, is a general framework for reasoning with uncertainty

digital twin

virtual model mirroring a physical object for real-time monitoring and analysis

ecological flow

the quantity of water required to maintain the health, stability, and biodiversity of river, lake, or other aquatic ecosystems

ecosystem health

the ability of an ecosystem to maintain a balanced state in its structure, function, and composition, and to adaptively respond to external disturbances, thereby preserving its long-term stability and ongoing biodiversity

hydrological monitoring

the systematic observation and analysis of the various components of the hydrological cycle, such as precipitation, evaporation, surface runoff, and groundwater flow

intelligent construction

in a broad sense, it refers to a general term of theories, methods, workmanships and technologies that integrate sensing technology, communication technology, data technology, construction technology, project management and other knowledge to sense, analyze, control and optimize the safety, quality, environmental protection, progress, cost and other contents of hydraulic structures and their construction activities, in order to promote safe, high-quality, green and efficient construction

in a narrow sense, it refers to the construction activities that transform the thinking, experience and behaviour of human construction activities into computational analysis and learning models and achieve autonomous automation

intelligent construction system

based on the intelligent construction support system, the intelligent construction system integrates intelligent construction technologies and intelligent construction management into a unified task collaborative information system

intelligent grouting

utilizing intelligent equipment and technology, core parameters of grouting construction processes can be acquired. The intelligent grouting system is capable of real-time analysis and automatic parameter adjustments by integrating three-dimensional geological models. This enables intelligent control of grouting processes, automatic configuration of slurry, and pressure-flow adjustments throughout the entire grouting process

intelligent temperature control

by employing intelligent temperature control equipment and data analysis platforms covering the entire concrete production chain, intelligent analysis and control of concrete temperature throughout the entire process of construction, which can perform a variety of tasks, such as real-time perception of spatial and temporal variations in concrete temperature, autonomous decision-making on temperature control measures, early warning analysis, and evaluation of temperature control effectiveness

Internet of Things

a framework of interconnected devices, sensors, and systems, enabling communication, data collection, and analysis

membership theory

membership theory, a core concept in fuzzy logic, primarily addresses issues of uncertainty. Within a fuzzy set, the degree to which each element belongs to a certain set can be represented by a value between 0 and 1, known as the membership degree

multi-source big data

large datasets collected from various sources or channels

parallel computing technology

a computation technology that allows multiple processors or computing nodes to work simultaneously to perform complex computing tasks

space-air-ground integrated technology

a comprehensive technological system that integrates space technology, aviation technology, and ground technology

water environment

the bodies of water on the Earth's surface and underground, including rivers, lakes, reservoirs, wetlands, groundwater, and the surrounding biological, ecosystem, and physical conditions connected to these water bodies

Section 1

Introduction

1.1 Background

Global warming and the growing energy crisis have accelerated the pace of low-carbon reform of the energy structure of the world's power system. Energy is the core of this problem and the key to solving it. It is crucial to achieve the emission reduction target stipulated in the Paris Agreement on Climate Change, promote the transition of power systems to renewable energy rapidly and extensively, and build a zero-carbon power system dominated by renewable energy [1]. Hydropower, a traditional yet clean and low-carbon source of power, boasting remarkable economic benefits and excellent regulatory capabilities, occupies a pivotal role in the construction of a zero-carbon system. Furthermore, hydropower already has an important position in the global energy system. In 2021, the global hydropower energy output accounted for about 16% of the global energy output, with a gain of another 3.7% in 2022 [2] [4].

Hydropower is one of the cleanest power sources, with a low greenhouse gas emission intensity compared to other energy types, and the lowest composite cost of renewable energy. Despite relatively high initial investment in hydropower development, it has a long service life and remarkable low operation and maintenance (O&M) cost, making it economically competitive compared with other energies currently available on the market. Hydropower has the highest energy conversion rate of all known energy types, with an efficiency of more than 90% under design conditions, and its reliability and flexibility are so high that it can be operated in a hybrid manner with such intermittent renewable energies as photovoltaic (PV) and wind power, helping the

power system to deal with the serious challenges posed by large-scale connection to intermittent renewable energies.

In recent decades, hydropower development has emerged as a pivotal contributor to national economic and social development and has rightfully taken its place as a cornerstone in global energy advancements. According to International Waterpower & Dam Construction, the global theoretical reserve of hydro energy resources stands at a staggering 41 309.5 billion kWh/year, with a technically feasible capacity of 11 754.9 billion kWh/year. This capacity is distributed across the world, with Asia holding a significant 50%, South America 18%, North America 14%, Africa 9%, Europe 8%, and Oceania 1%. Since the turn of the century, global hydropower development has consistently demonstrated a growth trend. The International Hydropower Association (IHA) forecasts that by 2027, the worldwide installed capacity of hydropower will surpass 1 450 GW [3]. As of 2022, Figure 1-1 illustrates the distribution of global installed hydropower capacity, highlighting China's prominent position with a 29.71% share, followed by Brazil with 7.87%, the United States 7.30%, Canada 5.94%, and Russia 4.01% [4].

In the contemporary era, the varying degrees of economic progress, hydro energy resources, and the stages of development have given rise to diverse scenarios in the development of hydropower across the globe. These scenarios are primarily characterized by the advancement of hydropower projects, the transformation and upgrading of existing hydropower stations, as well as the research and engineering demonstration of innovative hydropower technologies. Developed

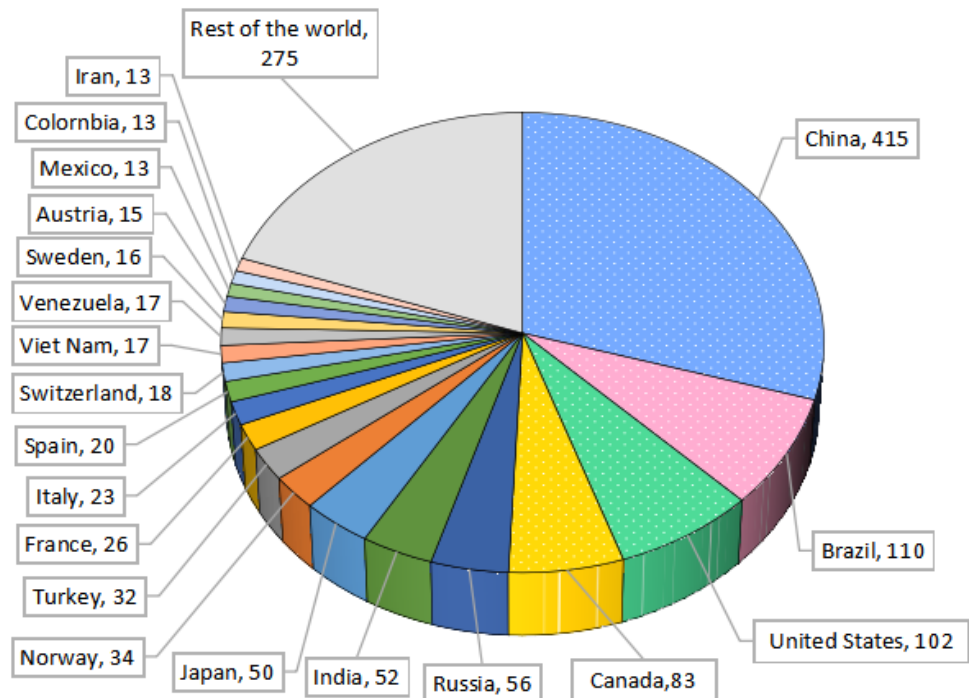


Figure 1-1 | Installed capacity of hydropower (GW)

nations in Europe and North America boast a significant number of hydropower stations, necessitating urgent efforts towards transformation and upgrading. Studies reveal that by 2030 over half of the world's hydropower stations will undergo modernization and upgrading. Meanwhile, hydropower in certain developing countries in Latin America, Southeast Asia, and Africa is experiencing a phase of rapid growth, exemplified by nations like Brazil, India, Myanmar, and Cambodia [5]. The most vibrant hydropower development is observed in rapidly expanding economies and emerging markets, particularly in East Asia and the Pacific, followed closely by developed water resource countries in South America.

As the world strives towards carbon neutrality, the zero-carbon power system imposes increasingly stringent demands on hydropower in terms of flexibility, reliability, and security. Internationally, hydropower is confronted with novel challenges arising from climate change,

shifts in the energy market, and disaster risks. Simultaneously, traditional hydropower exhibits certain shortcomings. For instance, there is a lack of comprehensive online monitoring of hydroelectric units and real-time, effective fault diagnosis. Additionally, hydroelectric unit operations and maintenance, as well as overhaul, often require a significant amount of manpower. Dam inspections are still particularly reliant on manpower, resulting in difficulties in fully utilizing monitoring data, insufficient risk identification and warning capabilities, and limited means to address natural disasters. Effectively evaluating the long-term safety of large underground powerhouses is challenging because of geological changes, high ground stress, long-term groundwater seepage, earthquakes and other factors. There is also a lack of effective evaluation methods and comprehensive control measures for the terrestrial and aquatic ecological conditions of cascaded hydropower stations.

With the ongoing technological revolution, the rapid evolution and convergence of information technology are propelling traditional hydropower towards intelligent development. In order to mitigate safety risks, cut labour costs, and enhance production efficiency, hydropower must also embrace smart technologies. Given the current global landscape of hydropower development, it is anticipated that existing hydropower stations worldwide will undergo significant intelligent transformations in the future. New hydroelectric units will also leverage innovative intelligent technologies, positioning hydropower as a pivotal force in driving the energy revolution and safeguarding energy security. To cater to the development and demands of the zero-carbon power system, innovation in hydropower technology is paramount, giving rise to smart hydropower. A substantial number of hydroelectric units in developed nations require transformation and upgrading, while new hydroelectric units in developing countries present construction needs. Consequently, there exists a vast market demand for smart hydropower solutions.

Furthermore, based on preliminary statistics and analysis, smart hydropower exhibits a profound connection with the eight UN SDGs. These goals include poverty eradication, hunger elimination, clean water and sanitation, affordable and clean energy, climate action, sustainable production and consumption, industry, innovation, infrastructure, decent work and economic growth. The globalization of smart hydropower holds the potential to significantly contribute to global ecological governance and the achievement of UN SDG objectives, particularly those pertaining to carbon neutrality and the establishment of a zero-carbon power system.

1.2 Definitions and scope

Smart hydropower, a blend of traditional hydropower with up-to-date information and data processing technologies, is distinguished by its comprehensive sensing, real-time analysis, intelligent control, and constant optimization. This innovative approach spans the entire lifecycle of hydropower projects, from, design, planning, engineering construction, operations to maintenance. Central to its objectives are ensuring the safety of hydropower projects, optimizing the utilization of water resources, preventing and mitigating reservoir disasters, and safeguarding ecological health. Smart hydropower aims to establish safe, reliable, economical, efficient, green, environmentally friendly, and harmonious modern power facilities. As such, it serves as a crucial underpinning for the low-carbon transformation of the energy and power industry and a vital component of the “zero-carbon” new power system.

The scope of smart hydropower encompasses both its core components and their extensions. The main body focuses on intelligence throughout the entire lifecycle of hydropower. This encompasses various stages such as investigation, planning, design of hydropower projects, intelligent construction, intelligent production of hydropower plants, intelligent regulation and utilization of water resources, safety monitoring, risk prevention and control, eco-environmental monitoring, protection, evaluation, pumped storage, as well as power generation of hydro-wind-solar hybrid projects. Additionally, the extension includes intelligence related to functions such as flood control, drought management, navigation, and irrigation, further broadening the application and impact of smart hydropower.

Section 2

Driving factors and demands

2.1 Climate change

The world faces numerous challenges stemming from climate change that demand urgent attention and action. Climate change is marked by widespread and rapid alterations in the global atmosphere, oceans, cryosphere, and biosphere, coupled with the increasing frequency of extreme weather events. According to the *Globe Climate 2011-2021* report issued by the World Meteorological Organization (WMO) in 2023, the decade from 2011 to 2020 was the warmest on record, with devastating impacts on food security and human mobility. Climate change also poses significant threats to human health, economic growth, and biodiversity. The emissions of greenhouse gases resulting from human activities are undoubtedly the primary cause of climate change, and there is now an international consensus on the need to address the environmental and climatic risks associated with global warming [6].

Boosting the level of terminal electrification and enlarging the share of non-fossil power are crucial strategies in addressing climate change and attaining carbon neutrality. Smart hydropower holds the potential to foster the utilization of non-fossil energy sources. According to the *Global Energy Assessment: CO₂ Emissions in 2022*, published by the International Energy Agency (IEA), global CO₂ emissions linked to energy surpassed 36.8 billion tons in 2022, with the power and heat sectors being the primary contributors to this increase. Hence, the low-carbon development of the power sector is pivotal in mitigating climate change. Hydropower is the backbone of low-carbon power

generation, supplying nearly half of the world's low-carbon power. It has surpassed nuclear power by 55% and exceeded the combined output of all other renewable sources, including wind, solar PV, bioenergy, and geothermal energy. Smart hydropower can facilitate wind-solar-hydro hybrids and enhance the consumption of non-fossil power through meticulous management and regulation of water resources.

The advancement of smart hydropower can significantly enhance the ability of hydropower stations to tackle climate change. Climate change's impact on hydropower is primarily due to alterations in precipitation, evaporation, and runoff patterns, which influence water availability and discharge, ultimately resulting in a slight overall decline in hydropower potential. According to relevant research, Latin America and South Asia are expected to experience a notable decrease in hydropower potential, while Western Europe, the Middle East, and North Africa are likely to see a more moderate reduction [7]. Smart hydropower can mitigate these impacts by anticipating and responding to extreme weather events such as droughts and floods through real-time monitoring, remote control, data analysis, and other functionalities.

2.2 Energy crisis

Geopolitical conflict is the main reason for the energy crisis, and the shift of fossil energy to renewable energy is an important direction. The energy crisis is one of the most urgent challenges in the field of global development. In this context, the green, low-carbon transformation of energy

has become an important direction. *The World Energy Outlook 2023* released by the IEA predicts that by 2030 the world energy system will have significant changes, clean energy technologies will play a greater role, and the share of renewable energy in the global power structure will be close to 50%. From the perspective of investment, the proportion of investment in non-fossil energy continues to rise. In 2022, the proportion of non-fossil energy in global energy investment was expected to increase by 60%.

The development of renewable energy is threatened by the stability of key mineral supply, but hydropower has only a low demand for those minerals. The energy system based on renewable energy technology is different from the traditional energy system. Renewable technology consumes more mineral resources, and the IEA's *World Energy Outlook Special Report* points out that the overall demand for mineral resources by clean energy technology will quadruple by 2040. The demand for lithium will increase by 42 times, graphite by 25 times, cobalt by 21, nickel by 19, rare earth by 7, copper by 2.7, and silicon by 2.3. However, the global distribution of mineral resources related to energy is highly concentrated, and the speed of capacity construction is far from meeting the development demands for the medium-term and long-term new energy industry, so the supply and demand relationship continues to be under tension. But hydropower is not easily threatened by shortage of key minerals because of its low material strength and limited demand for those minerals.

Hydropower is susceptible to seasonal and climatic influences, but smart hydropower can improve the safety and stability of hydropower stations. With new energy power generation, large-scale grid connection, increasing peak-valley load difference and development of long-distance transmission technology, hydropower will play an ever more important role. As a hydropeaking and energy storage power, hydropower offers

advantages like flexible startup and fast regulation, guaranteeing the grid's safe and stable operation.

Building on traditional hydropower, smart hydropower can be upgraded and then developed with wind, solar and other new energies in a coordinated trans-time-and-space manner. Together, they can achieve a wide range of hybrid energies that promote consumption of intermittent clean energy, alleviate peak-valley load contradictions of the system and provide a strong guarantee for the safe, stable operation of large-scale new energies connected to the power system. Such hybrids can play an important role in dealing with the energy crisis. Smart hydropower will play a more and more important role in global energy transformation under the premise of ensuring energy security in the future.

2.3 Government policies

Vigorously pursuing the development of renewable energy is a crucial avenue towards achieving the transition to clean and low-carbon energy systems. Various nations have already declared their renewable energy development objectives. In 2021, the European Union announced its intention to raise the proportion of renewable energy in primary energy from 32% to 40% by 2030. Meanwhile, the United States refreshed its "Rebuild Better" budgetary framework, committing to investing a staggering USD 550 billion in clean energy projects over the next decade. China, too, has explicitly stated its goal of increasing the proportion of non-fossil energy consumption to approximately 20% by 2025, with the proportion of energy output derived from non-fossil sources reaching around 39%. These initiatives demonstrate a global commitment towards harnessing renewable energy sources and fostering a sustainable energy future.

Smart hydropower excels in facilitating the transition to clean, low-carbon energy systems while simultaneously ensuring energy security. In recognition of smart hydropower's potential,

a series of policies aimed at promoting its development have emerged.

From the engineering construction perspective, China's policy emphasizes the acceleration of digital design and construction for hydropower and other traditional power plants, along with their intelligent upgrading. This involves conducting technical research on the intelligent planning and design, construction, operation, and control of hydropower projects.

Moreover, from the perspective of sharing technological advancements, China's policy mandates strengthened information disclosure related to water conservancy science and technology, as well as intelligent water conservancy. This includes the timely publication of digital twin basins, digital twin water conservancy projects, and the progress of intelligent water conservancy construction. Such measures aim to foster rapid technological progress within the industry.

2.4 State of the technology

The Internet of Things (IoT) and cloud computing technology serve as the fundamental backbone for data acquisition and computational support in smart hydropower systems. IoT integrates a diverse array of information sensing devices and networks, enabling seamless interconnection between people, machines, and objects regardless of location. This interconnection provides the crucial data foundation for the subsequent intelligent construction.

In the realm of hydropower, IoT efficiently acquires and summarizes data from a range of sensors, automated construction equipment, and monitoring devices. This comprehensive sensing, reliable transmission and intelligent processing ensure a holistic understanding of the system's operations.

Meanwhile, the vast, heterogeneous, and multi-dimensional data generated by numerous IoT

terminals present significant challenges. Cloud computing technology addresses these challenges by offering efficient data storage, computation, and analysis strategies. By harnessing distributed resources, it solves large-scale computational problems, providing computational support for the construction of advanced intelligent systems.

Therefore, the current advancements in IoT and cloud computing technology offer reliable and efficient capabilities for data sensing, aggregation, storage, analysis, and processing in smart hydropower systems. These technologies represent a pivotal means for advancing hydropower networking and realizing its full potential.

Digital twin technology offers a comprehensive, all-inclusive, lifecycle-spanning dynamic digital mapping solution for smart hydropower, providing a panoramic view of all elements and operations.

Digital twin technology serves as the digital representation of smart hydropower, leveraging physical models, sensor updates, and operational history data to create a dynamic digital replica of the real-world system. This technology integrates multi-physical quantities, multi-scale and multi-probability simulation processes, ensuring a precise reflection of the real-world ontology across its entire lifecycle on a digital virtual platform. Real-time status and other pertinent information are continuously transferred to the digital twin, dynamically capturing every aspect of the system's operations.

Currently, digital twin technology has found extensive application in intelligent manufacturing and engineering construction and played a pivotal role in the implementation of smart city initiatives and smart water conservancy. Within the realm of smart hydropower, this technology harnesses historical and real-time data to comprehensively and dynamically reflect the lifecycle of hydropower projects, from design and production to operations and maintenance.

Moreover, digital twin technology can be seamlessly integrated with big data, artificial intelligence (AI) algorithms, and models to simulate hydropower projects, conduct safety monitoring, and enable intelligent management and decision-making. This integration represents a crucial step towards digitizing hydropower, enhancing its efficiency, safety, and overall performance.

Big data and AI technology possess the capability to mine and integrate diverse information, offering multi-dimensional intelligent decision-making support that is tailored for smart hydropower. This allows for more informed and effective decision-making, enhancing the efficiency and sustainability of hydropower systems. Big data technology is centred on the meticulous cleaning, structuring, and integration of vast amounts of multi-dimensional and multi-form data, followed by its comprehensive analysis. In parallel, AI technology specializes in learning from vast datasets, generating intelligent decision-making capabilities, and enhancing decision-making proficiency.

These two technologies are mutually permeable, fostering a symbiotic relationship that propels each other forward. When confronted with the voluminous and diverse data generated by real-time hydropower IoT systems, big data technology comes into play. That technology is utilized to integrate and optimize this data, simulating and verifying the operational status and predicting future trends of hydropower stations. This is achieved by leveraging extensive historical data and selecting appropriate data mining, AI algorithms, and models. The objective is to streamline the intelligent management of hydropower stations, assist in decision-making and enhance the speed and efficiency of emergency responses. Big data and AI technologies serve as the backbone for improving the quality and utilization of hydropower data, representing the core technologies that power the smartification of hydropower.

2.5 Market demand

The hydropower industry is undergoing a transformation towards digital and intelligent development. Concepts such as the energy internet and integrated energy services have emerged, suggesting that Internet-based thinking will supersede traditional industrialized production and linear scale-benefit mentalities. Instead, it will become the guiding principle for efficient, healthy and sustainable enterprise development. While the automation systems of traditional hydropower stations suffice for current operational needs, they suffer from various limitations due to developmental stages and technological constraints. The construction and management of traditional systems tend to be fragmented, resulting in significant standardization gaps. Furthermore, the coordination between power grids and power plants remains inadequate. Moreover, the intricate information exchange among these systems coupled with low software consistency and excessive hardware duplication pose significant challenges to the enhanced application, management, and maintenance of the system. This results in complexities in intelligent decision-making and diminished efficiency. As industrialization and informatization continue to converge, it is imperative for traditional hydropower stations to undergo a transformation towards digitalization, networking, and intelligence. This transition will lead to a more rational allocation of energy resources and a substantial enhancement in energy utilization efficiency.

The hydropower industry faces a pressing need for equipment upgrading as hydroelectric units globally reach their twilight years. Worldwide, the average operational lifespan of hydropower stations is about 40 years. In North America, it is nearer to 50 years, while in Europe it stands at around 45 years. Furthermore, the average lifespan of decommissioned hydropower stations is approximately 60 years [8]. Given these statistics, it is evident that equipment upgrading in the

hydropower industry is not just a recommendation but a necessity to ensure the continued efficient and safe operation of these vital energy sources. To guarantee the seamless operation of hydropower stations, it is imperative to upgrade and modernize these aging facilities. This ensures their sustainable contribution to power security in the upcoming decades.

By integrating the latest information technology through modernization, we can not only prolong the lifespan of power generation assets but also enhance the utilization efficiency of hydropower stations. This will broaden their operational scope, enabling them to meet the demands of faster ramp rates and frequent startups and shutdowns. It will also aid hydropower in adapting to the increasingly intricate requirements of the current and future high proportion of renewable energy power systems, thereby continuing to provide invaluable and dependable energy services. Relevant research indicated that in 2021, Latin America and Asia urgently required the modernization of over 15 GW and 6 GW of installed capacity, respectively. To achieve this, a total investment (cost) of USD 8 billion was estimated to be necessary [9]. Such investment will play a pivotal role in enhancing the efficiency and sustainability of these hydropower stations, ensuring their continued contribution to the global energy landscape.

The commercial demands generated by the reduced operating costs of a smart hydropower economy are significant. Similar to wind power and solar PV power, hydropower boasts no fuel costs and an optimal power generation efficiency exceeding 90%, making it the most efficient of all varieties of power plant-based energy generation. This efficiency, coupled with the decreased operational expenses, makes hydropower a highly attractive option for meeting commercial energy demands. According to the statistics from the International Renewable Energy Agency (IRENA), the global levelized cost of energy (LCOE) for hydropower has exhibited a gradual upward trend

in recent years, increasing from 0.042 USD/kWh in 2010 to 0.061 USD/kWh in 2022, a cumulative increase of 47%. It is noteworthy that the cost per kilowatt hour for new hydropower stations still remains lower than that of new thermal power projects in the region, accounting for 96% of the comparison [10]. This highlights the economic viability of hydropower even amidst rising costs. The surge in utility costs can primarily be attributed to the increasingly challenging site conditions for new projects and the escalated installation expenses resulting from supply chain inflation.

The factors above have been the main drivers behind the rising costs of hydropower. However, digitization offers a promising solution by laying the groundwork for predictive maintenance strategies that can significantly reduce operational and maintenance costs. According to relevant research estimates, digitizing global hydroelectric units has the potential to boost annual energy output by 42 TWh, which translates to approximately 1% of the annual output. Furthermore, the annual savings in operational costs could amount to a staggering five billion US dollars [11]. This underscores the transformative potential of digitization in enhancing the efficiency and cost-effectiveness of hydropower generation.

2.6 Construction of zero-carbon power systems

The construction of a zero-carbon power system has given rise to a heightened demand for flexible resources. A notable transformation within this system lies in the integration of a high proportion of renewable energy sources at the power generation end, along with the decentralized connection of novel loads such as extensive distributed power and electric vehicles at the power consumption end. Consequently, the power system is confronted with significant challenges, including escalated instability risks, diminished moment of inertia, and complexities in maintaining supply-

demand balance. The prerequisite for these recent changes is the continuing necessity for increased flexibility in resources to uphold the reliability of the power grid. According to projections by the European Union Agency for the Cooperation of Energy Regulators (ACER), Europe's demand for intra-day, weekly, and annual flexibility resources is anticipated to reach 120 billion, 96 billion, and 80 billion kWh respectively by 2025, with further growth to 170 billion, 130 billion, and 86 billion kWh respectively by 2030 [12]. This underscores the urgent need for enhancing the flexibility of power systems to meet the evolving demands of the energy sector.

Smart hydropower offers exceptional flexibility and resilience to power systems, catering to the escalating demand for adaptable resources in the future. While traditional hydropower excels in providing a stable and controllable output, economic efficiency, and clean, low-carbon characteristics, meeting the fundamental requirements of a zero-carbon power system, smart hydropower elevates these capabilities. It orchestrates the joint operation of hydroelectric units with uncontrollable generating units, such as solar PV and wind power, capitalizing on the hydroelectric units' robust regulating capabilities. This not only enhances the flexibility and resilience of the power system but also optimizes its power generation benefits. Depending on the size of the reservoir, hydropower, offers remarkable flexibility in regulating power generation across various time scales, encompassing both long-cycle (spanning months and seasons) and short-cycle (within seconds or throughout the day) response capabilities. In comparison to coal-fired power, hydropower demonstrates a faster regulation speed for short cycles. For long cycles, hydropower stands out as the primary power type that will provide monthly regulation capabilities to the power system in the foreseeable future. Prominent examples of this include the Longyangxia hydro+solar hybrid project

(850 000 kW), which was grid-connected in 2015, and the Yalongjiang Hydropower Kela Phase I PV power plant (1 000 000 kW), the world's largest and highest-altitude hydro-solar hybrid power plant, grid-connected in 2023. Both these projects demonstrate how smart hydropower can effectively promote the consumption of renewable energy sources.

Despite its potential, smart hydropower faces numerous scientific and technical challenges in contributing to the construction of a zero-carbon power system. The widespread adoption of smart hydropower stations necessitates further optimization in areas such as operation control and maintenance management [13]. Key considerations include the following: balancing the relative sizes of smart hydropower and uncontrollable power capacities; developing hybrid control methods for seamless automation of smart hydropower, wind power, and solar PV power generation, which involves addressing the intricacies of short-term dispatch models and optimizing load allocation; and conducting stability analyses of integrated power generation systems encompassing hydropower, wind power, and solar PV power. Overcoming these challenges is crucial for harnessing the full potential of smart hydropower in achieving a sustainable and carbon-neutral energy future.

2.7 Work safety and disaster prevention and mitigation

The internal and external factors that impact the safety of hydropower operations are diverse and multifaceted. Among the most immediate internal factors are the personnel and equipment involved. Statistics reveal that human factors account for 80% of accidents, highlighting the crucial role of personnel and equipment safety management in enhancing the overall safety of hydropower stations. External factors, on the other hand, are typically related to changes in the external

environment, such as floods, earthquakes, geological hazards, and dam failures in upstream reservoirs. Other potential hazards include dam cracking due to terrorist attacks, spillway damage, landslides, and large-scale seepage incidents. To address these challenges, traditional safety management practices focus on fostering a strong safety awareness among personnel, providing safety skills training, and ensuring effective team safety management. Other essential components of a comprehensive safety strategy are quality management of equipment, including O&M activities, condition-based maintenance (CBM), and the establishment of long-term safety management and emergency response systems. By attending to these areas, significant enhancements can be made to the safety of hydropower operations and mitigate the risks associated with both internal and external influencing factors.

Smart hydropower offers a more efficient approach to site work safety control. Leveraging information technology, it enables proactive, preventive, comprehensive, and closed-loop control over the entire work safety process within hydropower enterprises. This facilitates the establishment of inherently safe hydropower systems. By deploying an intelligent monitoring network, smart hydropower reduces the labour intensity of site personnel while enhancing turbine operating efficiency. It also establishes equipment reliability management centres that assess the condition of equipment, providing precise guidance for daily inspection and maintenance. This not only enhances equipment safety and reliability but also cuts down on operation and maintenance costs through early failure warnings and diagnostics. Additionally, intelligent management standardizes work behaviours, boosts employee efficiency, and sharpens emergency response capabilities. The construction of intelligent power plants elevates safety levels on production sites, shifting the paradigm towards unmanned operations, restricted access power plants, and integrated operation and inspection practices.

Smart hydropower offers a highly accurate approach to disaster prevention and mitigation management. Leveraging precise weather forecasting, it integrates monitoring of water systems and debris flow warnings to enhance safety measures. By deploying collection equipment upstream, real-time data such as water level, discharge, over-warning thresholds, and meteorological simulations are collected and analyzed. This comprehensive monitoring of water conditions, meteorology, and geological hazards enables hydropower stations to formulate more efficient power generation plans, favourable trading strategies, and innovative reservoir management techniques. Moreover, smart hydropower provides precise and scientific decision-making support for rapid response, timely warnings, and coordinated regulation during extreme weather or unexpected accidents. It serves as a powerful tool and emergency plan for disaster prevention and mitigation, minimizing the losses caused by natural disasters such as landslides, earthquakes, and floods. In essence, smart hydropower not only enhances operational efficiency but also significantly improves safety and resilience in the face of potential disasters.

2.8 Environmental protection

Hydropower technology has made significant strides in environmental protection. While the environmental impacts of hydropower stations cannot be entirely eliminated, proper planning and management are crucial to minimize adverse effects. Fortunately, existing hydropower technology has already demonstrated its effectiveness in safeguarding the environment. The water storage capacity of dams not only supplies additional water for irrigation, drinking, and industrial use, but also regulates floods and generates economic benefits through afforestation efforts. These benefits serve to offset the environmental costs associated with inundated areas resulting from dam construction [14]. Furthermore, the ever-

growing implementation of fish passage facilities, the introduction of fish-friendly turbines into operation, and the development of ecologically restorative hydropower are all making significant contributions towards environmental protection.

Smart hydropower holds the potential to further enhance environmental protection efforts. To guarantee the sustainable development of this renewable energy source, the integration of information technology into all aspects of hydropower project construction, operation, and management is crucial. Strengthening ecological and environmental protection is paramount, necessitating the improvement of an eco-environmental protection measure system that prioritizes prevention, mitigation, and restoration. In terms of hydrological management, smart hydropower can leverage big data analysis and model prediction to assess the evolving trends and impacts on the water environment, thus facilitating the formulation of scientifically sound strategies for power plant siting and construction. In terms of ecological restoration, smart hydropower can enhance comprehensive monitoring and evaluation of ecosystem conditions. By flexibly regulating water flows and levels, it can restore the natural ecosystems of wetlands and river channels, thereby boosting biodiversity and ecological functions within water areas. Additionally, with regards to habitat modification, smart hydropower can conduct basin-wide ecological monitoring to identify crucial fish habitats such as spawning grounds, baiting areas, and overwintering sites. Scientific planning of fish habitat protection zones is essential to minimize the adverse impacts of hydropower construction.

Section 3

Characteristics and functions

3.1 Characteristics

3.1.1 Comprehensive sensing

The investigation, design, and construction process of hydropower projects is complex. The numerous electromechanical (E&M) equipment and hydraulic buildings/structures need to be monitored. Traditional sensors analyze and calculate data by using voltage and electric current flow after data transmission and conversion. This process involves single-dimension data analysis, and the information gained is relatively simple. With the development of technology, the implementation of intelligent monitoring using smart sensors and intelligent monitoring technology will be one of the key innovative technologies of smart hydropower.

a) Pose sensing technology. The pose state is the fundamental information reflecting the operational state of mechanical equipment during the construction and production/operational period of hydropower projects. It visually characterizes the operating status of mechanical equipment. Real-time sensing of mechanical equipment pose under outdoor working conditions can be realized through high-precision global navigation satellite system (GNSS) positioning. Technologies such as simultaneous localization and mapping (SLAM), laser radar, machine vision, ultra-wide band (UWB) and other technologies have been researched and implemented in indoor and tunnel environments conditions. Accurate analysis of construction machinery during the construction period and of intelligent inspection equipment, lifting equipment and other mechanical equipment during

the production period are realized by the application of the above technologies. This provides a foundation for the implementation of intelligent analysis and control.

b) Smart sensors. Unlike traditional sensors, smart sensors can conduct information processing. They can provide precise data typically unattainable through soft sensors or correlation measurements. Smart sensors can acquire, process, and exchange data because they are equipped with microprocessors. Compared with traditional sensors, smart sensors have three advantages:

- 1) High-precision information acquisition can be realized through software technology
- 2) Some degree of programming automation capabilities
- 3) Diverse functions

At present, smart sensors have been widely applied in robotics, industry, aerospace, agricultural production, and other fields. In the field of robotics, it can sense various external phenomena through human-like senses and provide corresponding response actions. In industrial production, it can quickly detect the product quality indicators (viscosity, hardness, composition, colour, surface smoothness, taste, etc.) that traditional sensors cannot identify, enabling online control.

c) Soft sensing technology. For the data measured by sensors, measurable variables (auxiliary variables) related to the estimated variables can be selected based on optimization criteria to build a mathematical

model. The model uses measurable variables as inputs and estimated variables as outputs. Thus, it can complete the estimation of important process variables (becoming dominant variables) that cannot be directly measured with computer software. This is a soft sensing technique, a new technology developed in the field of detection and process control in recent years. It provides a means for detecting and controlling variables that either cannot be directly detected with sensors or are difficult to detect. It is of great significance to production automation and product quality control, and it is an important focus for the research and development of detection technology and process control. The control mode will transition from traditional proportional-integral-derivative (PID) control to whole system optimization control, and eventually to advanced AI control through the implementation of the technology in power production. Furthermore, it will transition from single sensor measurements to correlation soft sensing and then to the intelligent measurements based on big data.

d) Image acquisition. The equipment in the power plant is complex, and there is a large amount of equipment. Potential hazards and equipment defects can be identified through equipment monitoring and manual inspections in traditional mode. However, this mode relies on personnel experience and a sense of responsibility. Defects may not be found promptly if there is a lack either of experience or of a sense of responsibility. Stable operation of equipment can be affected. In recent years, with the use of intelligent robots, unmanned aerial vehicles (UAVs), and cameras, intelligent inspection has gradually replaced traditional methods. Intelligent robots and UAVs with fixed or mounted cameras, along with other devices for high-precision data acquisition, capture images of equipment, environment, and

personnel at power plants. These images are then analyzed using AI technology for intelligent identification, enabling the assessment of equipment status, environmental conditions, and personnel behaviour. Replacing manual labour, robots, UAVs, fixed cameras, and other smart devices can conduct daily patrols and inspections based on pre-planned tasks. They can navigate and inspect based on predefined patrol points or temporary detection points issued during the inspection. Full coverage of information monitoring and comprehensive detection can be achieved.

e) Voiceprint collection. The vibration noise of power equipment is closely related to its mechanical structure, and it is an important indicator for analyzing the equipment's operational status. Machine sound can reflect the status of the equipment. For equipment parts or components with state changed due to wear, aging, or other reasons, the characteristics of their voiceprint signal will change accordingly. The advantage for judging equipment operating status by extracting characteristics from the power equipment's voiceprint signals is to realize online monitoring and non-contact detection at the same time. The sensor layout is also more flexible, low-cost, and electromagnetic signal free while collecting signals, and it will not interfere with the normal operation of the equipment. The information reflected by a voiceprint can be used as part of the equipment status to carry out equipment health diagnoses through intelligent voiceprint recognition technology.

3.1.2 Real analysis

a) Data mining. Data mining analysis technology comes from combining massive data with computing power. The technology addresses the challenges of collecting, storing, calculating and analyzing large volumes of data. It is used to advantage in various aspects of life, such as

in medical care, transportation, e-commerce, finance, and weather forecasting. It provides great convenience in people's lives. With hydropower, the application of data mining analysis technology mainly involves data analysis, diagnosis, mining, and processing in construction and production arenas. With the continuous development of technology, it can diagnose equipment failures, optimize equipment maintenance and achieve spontaneous judgment of equipment degradation. Data mining can thereby achieve operational optimization, economic management, and typical fault self-recovery through closed-loop control.

b) Image analysis. Image analysis technology is widely applied in various aspects of life. Image analysis technology is used in face and vehicle recognition, text extraction, image search, etc. Real-time tracking of personnel working on-site and monitoring mechanical operation status, as well as the construction environment, is essential during the construction of a hydropower plant. Regular inspections are necessary to assess appearance of machinery and equipment, equipment status, and production environment. Manual inspection is carried out on a regular basis in traditional ways. However, after the application of image analysis technology, analysis can be conducted for real images and video streams of different scenes by using mobile robots with fixed or mounted cameras. An AI analysis model can be built to judge abnormal state, replacing traditional manual inspection, and to achieve a full range of real-time analysis and feedback. Furthermore, it can not only save on manpower costs, but also avoid untimely discovery of defects from a lack of technical experience and sense of responsibility among personnel.

c) Digital twin. The application of digital twin technology can map the real-world environment in virtual space. Different from simulation technology, digital twin technology will need at least three elements, i.e. the modelling of real-world objects, the changing data about the objects and the environment, the dynamic characteristics of the modelling of the objects and the environment changed with the changing data. In both construction and operation of hydropower plants, the analytical model library and knowledge base are constructed and the digital twin platform for the construction and operation of hydropower plants is established. Its establishment is on the basis of comprehensively sensed data. Through the comparative analysis of analogue and real measurements, the analytical models of forecast, warning, preview (rehearsal), and plan are developed, to realize the intelligent analysis and strategy generation of the construction and production state of the hydropower plants.

3.1.3 Intelligent control

Intelligent control is a control mode that involves intelligent information processing, intelligent information feedback, and intelligent control decision-making. Intelligent control is a high-level application for real-time analysis and represents an advanced stage of control theory development. At present, intelligent control has been widely applied in the construction and production of hydropower plants.

a) Intelligent control during construction of hydropower plants. The construction process of a hydropower plant is complex. There are numerous construction links, the operating environment is harsh, and high construction quality is essential. Based on real analysis results, intelligent control of construction operations can be achieved by conducting intelligent research and development (R&D)

and upgrading relevant equipment used in the construction of hydropower plants. While that is going on, a feedback analysis on the site's operating environment and conditions is conducted to ensure operational safety and construction quality.

Current research and applications mainly include the following:

- Intelligent control of foundation works involves managing foundation grouting, deep overburden consolidation, cut-off wall construction, and more. The aim is to minimize human involvement in the construction process, using unmanned and autonomous systems that ensure construction quality in getting the hydropower plant operational.
- Intelligent control of earth and rock filling and concrete pouring. It involves intelligent blasting, intelligent transportation, intelligent filling, and unmanned operations of earth and rock block surfacing, intelligent concrete pouring, intelligent temperature control of concrete, etc.
- Intelligent installation of E&M and hydraulic steel structures (HSSs). Intelligent control is utilized for precise installation of E&M and HSSs by taking intelligent tools and equipment as the core components.
- Safety feedback control during construction period. To carry out feedback control for construction, flood control and other measures based on various safety monitoring and hydrometeorological monitoring data during the construction period. This is done by analyzing the real-time data and prioritizing operational safety.

b) Intelligent control of hydropower plants during operational period. There is a significant amount of equipment during the operation period involved. The intelligent

control for hydropower plants during operation period includes mainly:

- Intelligent optimization and control of hydroelectric units. The online monitoring system in hydropower plants can conduct operational status analysis for hydroelectric units, governors, and more. And it can provide emergency warning reports, improve emergency decision-making of operators, and reduce the failure rate by comprehensive sensing and real analysis. It can also carry out intelligent control for the start and stop control, intelligent monitoring, and equipment operation optimization of the hydroelectric unit.
- Intelligent decision-making assistance. There are many decision-making assistance complementary systems in smart hydropower stations to enhance the productivity of the power plants and reduce maintenance costs. The reservoir operation system can also provide intelligent decision-making analysis according to the requirements of meteorology and flood control to fulfil all operational regulation indexes.
- Optimization and control of multi-energy hybrid projects. Intelligent control can realize the coordination of hydropower, wind energy, solar energy, and other power generation resources. This ability is due to their interactive and friendly operation characteristics, which together ensure the safety and stability of power grids. At the same time, intelligent control can realize the coordinated dispatching of cascaded hydropower stations and pumped storage power stations in basins and improve the functions of hydropower plants in hydro-peaking, frequency modulation and emergency reserve.

3.1.4 Optimization and improvement

Smart hydropower is a dynamic evolutionary process. With the development of intelligent technology, the goal is to enhance the construction and operation intelligence of hydropower plants by integrating cloud computing, big data, IoT, AI and other technologies. New intelligent application scenarios are constantly realized to enhance the intelligence of hydropower plants. Constant improvement is also a general characteristic of smart hydropower.

In view of current development trends of smart hydropower, optimization and improvement are represented mainly as follows:

a) Integration. At present, most of the information on the O&M levels of hydropower groups in China is at a passive stage or transitioning from a passive to active service stage. With the increasing enterprise integration and intensive management requirements, the scale and complexity of information systems continue to rise. The stringent security situation about information, and the original information O&M management model, support tools, and passive service mode have not adapted to the current requirements of information O&M. It is necessary to learn from and integrate advanced ITIL/ITSM management standards and best practices, conduct an integrated design for information O&M system, transform the O&M mode, and establish the supportive, driving, and leading role of the information system for enterprise development.

The specific integration trends are as follows:

- For O&M management. To establish an O&M system that complies with the operation rules of centralized information systems; to form a unified O&M model and O&M management standards at the group level; to abandon the situation of separate O&M and develop a coordinated and efficiency working model that integrates the group headquarters and the grass-root units, with up-and-down linkage and clear definition of responsibilities.
- For O&M and technical services. The information system is a large and complex system, involving various equipment, platforms and application systems. System O&M will not only solve specialized information technology problems but also business application problems. System O&M is required to provide integrated technical services.
- For O&M support platforms. Overall monitoring and management of information systems can be achieved through the construction of an integrated and intensified O&M support platform. That platform can collect all kinds of alarm data, performance data, and configuration data in a timely manner. It can conduct integrated and unified analysis, query, report, and display, helping O&M management staff to conveniently and effectively locate system problems and shift O&M mode from passive support to active service. It can also complete the processing of events for all kinds of service requests and events by pre-defining an event management process and by achieving the standardization of information O&M management through the system platform. These objectives are accomplished through the organic combination of personnel, technology, and processes/operational procedures/standardized workflows. Building an integrated data support platform is necessary to connect the isolated data islands in all production and operation links and to carry out data management to meet the above requirements. The key technologies for this include efficient distributed database systems, structured

and unstructured data management, real-time data and relational data management, and unified data standards. A data platform integrating data acquisition, storage, processing, and analysis is built to mine the data value through the establishment of open and unified data standards.

- Building an integrated data support platform is necessary to connect the isolated data islands in all production and operation links and to carry out data management to meet the above requirements for seamless data integration, real-time analysis and pro-active O&M management. The key technologies for this include efficient distributed database systems, structured and unstructured data management, real-time data and relational data management, and unified data standards. A data platform integrating data acquisition, storage, processing, and analysis is built to mine the data value through the establishment of open and unified data standards.

- b) Unmanned/less-manned.** For improvement of construction and operation of hydropower projects, current construction and operation of intelligent power plants are gradually developing towards unmanned and less-manned directions. Unmanned or less-manned mode is based on comprehensive sensing, real analysis, and intelligent control. It comprehensively integrates various business demands and realizes unmanned and less-manned operations for special complex environments, using automation control as the main means. It can thereby comprehensively reduce the demands for human resources and improve operational accuracy in real-time. At present, research and application have been carried out in some scenarios, and unmanned and few-manned application scenarios will be further expanded to comprehensively

improve the level of site control along with the continuous development of informatization, intelligence and automation.

c) Self-learning and continuous evolution.

Numerous intelligent models are utilized for perception, assessment, early warning, and control in the construction and operation of hydropower projects. With the progress of artificial intelligence technology, the self-learning framework can optimize the parameters and structure of the intelligent model using the multi-modal data accumulated during the actual operational process. This enables the continuous evolution of the intelligent model and continues to strengthen the performance of each link and module, thereby elevating the overall intelligence of the system.

3.2 Functions

3.2.1 Improving the stability of hydropower plants and power systems

Smart power plants can achieve real-time monitoring and control of operating status in intelligent power plants through the application of comprehensive sensing, real analysis, intelligent control and other technologies. They can in a timely way detect and deal with equipment failures and improve the safety and stability of hydropower stations. Installation of intelligent operation equipment and terminals allows for a fully sensed operating status of the equipment, and by making full use of big data technology, deep mining and integrated self-diagnosis for key parameters of equipment operating status can be carried out. Using models and a data library, maintenance strategies and schemes can be independently developed, enabling forecasting, warnings, preview (rehearsal) and planning analysis of equipment running status.

After completion of equipment maintenance, the intelligent equipment can carry out self-

inspection analysis and independent assessment to ensure that the equipment can operate safely and normally, meeting work needs. At the same time, integration of smart hydropower plants with the Internet, cloud computing, big data and other technologies, allows real-time monitoring, fault diagnosis and maintenance management for hydropower stations. This integration supports remote monitoring and management of hydropower stations, enabling improvement of the operating stability of the hydropower plants, and preventing adverse conditions to ensure the stability of the power system.

Smart hydropower aims to provide a stable power system with hydropower as the main regulator. It can build a regional intelligent power plant dispatch model, reducing the influence of unstable power sources such as wind and wind on the power system, and promoting development of hydro-wind-solar hybrid projects.

3.2.2 Ensuring safety in construction and operation of hydropower projects

In the construction of hydropower projects, smart hydropower construction needs to proceed under the premise of safety in the difficulties of a complex environment, with numerous risk sources and extremely tough construction safety controls. At present, intelligent construction and intelligent site have been widely applied in the construction of hydropower projects. It can bring about:

a) Safety control of construction machinery operation. Posture perception, image recognition and other means are used to comprehensively perceive the location and operation status of machinery in the construction plant. That enables real-time analysis and warning of scenarios such as spatiotemporal cross-conflict and dangerous areas near construction machinery to comprehensively reduce the operation risk.

b) Safety control of operators. Image recognition, real-time positioning, wearable detector and other means are used to comprehensively perceive the location, physical state and operation status of personnel in the construction plant. That permits carrying out real-time analysis and warning of scenarios such as cross conflict with the construction machinery, stay in dangerous areas, failure to wear safety helmets and safety ropes and abnormal body state. A special area access mechanism for operators would be established to prevent non-designated personnel from entering the operation area, effectively reducing the safety risk to operating personnel.

c) Safety control of slope and underground engineering. Real-time analysis is conducted for slope location, for the geological safety hazards in the surrounding area of underground works and for timely warning of an abnormal conditions based on safety monitoring data from the engineering construction area, reducing the impact on operating equipment and personnel of rock bursts and slope and underground cavern collapses. Based on the intelligent sensing technology of underground engineering operating environment, real-time sensing of harmful gases, dust and other parameters of underground works can be also achieved, preventing impact on personnel and equipment.

d) Flood safety control. Real-time analysis for flood risk status of the construction area can be conducted through sensing results of hydrometeorological conditions and provision of real-time feedback on the emergency and risk avoidance scheme, ensuring the safety of personnel and materials.

In terms of hydropower project operation, safety control includes mainly reservoir area and slope, flood control, E&M equipment operation and

hydraulic buildings/structures, smart hydropower can realize:

- a) **Safety control of reservoir area and slope.** Water levels in hydropower plants change greatly, especially frequent are water level changes at pumped storage power stations. Real-time sensing and analysis feedback for the safety and deformation status of reservoir areas and slopes can be realized by providing monitoring devices for water level, deformation displacement, large-scenario deformation observation, allowing relevant precautionary measures to be taken in a timely manner.
- b) **Flood safety control.** It can conduct real-time analysis for flood risk status, and real-time regulation for the downstream release based on the sensing results of hydrometeorological conditions, guaranteeing the safety of the hydropower plant itself and the safety of people's properties downstream.
- c) **Safety control of equipment operation.** The real-time operation state sensing and analysis for various types of equipment can be realized in hydropower plants based on intelligent sensing equipment, to timely find and deal with abnormal cases and ensure operation safety of equipment.
- d) **Safety control of hydraulic buildings/structures.** Real-time monitoring for deformation and seepage status of water retaining buildings, water releasing buildings and waterway, and power generation buildings can be carried out, and abnormal cases can be dealt with in a timely manner to achieve safety risk prediction and warning decision-making of buildings.

3.2.3 Improving economic aspects of hydropower generation

Intelligent sensing, analysis and dispatching in smart hydropower plants can reduce the operation risk of power plants, make full use of hydro energy

resources, and effectively enhance the economic efficiency of hydropower generation.

- a) **Operation risk control.** Through effective control of engineering safety during the operation period of hydropower plants, it can realize effective prevention and control of risks of to ensure the stability of hydropower generation
- b) **Efficient dispatching of hydropower plants.** A regional-overall intelligent power plant dispatching model can be built with relevant results of electric power system integrated through the sensing of hydrometeorological conditions of hydropower plants. This reduces the impact of wind, solar PV and other unstable power on the electric power system and promotes development of hybrid hydro-wind-solar projects.

3.2.4 Promoting environmental friendliness of hydropower projects

Intelligent construction for engineering construction and operation process can effectively improve the environmental friendliness level of hydropower projects Here are the main aspects of this improvement :

- a) **Dust and noise control in construction areas.** A great deal of earth and rock excavation and filling work is generally required for hydropower projects, and the dust and noise control directly affect the surrounding environment. The explosive cartridge for one-blast excavation in the rock quarry and the ambient humidity can be controlled accurately by the application of intelligent control technology, effectively reducing dust and noise.
- b) **Intelligent equipment-based low-carbon construction.** Intelligent analysis and control of the operation path and mode of the construction equipment can effectively reduce equipment carbon emission by shortening its

operation time. The large-scale application of electrified intelligent equipment can further reduce carbon emissions and air pollution.

c) Water ecological health control during construction and operation period.

Intelligent wastewater treatment measures can be developed to realize zero wastewater discharge in the construction period and the ecological regulation in operation period.

d) Intelligent regulation of reservoir water level during operation.

Fully considering the upstream and downstream water supply relationship and the water supply flow for power generation and so on can achieve reservoir water level regulation and effectively improve the accuracy for judging upstream and downstream water levels.

3.2.5 Others

Intelligent coordinated operation (regulation): Intelligent coordinated operation is carried out to comprehensively enhance the efficiency of smart hydropower. It takes full consideration of upstream and downstream flood safety, energy output control, navigation and flood control, water supply for irrigation and requirements for water level landscape based on comprehensive sensing of upstream and downstream hydrometeorological conditions.

Section 4

Key technologies and challenges

4.1 Investigation, planning and design of hydropower projects

4.1.1 General

Modern water conservancy and hydropower projects are characterized by large scale, wide scope, complex layout, large investment (cost), long development and construction cycles, many participants and potential impacts on the ecological environment. Therefore, it is necessary to comprehensively control safety, quality, progress, investment (cost) and the ecological environment. The investigation, planning and design of hydropower projects are characterized by complex natural environments, many disciplines, long planning cycles, high systematic requirements, and various social and environmental constraints. Therefore, successful hydropower projects can be guaranteed by thorough and systematic planning, analysis and decision-making.

As water conservancy and hydropower projects are beginning to be built in severe cold, high-altitude and high-seismic intensity zones, hydropower projects face a lot of challenges in terms of investigation, planning and design. In investigation, they are facing such difficulties as insufficient geological exploration equipment in complex conditions of super-deep underground spaces, high-precision geological modelling, and insufficient monitoring, assessment and forecasts for geological risks. In planning, they face such challenges as a break in the assumption of hydrological consistency under changing climate conditions, the difficulty of obtaining hydrological data in data deficiency regions. In design, they face a series of technical problems including

treatment technology for dam foundations placed on deep and thick overburdens; flood release and energy dissipation protection technology under high head and large discharge condition; anti-seismic technology for high dam and high slope, deep underground works and rock deformation; and stability control technology for high and steep slopes.

An important way to achieve high quality, high efficiency and safe construction projects is by strengthening technical breakthroughs, R&D of new materials, new technologies, new workmanships and new equipment, and by using digital, intelligent construction means to enhance the construction capacity of projects. At present, the investigation, planning and design of hydropower projects are transforming from traditional survey to integration of space-ground- information, one single project to cascaded projects of the basin, project priority to ecological environment priority, single energy to integration of plant-grid-load-storage and multi-energy hybrids.

With the rapid development of information technology, data has become a new production resource. The informatization, digitization and visualization technologies have been adopted in the engineering investigation, design and planning, which has greatly improved the construction level and efficiency. At present, building information modelling (BIM) technology has been widely used in design, construction and operation management. New technologies such as Big Data, Cloud Computing, IoT, Beidou Navigation, and 4S will further promote the efficiency and intelligence of design, construction and operation.

The digital-based whole lifecycle management system of hydropower projects and the integrated information system of basins will also be widely promoted in the industry soon.

4.1.2 Key technologies

a) Plant-grid-load-storage integration technology.

Plant-grid-load-storage integration refers to the power plant, power grid, power load and storage system organically integrated together to form a comprehensive energy system. This integration forms the inherent requirements for power industry to adhere to the system concept and to achieve the objective need for high-quality development of the power system. Acceleration of the building of clean, low-carbon, safe and efficient energy systems and enhancement of the clean energy utilization level and power system operating efficiency tend to promote coordinated development of the regional plant-grid-load-storage and optimal allocation of power resources.

In the steady progress toward a zero-carbon power system, understanding of the plant-grid-load-storage integration has gradually deepened and unified, and is no longer confined to specific projects. The research focus is shifting from project to systems, indicating that the system of power plant, power grid, power load and power storage can be referred to as plant-grid-load-storage integration, with attention not only to all links of the system integration of the power plant, grid, load and storage, but also to a number of links of the power plant and power grid, such as local integration.

In terms of specific planning, the plant-grid-load-storage integration can be big or small in size, large to the provincial, regional, municipal and county levels, and small to the park or building level. On a big scale, the plant-grid-load-storage is presented as a

regional power system. Multi-energy hybrid integration, renewable energy integration, and basin integration are specialized forms of this integration. To realize plant-grid-load-storage integration, these forms are driven by the power plant, supplemented by grid and load, and combined with regional power grid planning and load development needs. On a smaller scale, integration projects focus more on practicality to achieve a coordinated configuration of power plants and loads within a small scope (if necessary, with supplementary support from the external grid).

In power plant-grid-load-storage integration, each link and each component have a role within the system. The power plant side is often based on the characteristics of different power outputs and the analysis of power plant hybrid possibilities of various types to achieve a multi-energy hybrid, enhancing the energy utilization rate and the ability to supply power. The power grid side will be realized through implementation of transmission and transformation projects, either to facilitate the power plant side and the load side of the two-way linkage to achieve power supply and power demand balance in a local area, or to participate in a wider area of electric optimization to ensure power consumption and reduce non-power consumption. The load side needs to adapt to the construction of new power systems, from the traditional “plant with the load” to “plant-load interaction,” to enhance the load response capability. Energy storage can improve the peak regulation capacity of a system according to the output characteristics of the power plants and the peak regulation demand of the system. It does so through the allocation of electrochemical energy storage, pumped storage, and other means.

Plant-grid-load-storage integration technology, can realize the efficient use of energy,

the reduction of carbon emissions, the improvement of stability and reliability of power system, and the promotion of the large-scale application and popularization of renewable energy.

- b) New investigation technology for hydropower projects.** The most commonly used survey techniques in hydropower projects include engineering geological mapping, engineering geological exploration, engineering geological testing, hydrogeological testing, laboratory and site geotechnical physical and mechanical properties testing, engineering geological and hydrogeological monitoring and observation. At the preliminary investigation stage of hydropower projects, the traditional investigation methods are mainly used and combined with information and intelligent technology to obtain the geological data of hydropower projects. Geological survey technology of hydropower projects has made progress and breakthroughs like remote sensing technology and computer and information technology have been made in the traditional exploration technology.

Currently, remote sensing technology, Geographic Information System (GIS) technology and Global Positioning System (GPS) have been widely used in the entire geological investigation of hydropower projects. Application of remote sensing technology in hydropower project investigation has obvious advantages. It can not only obtain a broad vision, a large amount of information, a strong sense of independence, and quick data acquisition, but it can also effectively improve the effective coverage area and the efficiency and accuracy of surveying for hydropower projects. On a micro level, it can employ the digital photography geological logging technology and 3D laser scanning technology. GIS technology can build a more scientific GIS, provide a large amount of data and information support, and effectively process a large amount

of data and information. GPS technology can identify the location of geological surveying and customize a reasonable and scientific construction plan according to the local geological conditions; it also provides such advantages as fast survey speed, convenient operation, and high accuracy of results.

At present, computer and information technology have mature applications including numerical computation, computer mapping, office automation, database, 3D visualization, numerical simulation, etc. The development of computer technology in engineering geology applications will allow 3D visualization, network collaboration, expert intelligence and integration. Looking to the future, with the development of information technology and network technology, geological survey technology in hydropower projects will continue to move towards digitalization, networking, and intelligence to provide technical support for more complex mega project in the future.

- c) Continuous breakthroughs in dam-building technology.** In recent years, a series of major breakthroughs have been made in high-performance concrete materials, rapid construction of high concrete dams, temperature-controlled anti-cracking of massive concrete dams, modification of impervious earth materials, anti-extrusion breakage of concrete faces, utilization of soft-rock materials for dam construction, connecting structures for high mixed dams, earthquake fortification for high dams, intelligent rolling for high embankment dams, treatment of ultra-deep overburden foundations, control of the deformation and stability of ultra-high slopes, and high-head flood release and protection of energy dissipation, etc. During this period, new technologies of rockfill concrete and cemented sand and gravel dam construction were also invented, which have been widely used in the world.

The key technologies that need to be successfully developed for dam construction technology in the future include the following:

- foundation treatment with a depth of more than 500 m in areas with a seismic intensity of Class IX,
- construction technology of deep-buried large-diameter tunnels and large-scale underground caverns, and
- technology of hazard mechanism and risk prevention and control of large-scale landslides in the basin.

d) Design and manufacturing of large hydroelectric units. The hydroelectric unit is the core equipment of the hydropower station converting hydro energy into electric energy, and the design and manufacturing of large hydroelectric units are the centralized reflection of hydropower equipment level. Today the world's main turbine types include Francis, Axial flow, Tubular and Pelton.

In terms of conventional hydroelectric units, the design and manufacturing capacity and level of hydroelectric units have made one stage-by-stage leap after another. Thanks to the unremitting efforts of project builders and researchers, a series of innovative achievements have been made in electromagnetic pole winding, high-efficiency cooling, thrust bearing, HV insulation, high-strength materials, manufacturing of key components of hydroelectric units, etc. Technical standards for the design, manufacture, installation, measurement and control of megawatt-class hydroelectric units have also been formulated.

In terms of reversible pump turbine units, the concept of pumped storage power station was first known in the 1920s. A hydraulic pump is used to pump water to a high storage tank, where it then releases the hydro energy to

generate power through the turbine when electric power is needed. The efficiency of such hydroelectric units was relatively low, but they laid the foundation for subsequent developments. Since then, the pump turbine unit has gone through the pump turbine type in the 1950s, the dual-unit complementary type in the 1970s, the dual-chamber type in the 1980s, and the variable speed control type from the 1990s to the present. With the continuous progress of technology and growth in demand, pump-turbine units feature high head, large capacity, and high speed, which constitute significant breakthroughs in design and manufacturing. In the future, with the rapid development of renewable energy and the intelligent demand for power systems, pumped storage power station units are expected to further improve efficiency, flexibility and sustainability.

e) Digital design. At present, the construction of hydropower projects governed by mechanization, informatization, and digitization. In recent years, with the rapid development of cloud computing, big data, IoT, AI and other modern information technology, data technology and sensing technology, the construction of hydropower is moving towards digitization and intelligence. In the development of hydropower projects, digital and intelligent technologies have been widely used in design, modelling, simulation, optimization and data management. By means of systematic, in-depth research on digital intelligent collaborative design of hydropower projects, many digital and intelligent design outputs of hydropower projects have been developed, which encompass the entire investigation and design process and all types of hydropower projects.

By combining the extension of its own industrial chain and the demands of the market and the owners, the investigation

and design contractors continue to promote the R&D of the whole management lifecycle of hydropower projects and systems at construction and operation management stages. For example, the comprehensive application of informatization means based on BIM technology has brought obvious results, and BIM + virtual reality has enhanced the experience of the design environment. BIM + GIS realizes the deep integration of design products and geographic information space. BIM + mobile application has expanded the application timeliness and application field of design products. BIM + database technology integrates design information data, forming a digital design product delivery platform with traceable, searchable and convenient information. The delivered design information model can also further transfer to the construction and operation management stages, creating more application value.

In addition, management for quantity of works, virtual construction, fine control of engineering construction and other aspects have also achieved phased research results, including 3D geological modelling system, 3D design system of slope, auxiliary system of large volume 3D reinforcement drawings, virtual simulation construction interaction, system document collaborative editing system, 3D digital delivery system. Together these advancements have laid a good foundation for the investigation and design of hydropower projects and for the integrated information management of engineering construction.

In sum, the digital and intelligent design technology provides an efficient, accurate and reliable method to design and optimize hydropower stations. It can improve design efficiency, reduce costs, enhance performance of hydropower stations, and provide support for O&M of hydropower stations. With

continuous development of digital technology, the digital design technology will continue to evolve, innovate and assist in making hydropower projects smarter, more efficient and safer.

4.1.3 Challenges

Hydropower is an important part of the power system, characterized by clean, efficient, stable and renewable energy. The development of hydropower is not only due to the need to drive development of new energy, optimize the energy structure, and reduce carbon emissions, but also the need to achieve comprehensive utilization of water resources, while ensuring hazard prevention and mitigation and ecological protection. At present, the hydropower resources to be developed are mostly in the severe cold, high altitude, high seismic intensity areas, where the special physical geographic environment, complex regional tectonic background, fragile ecological environment and other complex construction conditions increase the difficulty of planning, investigation and design. The main technical challenges facing the hydropower construction in the new era are as follows:

- Building technology of dams on deep and thick overburden
- Serious threats and challenges to project safety from strong earthquakes
- Large-head, high-discharge flood release and dissipation and protection technology
- Adaptation of headrace tunnels in active faults
- High-performance concrete with high frost and carbonation resistance
- Design and manufacture of hydroelectric units with large-head and high capacity
- Eco-environmental protection of water conservancy and hydropower projects

- Risk prevention and control of basin systems and safety management of the whole lifecycle of projects
- Digital survey, plan and design for hydropower projects

4.2 Intelligent construction of hydropower projects

4.2.1 General

With the technological innovations of the industrial revolution, engineering construction also changed. Innovative tools and construction methods gradually liberated humans from heavy and dangerous work. Taking the development of water conservancy and hydropower projects as an example, the history of technology mainly falls into four stages:

- The stage of manpower and animal power, dominated by hand-drawn design and manual management, and representative projects such as the Xinjiang and the Finicky Dam
- The stage of mechanization and automation, during which computer technology and large construction machinery began to be widely used in construction operations. The offline professional management mode with the participating entities as the main body gradually formed, and representative projects are the Hoover Project and the Three Gorges Project
- The stage of digitization, during which BIM/GIS, 3D designs, numerical simulation, and other technologies were widely used in the construction of water conservancy projects, forming an information construction management mode based on digital dams; representative projects are the Nuozhadu and the Xiluodu
- The stage of intelligence, during which IoT, cloud computing and AI began to be applied in engineering construction while facing

complex engineering environment and building challenges. Real-time, online, comprehensive and intelligent analysis and utilization of data generated by engineering construction activities became the internal requirements of engineering construction. Efficient, high-quality, green, and safe engineering construction based on data-driven approaches has become a new pattern, as represented by China's Baihetan and Wudongde projects

In a detailed sense, intelligent construction of hydropower projects refers to theories, methods, workmanships and technologies that integrate sensing technology, communication technology, data technology, construction technology, project management and other knowledge to sense, analyze, control and optimize the safety, quality, environmental protection, progress, cost and other contents of hydraulic structures and their construction activities, so as to promote safe, high-quality, green and efficient construction. In a broad sense, it refers to construction activities that transform the thinking, experience and behaviour of human construction activities into computational analysis and learning models that achieve automation.

4.2.2 Key technologies

From digital construction to intelligent construction development of hydropower projects, there is a technology spectrum consisting of intelligent temperature control, intelligent rolling, intelligent vibration, intelligent grouting, intelligent vibroflotation, intelligent safety, intelligent E&M and a series of other intelligent construction technologies, which all continue to enrich, improve and iteratively upgrade.

- a) **Intelligent simulation.** Intelligent simulation includes construction progress simulation and dam states simulation. Construction progress simulation mainly uses monitoring data – including stress, strain, deformation,

temperature, seepage and seepage pressure – to duplicate the main parameters of the dam foundation and concrete. It simulates the whole process of the dam, from the first block of concrete to the impoundment operation of the reservoir to provide a panoramic reproduction of the stress, temperature, displacement and seepage fields, along with other service states, from the construction period of the dam to its operation period.

The simulation study of a dam states makes comprehensive use of the basic theories and methods of engineering geology, mechanics, hydraulics, materials and other disciplines, and adopts such comprehensive means as foundation test, site monitoring and feedback, theoretical analysis and numerical simulation to study the key technical issues. It provides a simulation of the whole process of the dam's construction and the evaluation of the overall safety of the dam.

b) Intelligent transportation and pouring. The transportation process of dam concrete refers to the process of unloading concrete from the batch plant into the transportation tool and delivering it to the block surface through horizontal and vertical conveyance. The traditional manpower-based management of loading, transfer, unloading, the running status and collision risk of cableway, transportation time and other key information often lacks efficiency in a non-controlled state. There are construction quality and transportation safety risks. In view of the above problems, the integration of satellite positioning technology, radio frequency identification technology, radio frequency communication technology, ultrasonic ranging technology and other IoT technology, the intelligent control technology of the concrete transportation process of dams is called for. Supported by data collection and state monitoring, this integration allows real-time display of the concrete transportation process and a matching analysis and intelligent

feedback control of the loading-transferring-unloading process.

c) Intelligent vibration. Spreading and vibration are key processes of concrete pouring; its quality directly affects the safety and stability of long-term operation of the concrete dam. The traditional quality control of spreading and vibration is mainly achieved through construction self-inspection and site supervision, which is limited by subjective factors such as the personnel's energy and experience, and a lack of quantitative assessment. Quality inspection is mostly the control after the fact and has a high cost. In order to improve the spreading and vibration efficiency and guarantee the construction quality, intelligent vibration was proposed. To ensure the vibration quality of concrete block surface, intelligent vibration uses IoT technology, AI technology and other means, working through real-time comprehensive sensing of vibration information, intelligent analysis of concrete vibration quality and feedback control.

d) Intelligent rolling. Intelligent sensing of rolling parameters is based on digital rolling monitoring and sensing technology that integrates accelerometers, UAV, computer vision and other new sensing and measuring equipment and technology to realize accurate sensing of construction information in the rolling operations. Intelligent sensing provides a data basis for intelligent evaluation of rolling quality and intelligent feedback control of the rolling process. In the feedback control of intelligent rolling, unmanned rolling technology is another major breakthrough, which has changed the traditional manual control of roller operations, reducing human intervention in the operation process through the underlying control mechanism and intelligent control algorithms, thus further improving the operation accuracy and efficiency.

- e) Intelligent temperature control.** With intelligent temperature sensing-analysis-control as the core, comprehensive methods including theoretical analysis, numerical computation, and on-site monitoring are used to propose the theoretical methods, mathematical models, and key technologies of intelligent monitoring and control of crack prevention of mass concrete, effectively managing the temperature of concrete. Forming the monitoring method for the elements of temperature control of mass concrete, the analysis method takes the thermodynamic parameter inversion of mass concrete, the evaluation of temperature control effect, the prediction of water flow, and the simulation of temperature stress and transverse joint opening, along with temperature control measures based on the theory of intelligent cooling.
- f) Intelligent grouting.** The research on intelligent grouting can be divided into pre-grouting, grouting, post-grouting and grouting systems. In the pre-grouting research, the relationship between the volume of cement slurry injection and hydraulic conductivity of the cracked rock mass of the dam foundation based on the fractal theory will provide the basis for the intelligent grouting closed-loop control theory of real-time collection, dynamic analysis and intelligent feedback. In the grouting research, the theory of automatic grouting control is used, and numerical simulation is used to simulate and control the uplift deformation. In the post-grouting research, the grouting quality is evaluated by using water pressure experiments, core information, geological radar and acoustic wave detection. An intelligent analysis and feedback control method of grouting effect allows post-control of the grouting quality through the intelligent prediction and analysis of the grouting effect, synthetic evaluation and feedback control.
- g) Intelligent vibroflotation.** The traditional vibroflotation method has many shortcomings, such as incomplete parameter perception, imprecise construction control, non-intelligent construction equipment, offline quality management, and inadequate evaluation systems. The application of intelligent vibroflotation technology is urgently needed to overcome these shortcomings, ensure the construction quality of vibroflotation foundation improvement, improve management efficiency, and guarantee construction safety. Intelligent vibroflotation utilizes modern information and communication technology, construction technology, advanced equipment, and project management methods to digitally control and continuously optimize the construction process. It achieves a comprehensive perception of construction data, real-time analysis of construction status, intelligent control of construction processes, continuous optimization of construction parameters, and online management of construction quality.
- h) Intelligent ventilation.** Based on the demands for ventilation and dust removal in underground powerhouses and caverns during the construction of hydropower projects, a real intelligent construction ventilation system based on the integration of “sensing-calculation-evaluation-control-management” is established for real sensing, real-time calculation, scientific evaluation, closed-loop control and efficient management. It effectively improves the intelligence level of ventilation control and provides support for creating a safe, efficient, green, low-carbon and intelligent ventilation environment.
- i) Intelligent E&M engineering.** The intelligentization of E&M engineering covers the stages of design, manufacturing, installation and operation. At the manufacturing stage, with the development of intelligent manufacturing, intelligent robots are used in

the welding and other manufacturing links of hydroelectric units. At the same time, due to the irregularity of large hydropower components, robot welding is also used in some special components and hydroelectric unit positions. For example, there are a large number of welds in semi-closed spaces, special positions where welding is difficult, and positions that cannot be welded manually, the robot can achieve high-quality welding. At the installation stage, the application of equipment intelligence technology has been further deepened. The integrated application of intelligent technology and the promotion of standardized construction in the installation of hydropower equipment have made a qualitative leap in the efficiency and accuracy of equipment installation, realized the orderly connection of all links, and significantly improved the management level of engineering construction.

- j) **Intelligent construction management technology.** The intelligent construction management of hydropower stations is centred on the management of construction such as safety, quality, environmental protection, schedule and cost. It focusses on performance domains such as stakeholders, team, development methodology and lifecycle, planning, project work, delivery, survey and uncertainty. The general goal is to maximize the long-term overall value of the large hydropower stations. By using digital and intelligent technology, the project management elements can be performed in a real-time interactive and collaborative manner. This approach enables real-time, on-site, in-kind, real people, real data management, allowing intelligent construction activities can be sensed, analyzed, predicted, and controlled. As a result, high quality, safe, green, efficient and economic project construction performance can be achieved, creating value throughout the entire lifecycle of the project. An intelligent

construction management system is illustrated in Figure 4-1.

4.2.3 Challenges

Future hydropower development faces the complex environment of frequent geological hazards, increased labour cost and tightened environmental constraints, such as severe-cold and high-altitude areas, dry and hot river valley areas. Intelligent construction technology has become necessary to ensure project safety, improve project quality, manage construction progress, and reduce construction costs. However, the development of intelligent construction technology itself faces the following challenges:

- How it can contribute to low-carbon and green development
- Mutual adaptation between the production mode of intelligent construction and humans
- Data, information, and network security
- Full scenario digital twin and real-time dynamic online simulation
- Development of networks, satellites and other infrastructure support in complex environments
- Iterative upgrading and multi-scenario rollout of existing intelligent construction technology
- Application of blockchain, knowledge graph, generative large language model, etc. in intelligent construction

4.3 Intelligent production in hydropower plants

4.3.1 General

Intelligent production of hydropower plant refers to the intelligent upgrading of hydropower production business, i.e. the operation, maintenance and safety of hydropower plants, which are based on automation, informatization and digitization. Through the application of new generation of information technology, this approach enables

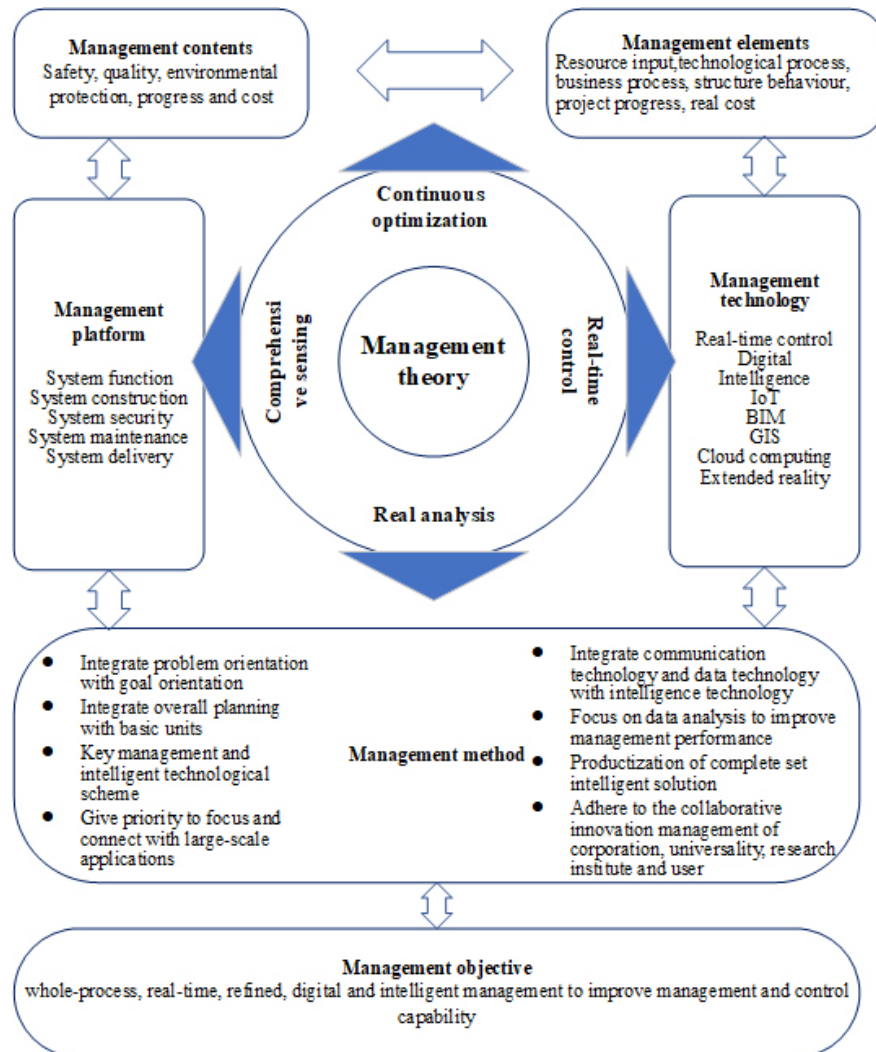


Figure 4-1 | Intelligent construction management technology system

the intelligent management and control of the production business, ensuring intrinsic safety, reliable operation and optimal benefit of hydropower plants. Intelligent production is achieved through data analysis and automation control of real-time monitoring of equipment operation status to improve the operating efficiency of hydropower plants and energy output, reduce the waste of resources and equipment maintenance and operating costs, and reduce the risk of accidents. The premise of intelligent hydropower production is the need to establish an integrated intelligent monitoring and management

system and collect real-time sensor data. This data, processed through the turbine electrical coupling model, enables real-time analysis and optimization of operation, while using data mining and fault diagnosis technology to detect problems. The system triggers alerts and takes appropriate measures when risk indicators approach or reach thresholds. The integrated system not only helps to improve the safety and reliability of the hydropower plant, but also improves their efficiency and economy, and the whole system makes the operation of the hydropower plant smarter.

4.3.2 Key technologies

- a) **Sensing technology.** Comprehensively collects data on the dam, equipment, environment, operation and personnel behaviour to realize a comprehensive collection of production elements of the power plant. It establishes a perfect data storage, processing and analysis platform. It also realizes orderly storage, effective integration, efficient processing and intelligent analysis of various types of data. Additionally, it provides effective data analysis methods, data support for safe operation, lean production and excellent operation of the power plant.
- b) **Control technology.** Through real-time collection of operation information of hydropower plant equipment and application of advanced communication and artificial intelligence technology, the remote and intelligent auxiliary control of hydropower station can improve the operation efficiency and intelligent operation level of hydropower plant and reduce the input of human resources. The abnormal equipment can be automatically identified and alarms can be sent to operators in time to improve the reliability and availability of equipment.
- c) **Inspection technology.** Automatic inspection is achieved in an all-round and real-time manner through the information system. The inspection scope covers various types of equipment and systems such as turbines and generators of the plant, transformers, flood-release facilities, transmission equipment, customizing of professional inspection reports, automatic acquiring and filtering, calculation, statistics, and timely acquisition of anomalous data. It also encompasses 3D virtual power plant monitoring, both intuitive and visual, and displays the equipment operating status in a real-time manner, along with associated production data, robot inspection data, geographic information system data, electronic fence information, real-time production data of equipment and information system information – and all displayed in the 3D scene, enabling “what you see is what you get”.
- d) **Trend analysis technology.** Set trend warning function for measurement points with stable trend changes in the system, such as pressure, flow, vibration, pendulum, liquid level, power, current, voltage, temperature and other signals. Set periodical trend change limit value according to the historical change trend and the nature of the measurement point data. The limit value is usually less than the fixed alarm threshold, from which the equipment anomalies can be found in advance.
- e) **Intelligent warning technology.** Use cloud computing, big data, IoT, AI and other technologies to mine and analyze the massive, diverse equipment domain data resources of the hydropower plants; use knowledge-driven and data-driven methods to predict and warn about equipment operation status, automatically capture the early signs of equipment abnormality, and launch warning in advance in combination with equipment operation mechanism. Intelligent warning includes mainly dynamic threshold alarm, static threshold alarm, multivariate alarm, linkage alarm and correlation alarm.
- f) **Fault diagnosis technology.** Summarize the laws of equipment operation, fault characteristics, etc., based on historical data, combined with equipment operation mechanisms, with the help of massive data mining, machine learning, statistical analysis and computation; automatic diagnosis and location of equipment faults; accurately judge the type of faults, location and cause of the fault. Fault diagnostic methods includes mainly the mechanism diagnosis method, data mining method, health sample method, fault diagnostic decision method.

g) Assessment technology for overhaul.

Make full use of the status monitoring system of power plant to provide such monitoring information as vibration, temperature and voltage; synthesize operating environment and other factors to research and establish one set of scientific and applicable equipment health status evaluation system; establish one mature and stable equipment status intelligent assessment model, analyze the indicators of equipment state, make an integral and overall assessment on equipment health status, reflect equipment operation status more truly, and change the periodic maintenance to CBM.

h) Maintenance for key equipment.

Laser cladding technology is used to remedy surface damages and defects of turbine runners, hydraulic hoist cylinders, servomotor cylinders, etc., to realize green and environment-friendly maintenance, improve the maintenance quality and equipment life, and reduce the maintenance period and cost. The automatic grinding equipment for turbine is used to repair and grind the inside wall of the turbine blade/runner chamber, so as to solve the problem of manual grinding with high intensity and low efficiency, which seriously jeopardizes the physical and mental health of the workers due to such harmful factors as dust, noise arising from the grinding operation. Underwater equipment for hydropower stations is used to check the inside of underwater small-diameter pipeline, clean underwater concrete facade and clean foreign matter on bottom slab, grind metal surface corrosion, etc. The mechanical claw is used to clamp the object to be cut and a hydraulic cutting disk (instead of divers) is used for cutting to achieve unmanned underwater operations. They effectively avoid the risk of diver's personal safety and breaks through the limit of artificial diving depth and work intensity.

4.3.3 Challenges

There are many types of hydroelectric units, and the operation standards and monitoring requirements vary for different types and capacities of hydroelectric units. The theoretical basis of the existing sensor arrangement is outmoded: the monitoring points focus on a single-point and are independent, and so cannot consider the whole. During the transition process of hydropower stations, the coupling relationship between parameters of turbine electromagnetic subsystems is complicated, and the types of hydroelectric units are also diverse, so it is necessary to consider the applicability and accuracy of the theoretical model in different types of hydropower stations. In analyzing and summarizing the huge amount of data collected from status monitoring, inconsistencies in the frequency of hydraulic, mechanical and electrical collection and in the time scale present a problem. Integrating status data from multiple power plants, multiple specifications and multiple time scales, and using the mined data to conduct multi-source coupling fault analysis for fault diagnosis, prediction and assessment of the early state process of the equipment remains a problem to be solved. Hydropower plant modules are coupled with each other, and their operation mechanism is complex; they are also affected by a variety of external environmental factors, resulting in differences in the service life of their components.

Main challenges to intelligent production in hydropower plants include:

- Scientific and standardized arrangement of intelligent monitoring of hydroelectric unit operation status
- Coupled hydroelectric unit model combining mechanism model and big data-driven model
- Status monitoring and fault diagnosis
- Dynamic risk assessment criteria for smart hydropower plants
- Overhaul and O&M of hydropower plants

4.4 Intelligent scheduling and utilization of water resources

4.4.1 General

Water resources scheduling is an important approach of water resources utilization, but also an important part of the construction and operation of hydropower projects. Reservoir scheduling is achieved by its own regulating and storing capacity, and reservoir inflow is regulated and stored to control the reservoir level according to the actual situation and the hydrological forecast. Under the premise of ensuring the safety of hydropower projects, the regulation of water resources of a reservoir is conducted scientifically to achieve flood control and maximize the comprehensive use of water resources to meet the needs of the industry development.

Intelligent scheduling and utilization of basin water resources are based mainly on the centralized regulation of the basin, with comprehensive sensing, intelligent analysis, intelligent regulation and autonomous evolution as the goal. This approach also integrates such information as meteorology, hydrology, flood control, power generation, comprehensive water use, system supply and demand, spot power and operation parameters of power plant. The goal is to establish a complete multi-objective intelligent regulation model and achieve a new mode of hydropower system scheduling and control. This new model and mode rely on comprehensive sensing and intelligent scheduling utilizing accurate basin-level hydrological forecasts, long-medium-and short-term meteorological and hydrological forecasts, plus massive information on grid load, hydroelectric unit status, equipment status, spot price, etc.

4.4.2 Key technologies

a) **Optimized scheduling and control of cascades under integrated utilization and grid constraints.** The cascaded hydropower stations in the basin face the demand for

comprehensive utilization and complex grid constraints, and it is necessary to construct a model and solution method for the optimal scheduling of the cascades under those grid constraints. Aiming at optimal scheduling issues and requirements, a hybrid control model for power plant units is constructed while considering conventional constraints related to hydroelectric units, reservoirs, and cascades, as well as power grid safety and stability constraints, ecological flow constraints, spot price constraints, multi-energy hybrid constraints, etc. In addition, a scheduling model for optimizing hydropower stations in complex vibration zones with high head and a scheduling model of maximum energy output under energy storage process constraints are constructed.

- b) **Integration of multi-constraint flood control forecast and scheduling for cascaded hydropower stations.** The flood control forecast and scheduling optimization theory of cascaded hydropower stations integrates a variety of complex constraints. One of the key technologies of flood control forecast and scheduling theory is obtaining a highly operable flood control scheme that fully considers risks. Through a variety of constraint integration, this approach achieves a high degree of simulation of the actual flood control demands of the model and obtains a flood control scheme that conforms to practice and actual conditions.
- c) **Optimal scheduling of inverse-regulated hydropower stations for special demands.** When the basin-level cascaded hydropower projects undertake the important peak-regulating task of the power grid, they must consider special requirements for navigation, fish breeding and other needs for flow stability that contribute to the prominent contradiction between big outflow fluctuation and the special demands of hydropower plants maintaining flow (discharge) stability. The theory of optimal

scheduling of inverse-regulated hydropower plants considers both the function expression of the water head connection of upstream and downstream hydropower plants and the close connection and mutual influence of upstream and downstream, forming a coupling output-reservoir level-discharge relationship.

d) Integrated meteorological and hydrological forecasts of the basin. In terms of meteorological forecasts, with the rapid development of computer technology, numerical meteorological forecasting models have developed rapidly. Different countries are actively promoting the development of high-resolution numerical meteorological forecasting models, such as the Integrated Forecasting System (IFS) of the European Center for Medium-Range Weather Forecast (ECMWF), the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP) of the United States, and the new generation of Global/Regional Assimilation and Prediction System (GRAPES) in China. In terms of hydrological forecasts, the distributed hydrological model based on physical mechanisms has developed rapidly. It can fully consider the physical process of meteorological, hydrological, underlying surface and other elements in space and time, and simulate many variables such as hydrology, water resources, ecological environment. It is at the leading frontier in theory and is already extensive in application.

In combination with basic observation elements of meteorological stations, satellite and radar remote sensing data, of water level and discharge information of the main streams and tributaries in the basin, and of soil cover and land use in the basin, the distributed hydrological model is coupled with a numerical weather prediction model in a bidirectional way. Important physical processes, including precipitation, evapotranspiration, infiltration

and soil water movement, runoff generation and production and confluence, surface runoff and subsurface runoff in the basin, are studied, to form a coupled meteorological-land surface-hydrological model. It is a promising hydrological simulation and forecasting technology. Integrated meteorological and hydrological forecasting is greatly helps an in-depth understanding of the water cycle process in the basin prediction of flood in the flood season, and for the safety of flood control.

e) Intelligent decision analysis of basin-level cascaded reservoirs. There is not only the hydraulic connection in time periods for the hydroelectric units between upstream and downstream cascaded reservoirs, but also the complex correlation relationship in power. Additionally, joint optimal scheduling must consider the very complex grid, basin, power plant, and hydroelectric unit operation requirements and spatiotemporal coupling constraints. Furthermore, intelligent decision-making analysis of cascaded reservoirs in the basin must look at such complex constraints as contract performance, comprehensive utilization requirements of reservoirs, peak scheduling requirements of the power grid, power/energy output balance constraints, upper and lower limit constraints of energy output for different trading varieties, hydroelectric unit startup and shutdown, etc. Intelligent decision analysis should, moreover, establish a multi-dimensional trading power optimization model for hydropower cascades, a power curve coordinated decomposition model, a cascaded reservoir level control method according to time scales from long-term to short-term. Finally, it needs to produce efficient, economical and comprehensive utilization of cascaded hydropower resources in multi-level power markets, multiple trading varieties, and the range of time scales

dispatching operation schemes for each power plant to provide decision makers with the best options based on different flow process constraints, multiple water level control scenarios, multiple cascaded reservoir operation modes, etc.

During the high-flow season of the basin, the intelligent decision-making analysis of the cascaded reservoirs also requires the construction of a flood control optimization scheduling model and an intelligent control strategy for flood gates based on hydrological forecasts and flood gate operation rules. Based on the flood control rules of cascaded hydropower projects and gate opening and closing rules, a safe power generation and flood control and release model for upstream and downstream reservoirs is established to optimize the order and time sequence of collaborative operations of upstream and downstream reservoirs. An intelligently formulated gate control scheme for flood release is also put in place. Considering water quality, runoff volume, sediment concentration, different geological conditions, and geological hazards under the conditions of safe flood control, the impacts on the safe and stable operation of the reservoir are analyzed to establish and optimize the cascaded emergency flood control scheduling in the basin, as well as flood control rescue at each hydropower project. This approach not only allows decision-makers to determine the flood control scheme early on and then achieve accurate and efficient emergency command, but also ensures the safe operation of each reservoir, achieving cascaded flood control safety and optimized scheduling in the basin.

- f) **Intelligent scheduling and operation of basin-level hydropower cascades.** Based on the intelligent decision-making analysis of basin-level hydropower cascades, the intelligent scheduling and operation of basin-level hydropower cascades can track

all kinds of reservoir scheduling schemes provided by the decision-making analysis in the whole lifecycle, and they can adjust the execution of the scheduling scheme in time. Intelligent scheduling operation of basin-level hydropower cascades can be composed of spot market scheduling operation, auxiliary market scheduling operation, emergency scheduling operation and other key coupled modules. The scheduling system relies on the computer monitoring system and completes the intelligent management of monitoring information, intelligent processing of alarm information, and intelligent analysis of operating trends through the collection of all kinds of data from the monitoring system. All this is ultimately delivered and displayed to the operating personnel in an intelligent and visual manner. The system also meets the demands for grid frequency stability, power plant operation efficiency and facilities management (FM) market revenue enhancement under the new power system and establishes a network command and interaction hub in the integrated mode of scheduling and control, which greatly reduces incorrect operation and regulation events.

4.4.3 Challenges

In the future, the intelligent scheduling and utilization of water resources will deeply unify the power dispatching and hydraulic scheduling towards an integrated, digital and intelligent orientation. It will also develop a multi-objective intelligent scheduling scheme for water resources utilization through the overall analysis of the status of full-cycle hydroelectric units, system load demand, grid line maintenance, and other types of energy structures and constraints and, further, it will combine with the accurate prediction results of rainfall runoff. However, intelligent scheduling and utilization of water resources face the following challenges:

- Integrated water utilization under multi-objective constraints in large series and parallel cascaded reservoirs
- Meteorological and hydrological forecast model coupling and model optimization and upgrading
- Risks to the scheduling and management of transboundary water resources in a changing environment
- Changed role of hydropower in the new power system mode
- Adverse effects of frequent extreme weather events on runoff forecast and water resource utilization in the global warming background
- Protection of water resources and pollution control

4.5 Safety monitoring and risk prevention and control of hydropower projects

4.5.1 General

With regards to such difficulties as the insufficient capability of safety risk prevention and control, and of weak intelligent diagnosis and collaborative management abilities of hydropower projects in China at this stage, the new generation of information technology is used for deep mining, active exploration and scientific arrangement. Closely embracing the connotation and goal of intelligent management on the safety of reservoirs and dams in China, based on data-driven intelligent sensing (risk identification) and emergency response for reservoirs and dams one set of key technologies is researched and developed as:

- Deeply integrate the risk concept, explore the safety intelligent decision-making methods of hydropower projects that organically combine the whole chain, such as holoception, data transmission, monitoring and warning, safety diagnosis, joint control and regulation,

emergency decision-making, danger removal and reinforcement, degradation and scrapping, decommissioning assessment

- Develop a dam safety intelligent management system that integrates real-time monitoring, safety diagnosis, risk identification and hierarchical response
- Complete the upgrading of safety intelligent management technology for hydropower projects. Innovate and develop an intelligent management mode for China's reservoir/dam safety
- Significantly improve the level of safety diagnosis and intelligent management for large water conservancy and hydropower projects
- Lay a solid foundation for the improvement of daily and emergency management efficiency of China's reservoir/dam
- Ensure a safe operation. And promote the safe development and efficient use of water resources in the basin

4.5.2 Key technologies

4.5.2.1 Intelligent sensing and information integration technology of safety factors in hydropower projects

Dam safety monitoring is an important measure for the management of dam safety and is a necessary means to understand the safety status of dams during operation. However, in actual operation, due to the influence of the number and location of monitoring instruments, it is difficult for the monitoring data to fully reflect the actual safety status of the dam. Therefore, the assessment of dam safety needs support by other data. Currently, various types of support for dam operation and management and safety monitoring system are online, more and more unstructured data are present, including dam safety inspection images and a variety of reports, text, audio recordings and monitoring video and other types of data for

the key defects. These unstructured data are of great reference value for dam safety assessment. However, from unstructured data it is difficult to extract information, like how to quickly identify the signs of insecurity of the structure, evaluate the dam safety status in a real-time and accurate manner, identify and deal with the potential safety hazards of dam in a timely manner, and ensure the safety of dam operation.

4.5.2.2 Multi-source monitoring data acquisition

- a) **Monitoring of internal stress distribution in dam.** Relying on interpolation of discrete measurement point data to derive the distribution pattern of concrete stress gradient in the dam has provided a solution to the continuous change of internal stress in concrete dam in cases of emergency by providing a measured sensing solution, which further strengthens the monitoring capability of internal stress gradient in concrete dam.
- b) **Acquisition of inspection data.** Regular inspection is an important measure to maintain the safety of dam works, and the existing inspection methods are mainly manual inspection and recording. With the increase in the age of dams and the influence of superposed environmental changes, the work quantity and difficulty of manual inspection has gradually increased. Using deep neural network technology, a hydroelectric power station's intelligent inspection device has also been optimized. This device not only improves the traditional manual inspection process but assists in defect detection and automatically generates inspection reports.
- c) **Underwater 3D digital detection.** Remotely operated vehicle (ROV)-multi wave beam detection, 3D laser scanning and close-range camera technology are used to scan the stilling pool, reservoir area near the dam,

upstream dam face, waterway pipeline and river channel in the reservoir area to obtain 3D digital information of the river bottom and hydraulic structures (underwater part) and to provide basic data for later work. Using integrated underwater detection technology, precise positioning and quantitative analysis of underwater defects in hydraulic structures can be achieved. Additionally, integrated above-water monitoring technology facilitates digital inspection, dynamic monitoring, and quantitative analysis of dams, galleries, flood outlets/tunnels, and high-risk slopes.

- d) **Collection and labelling of monitoring data.** For the monitoring and inspection data of the dam, the data of monitoring instruments are numerical and do not require labelling. The dam inspection and monitoring data include image, video, audio and text reports, of which the defective parts on the image or video can be accurately labelled by the pixel-level image labelling tools. For text content, the defect information described in the text can be marked according to the keywords or specific attributes in the text and for audio, it can be jointly marked according to the text or image to which it belongs. Among all kinds of data related to dam safety monitoring, there are almost no data about threats to dam safety. At present, there are few dam safety accidents, and there are almost no relevant monitoring data. The data are of low reference value. It is a typical scenario in which no negative sample data are available. Using the positive and unlabelled (PU) learning model based on the training of historical data of dam monitoring, it is very suitable for analyzing the decision boundary of dam safety.

4.5.2.3 Extraction of multi-source and multimodal features

- a) **Multi-source of data.** Seismic monitoring data come from the results of earthquake monitoring in the strong earthquake system; monitoring data of reservoir bank slope and safety monitoring data come from the results of monitoring instruments deployed in the project; water and rain regime monitoring data come from hydrological and water environment measurements; and inspection and monitoring data come from the data collected by inspection operation and monitoring equipment.
- b) **Multimodality of data.** The data collected by different equipment are a mixture of structured and unstructured data, which reflect safety behaviour of an aspect in a specific environment and are closely related to the overall safety behaviour of the dam. The monitoring data is the numerical representation of the dam safety behaviour, while the text, image and other data are the apparent representation of the dam safety behaviour, both of which can be used to evaluate the dam safety and are the modal data of the dam safety behaviour, i.e. multimodal data.

4.5.2.4 Integration of multi-source and multimodal data

- a) **Characteristic integration network.** The original multi-source and multimodal data is a representation of the dam safety behaviour at a certain moment. By means of the multi-source and multimodal feature extraction model, the required feature information can be extracted, and the complementation and verification between the information can provide information with stronger discrimination ability for the decision model of dam safety. But there is also noise and redundant information. For this reason, a feature integration network is designed for the multi-source and multimodal

feature information, which while merging (eliminating) redundant information achieves the effect of dimensionality reduction.

- b) **Integration of analysis result.** Take the characteristics of each mode as the input of the subsequent business model and give the evaluation of the dam safety behaviour. Take these evaluation results as the input of Dempster-Shafer evidence theory, use Dempster-Shafer evidence theory to integrate the results of multiple business models and get the final evaluation results.

4.5.2.5 Risk identification and hierarchical warning of emergency in hydropower projects

- a) **Time-series prediction of safety monitoring data.** The time-series prediction of a single measurement point for safety monitoring of hydropower projects is based on the identification and evaluation of monitoring instruments at all observation points under measurement. The threshold analysis and judgment of each measurement point are carried out with reference to the current workflow of dam safety monitoring data compilation and data analysis. The model and its parameters are trained on the long series of monitoring data. The most suitable predictive analysis model and its supporting parameters are selected, upon which, after using data anomalies to deal with the measured values in the recent period of time, the threshold values of the measured points are calculated and compared with the measured value of the same day. That allows making a preliminary judgment on the measured values of measured points on the same day.

The number of measurement points and the trend of measurement values are different for different dams, so it is time-consuming and labour-intensive to manually adjust the

parameters for different measurement points. It is also not possible to update them in real time. With reference to the idea of automatic machine learning, the automatic model matching method is introduced to reduce the links of manual parameter adjustments and ensure the accuracy and universality of the model prediction. As shown in Figure 4-2, the time-series prediction of safety monitoring data consists of two steps. Model and parameter matching in the offline phase and threshold calculation and judgment in the online phase. The offline phase mainly focuses the selection of the best prediction model and its parameters for the measurement points, and the online phase mainly focuses the judgment of the threshold calculation and the regular evaluation and updating of the model.

4.5.2.6 Correlation analysis of spatial and temporal characteristics of monitoring data

The spatial-temporal correlation analysis, as a method of data anomaly analysis, is used to review the accuracy of the evaluation results and reduce the rate of false alarms after the evaluation of a single measurement point. The similarity partitioning of measuring points can be used to distinguish and categorize the whole dam behaviour according to the similarity (or dissimilarity) of the effect size of each measurement point. Considering the spatial dependence between dam observation points and the time dependence between dam monitoring data, the spatial-temporal correlation analysis of dams usually requires the integration of multiple methods for comprehensive analysis and modelling.

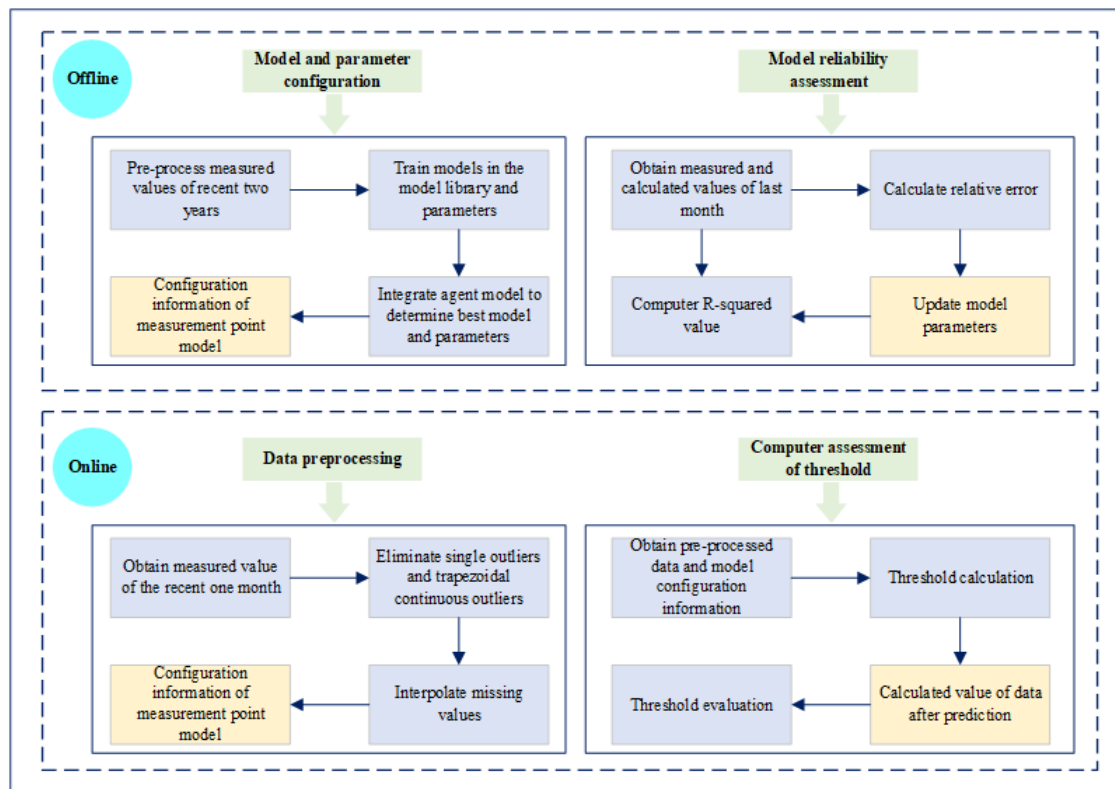


Figure 4-2 | Schematic diagram of working process of model based on automatic matches

4.5.2.7 Formulation of hierarchical warning indicators for monitoring

The monitoring items for dam safety can be divided into several categories, such as environmental monitoring, deformation monitoring, seepage monitoring and stress-strain monitoring. Among them, deformation monitoring includes mainly surface deformation and internal deformation of the dam body (foundation); deformation of the impermeable body, interface, joint (crack); deformation of the voids; deformation of the bank near the dam and deformation of the surrounding rocks of the underground caverns. Seepage monitoring includes the uplift pressure, seepage pressure, seepage volume and water quality analysis. Stress-strain monitoring includes mainly pore water pressure, soil pressure, concrete stress-strain, reinforcement (steel slab, anchor) stress, prestressed anchor cable anchorage force. At the same time, there are also seismic monitoring, hydrostatic/hydrodynamic monitoring and other special monitoring items to evaluate the operational status of the reservoir and dam.

The main objectives of the development of monitoring indicators for safety are to assess and predict the capability of resisting potential loads on the basis of the load resistance that the dam and foundations have already been subjected to, and thus to determine the warning and extreme values of the monitored effect sizes under the aforesaid load combination.

4.5.2.8 Formulation of online hierarchical evaluation system and dynamic weighting

Based on the concept of monitoring design and data analysis, a synthetic evaluation model is created with vertical dimensions from single measurement points to instrument type, monitoring items, basic parts and buildings/whole structures. The model also incorporates horizontal dimensions enabling comparisons of the importance of elements at the same level, while

considering the spatial and temporal correlation of the entire evaluation system. Meanwhile, fuzzy theory, hierarchical analysis method and affiliation matrix are combined to analyze the building comprehensively and to judge the safety states of each part of the building as well as the structure as a whole. The synthetic evaluation of dam safety is a complex problem with multiple hierarchies, multiple indicators and multiple criteria; it is a significant task with high requirements and requiring a certain amount of input.

In the synthetic evaluation, the evaluation principle can be summarized as follows:

a) Fuzzy evaluation method of safety evaluation:

The theoretical basis of fuzzy comprehensive evaluation method (FCEM) is fuzzy mathematics. According to the membership theory of fuzzy mathematics, qualitative evaluation is transformed into quantitative evaluation, and then synthetic evaluation of each index is conducted by using the fuzzy transformation principle. The specific process of fuzzy comprehensive evaluation is the following: Determine the fuzzy set of factors (called factor set U) that affect the overall goal according to the evaluation goal, then set the evaluation grade of these factors to form the fuzzy set of comments (called evaluation set V). Calculate the attribution degree of each factor to each evaluation grade (called fuzzy matrix or evaluation matrix R) Determine the weight distribution of each factor in the evaluation goal, obtain the quantitative solution value of the evaluation through the synthesis of fuzzy matrix, and finally determine the final evaluation result of things according to the maximum membership principle.

b) Synthetic evaluation of dam buildings safety:

The fuzzy relation matrix R and weight matrix ω calculated by analytic hierarchy process (AHP) is synthesized according to a certain composition operator, and then the synthetic evaluation set B can be obtained.

Finally, according to the maximum membership principle, the stability of dam buildings and all hierarchies can be obtained for synthetic evaluation and warning.

4.5.2.9 Monitoring information-based risk identification

The dam safety risk analysis (see Figure 4-3) is divided into five aspects: site safety inspection, earthquake impact, dam structure function, seepage analysis, and flood impact. For different types of embankment dam structures, the items within the designated scope can be freely selected for restructuring, and the optimal item can be selected for risk analysis and calculation.

Qualitative analysis of reservoir/dam risks is carried out. According to *Measures for Safety Appraisal for Reservoir and Dam, Guidelines for Safety*

Assessment of Reservoir and Dam and the actual situation in China, the reservoir/dam risks are divided into four classes: Class I (extremely high risk), Class II (high risk), Class III (medium risk) and Class IV (low risk).

4.5.2.10 Emergency response mechanism for hydropower projects

a) **Analysis of evolution mechanism of emergency chain.** For the classification and characteristics of emergencies for water projects, we summarize and analyze their causes and evolution paths and establish a chain effect model to reveal the evolution mechanism of reservoir/dam emergencies to provide a scientific basis for emergency decision-making. We do this using domestic and overseas accident cases. The chain

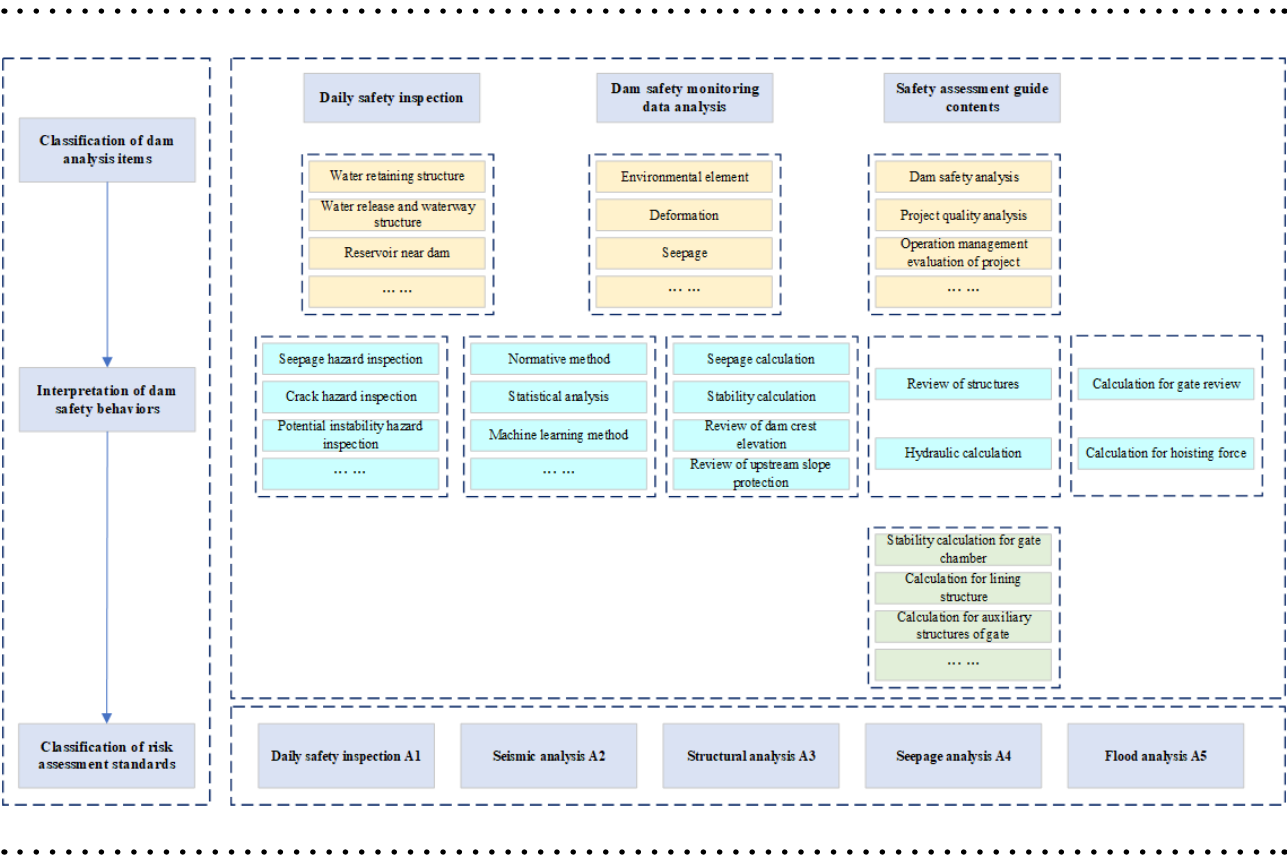


Figure 4-3 | Framework for real-time analysis of dam safety decisions

structure of hydropower project emergencies analyses sub-events, and the similar events concentrated in the sub-events, and then classifies and processes the conditions that induce the sub-events, creating a clearer and more hierarchical view of complex reservoir/dam emergencies.

b) Logic relation of emergency response mechanism for unexpected events.

Based on the emergency response process and information flow, combined with the roles of decision-makers and emergency response objectives, the emergency response mechanism is divided into a risk monitoring and sensing stage, a risk identification and warning stage, an emergency response and treatment stage, and an emergency ending and assessment stage, establishing a logical structure for the emergency response mechanism.

c) Danger monitoring and sensing stage.

This stage covers the occurrence and development of a dam emergency, managed mainly by means of the intelligent sensing and information integration. Key hazard-causing factors and emergencies triggered by environmental changes, are detected through intelligent sensing, with multi-source and multi-modal data integrated and reported by grass-root decision-makers.

d) Risk identification and warning stage.

At this stage, the expert decision-makers (experts, scholars and professionals, et al.) use hierarchical analysis method and fuzzy theory of the dam risk rapid identification model based on monitoring data, site safety inspections, and safety review results of the risk level identification criteria to identify the risks and determine the level of warning. Consultation information and decision-making information are produced at this stage, and provided to the emergency commander and

for further guidance of emergency response activities.

e) Emergency response and treatment stage.

According to the level of warning, the emergency commander starts the corresponding emergency response action, deals with emergency rescue, organizes the emergency collaboration team and the public to carry out rescue activities, track the evolution of the events in real-time, and constantly adjust the emergency disposal scheme.

f) End of emergency and aftermath stage.

The end of an emergency shall be declared as soon as possible after the hazard is under control, the alarm is removed, the people at risk have been evacuated and resettled, the floods have receded, or the water pollution is under control. After the end of the emergency, a series of aftermath and assessment work is required: a comprehensive and systematic investigation and analysis of the incident's causes, along with a comprehensive analysis and evaluation of the emergency response process should be conducted.

4.5.3 Challenges

The safety monitoring and risk prevention and control technologies for hydropower projects face the following challenges:

- Theory and method of intelligent inspection collaboration and regulation for natural hazard and damage of dam and reservoir
- Numerical identification of damage from natural hazards under coordinated inspection conditions
- Automatic and efficient feature extraction and effective integration of structured and unstructured hydropower project safety monitoring data with multi-source and multi-modality

4.6 Eco-environmental monitoring, protection and evaluation

4.6.1 General

The monitoring, protection and evaluation of the ecological environment of hydropower projects are designed to carry out comprehensively and systematically investigate, monitor and assess the natural environment and ecosystems. This effort aims to understand the structure, function and service value of the ecosystems in areas affected by hydropower projects, providing a scientific basis for ecosystem protection and restoration. The scope of the ecological environment's monitoring, protection and evaluation encompasses hydrological regime (including sediment, meteorology, soil and water conservation), ecological flow, water environment (such as water temperature and water quality), water ecology (including zooplankton/phytoplankton, benthic organisms, aquatic plants, and fish), terrestrial ecology, and construction-related impacts (like noise and atmospheric pollution).

Smart hydropower utilizes an advanced system for ecological environment monitoring, protection, and evaluation, featuring online water environment sensing, data mining, dynamic analysis, intelligent assessment, real-time warnings, and linked regulation and control. This system encompasses the intelligent deployment and control of monitoring networks, high precision layered sampling from deep water, in situ real-time monitoring and analysis, indicators for assessing the health of lakes and reservoirs, and multi-reservoir linkage for ecological regulation. Management is characterized by digitalization, information technology, and intelligence, ensuring the safety of the water environment and ecology for basin-level cascaded reservoirs. Key technologies for this smart approach include intelligent sensing for all ecological elements, integration and computing technology for ecological data, and dynamic control technology for maintaining ecological environmental health.

4.6.2 Key technologies

4.6.2.1 Intelligent sensing technology for all elements of ecological environment

- a) **Intelligent space-air-ground integrated technology for hydrological monitoring.** Building on the foundation of traditional water conservancy monitoring systems, this approach incorporates intelligent sensing and communication technologies to develop an integrated space-air-ground water conservancy sensing network. This network is designed to monitor and intelligently analyze the characteristics of water-related objects and their environmental conditions, see Figure 4-4. The goal is to achieve automated monitoring across all hydrological elements and their full range. It enables the complete automation and intelligent processing of the collection, transmission, reception, and analysis of hydrological information, including its prediction, forecasting, and evaluation.
- b) **Intelligent water environment monitoring technology.** Utilizing a multi-dimensional, high-density water quality monitoring system allows for the capture of water environment data with unparalleled detail in both space and time. This system facilitates the automated and intelligent collection of various data types, including water quality, water bodies, pollutants, and basins. Such comprehensive data gathering supports the visualization of environmental improvements, enables the traceability of environmental pollution, and aids in various other analytical applications.
- c) **Intelligent fish recognition technology.** Fish serve as crucial indicators of ecosystem health. In the reservoir area of a hydropower project, an underwater pan & tilt equipped with high-resolution cameras continuously captures images of fish passage. Intelligent algorithms then perform statistical analyses on the video, identifying fish species, counting numbers, and tracking movement directions, etc. This

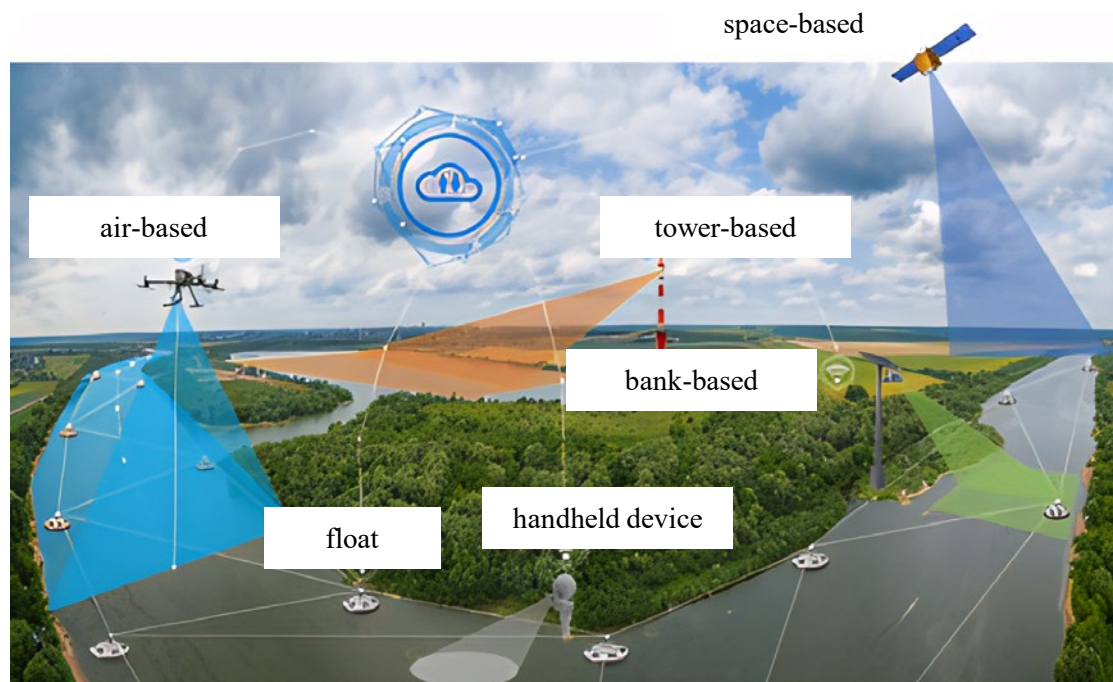


Figure 4-4 | Space-air-ground integrated water conservancy sensing network

process provides essential background data for assessing the ecological health of hydropower projects.

d) Intelligent algae recognition technology. Leveraging deep learning algorithms and expert knowledge alongside automation system integration technology, the AI planktonic algae identification system achieves seamless integration of automatic sampling, precision photography, image screening, automatic identification, and result output. This significantly minimizes errors associated with variability in personnel experience in algae identification, enhancing the normalization and standardization of algae monitoring. Furthermore, it increases the frequency of algae monitoring and the efficiency of warning systems.

e) Intelligent monitoring and identification technology for noise sources. Integrating automation, AI, IoT, and other technologies, this approach utilizes deep learning and sound source localization based on the time difference of noise arrival to accurately identify and pinpoint the origin of construction noise. It further controls the network camera for video forensics, determining the responsible entity for the noise pollution. This enables intelligent and precise monitoring of the construction noise pollution sources in hydropower projects.

4.6.2.2 Data integration and computing technology for ecological environment

- a) **Distributed big data fusion and integration technology.** The terminal flow sensors, water quality monitors, space scanners and GPS and other IoT devices are integrated to form a communication system (see Figure 4-5) with the help of intelligent collaboration between multiple edge nodes and the fog nodes, to enable instant data extraction at the field level, real-time level and short-cycle level, along with data cleaning, classification and mutual feedback for multi-source big data.
- b) **High-performance parallel computing technology for space-ground-water integrated model.** A high-performance parallel algorithm of space-ground-water integrated model is established in the cloud for large-scale watershed models of meteorology, land non-point sources, hydrodynamics, water quality and water ecology, which are based on distributed cells or block space grids. For load balancing of parallel computing, the homogenization block processing is conducted, and the boundary condition nodes are set up. Based on the strong and weak coupling relationship between models,

the model application nodes are set up according to the logical sequence to establish the distributed communication basis of the numerical simulation area segmentation and function decomposition. This technology can improve the high-performance computing power of water environment and ecology simulation and prediction in the cloud of hydropower project.

4.6.2.3 Dynamic control technology of ecosystem health

- a) **Big data-based evaluation technology for ecosystem health.** The concept and connotation of ecological environmental health of hydropower projects are scientifically defined from a new perspective, the key factors affecting health are identified. A health evaluation index system and evaluation standards are also constructed. In addition, a health evaluation model is established, and an ecological environmental health evaluation is carried out based on massive monitoring data of hydrological regimes, ecological flow, water environment, water ecology, terrestrial ecology, construction elements, to reveal the health status and the dynamic evolution trend.

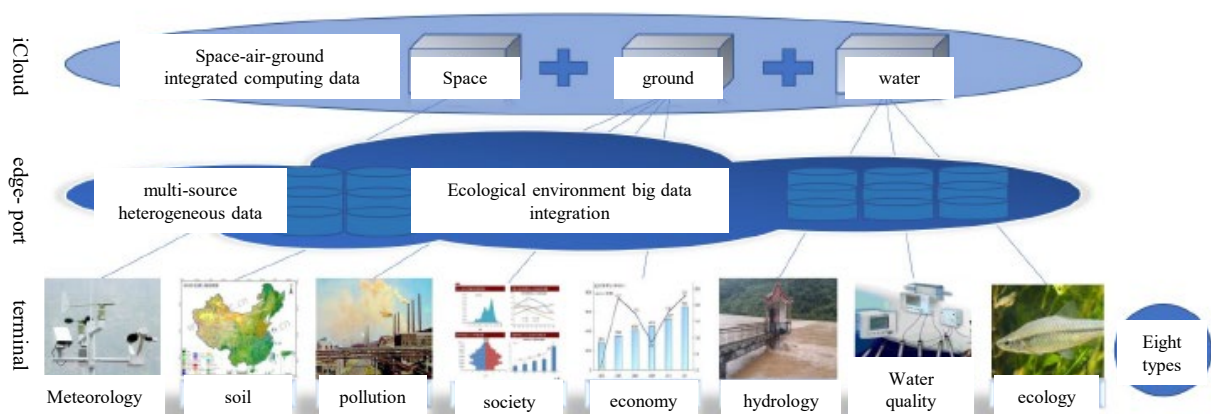


Figure 4-5 | Multi-source heterogeneous ecosystem big data integration for hydropower projects

b) Intelligent regulation technology for ecological flow. To furnish robust scientific backing for the integrated management and mitigation of ecological risks associated with hydropower initiatives, the approach is to:

- identify the ecological risk zones in the basin under the influence of hydropower projects, expounds the ecological risk characteristics of different zones
- provide quantitative analysis of the impacts of planned energy output and reservoir capacity on ecological flow regulation
- introduce the set-pair analysis method and analyze the comprehensive benefits of different ecological flow regulation measures in a real-time manner based on the real-time monitoring results near the ecological flow release measures

c) Intelligent control technology for stratified water intake in reservoir. Leveraging real-time monitoring data of reservoir water temperature, this approach propels numerical model computations to analyze and derive a stratified water intake strategy. Utilizing T-SQL database language, a specialized database program is developed, featuring specific functionalities to facilitate the path planning and automation of stratified water intake gates at hydropower stations.

d) Construction water conservation and intelligent sprinkler technology. The water circulation-collection system and intelligent numerical control water-saving control system are established at the construction site. Wastewater from production and living purpose and rainwater are drained to the tertiary sedimentation tanks through the site drainage ditches, where recycled/reclaimed water after filtering is stored. During the construction operations of the project, the dust at the construction site is monitored in real-time through the combination of

intelligent numerical control programmable logic controller (PLC) system and sensors. If a warning value is reached, the dust suppression spray system can be automatically started to achieve the effect of dust suppression.

4.6.3 Challenges

By integrating the intelligent sensing and dynamic monitoring of all elements of the ecological environment, along with the risk identification and response of ecological environment of hydropower projects, the modern information technology and data processing technology are comprehensively applied to achieve a breakthrough from the health evaluation of a single evaluation period to the health evaluation of the whole lifecycle of hydropower projects, as well as from static point-in-time evaluation to a dynamic assessment encompassing prediction and forecasting capabilities.

The future development of ecological environment monitoring, protection and evaluation can be summarized in the following aspects:

- High-performance processing and full-scenario real-time simulation of ecological big data
- Intelligent identification and warning of ecological environmental risks in hydropower projects
- Intelligent dynamic evaluation for whole lifecycle health of hydropower projects
- Health-based ecological regulation decisions for reservoir(s) with multi-source data

4.7 Pumped storage

4.7.1 General

At present, world energy is in a critical period of green low-carbon transformation and development, and the development of new energy is on a large scale. But wind and solar power generation

have intermittent and fluctuating characteristics, which impacts the power grid. Pumped storage power in collaboration with wind power, solar power, nuclear power and thermal power can promote a level of new energy consumption to the power system. The alternating operation of power generation and water pumping can realize the peak shaving and valley filling for the power system and improve the operational stability of the power system. Therefore, pumped storage is currently the most economic and most effective power regulation system, with the most value to large-scale development.

As a large-scale energy storage system with multiple functions such as peak shaving, frequency modulation and phase modulation, pumped storage can efficiently undertake the peak shaving tasks of the power system, reduce investment in load-shaving thermal power units of already high investment and high environmental pressure, and significantly reduce the use of coal to achieve the goal of peak-shaving and carbon reduction. To achieve valley filling and carbon reduction when the power load of pumped storage is low, the surplus electric power generated by the thermal power plant is used as the pumping power, improving the stability of the thermal power unit operation and equipment utilization rate. Pumped storage is a kind of clean energy power, energy storage power and regulating power, which can solve the power balance and power quality of the grid, while effectively help realize a zero-carbon power system.

Pumped storage hydroelectric units, unlike conventional hydroelectric units, integrate pumping and power generation functions and are characterized by high head, high speed, forward and reverse rotation, and frequent conversion of multiple operating conditions, which makes equipment manufacturing and operation control difficult. The key technologies of pumped storage include pump-turbine technology, power generation motor technology and control system

technology, variable-speed pumping and storage technology, and digital and intelligent technology.

4.7.2 Key technologies

a) Pump turbine technology. The pump turbine is the core equipment of a pumped storage power station, and it plays a crucial role in the power conversion efficiency and operational stability of the power plant. The key technologies mainly include the design and selection of pumps and control and optimization of pump performance parameters. In the design and selection of pumps, the efficiency of the pump, head (lift), flow and speed and other parameters are required. According to the specific requirements of the power plant, the appropriate pump model also needs to be determined. In the control of the performance parameters of the pumps, the pumps shall be reasonably adjusted and optimized according to such factors as grid load and energy storage demand in order to improve the efficiency and operational safety of the pumps.

b) Generator-motor technology for power generation. Another key equipment of the pumped storage power station is the generator-motor, whose main function is to convert the kinetic energy of the water flow into electric energy. The key technologies of the generating unit include the design and selection of the turbine, the selection and control of the generating unit and the hydrodynamic analysis of the turbine. In the design and selection of the turbines, it is required to consider such factors as hydrodynamic efficiency, characteristic curve, speed range and stability. The appropriate turbine model should be determined according to the specific requirements of the power plant. In the selection and control of the generating unit, it is necessary to determine the suitable generator model and control

strategy according to such factors as grid load and energy storage requirements. In addition, hydrodynamic analysis of the turbine can help optimize the blade shape and water flow distribution of the turbine, thereby improving the efficiency of the turbine and the operational stability of the generating unit.

c) Control system technology. Key to the operation of the whole power plant is the control system of pumped storage power station, which monitors and regulates the pumping, storage and power generation processes. The key technologies of control system include automation control technology, data acquisition and processing technology, communication technology. Automation control technology is used mainly to realize automatic control and operation regulation of the power plant, including automatic adjustment and optimization of pumping and generating units. It is also used to realize the coordinated operation of the power plant and power grid. Data acquisition and processing technology is used to monitor and analyze the operating parameters of the power plant in real time, which helps the operation personnel to grasp the working status of the power plant and carry out fault diagnosis and maintenance. Communication technology is used to achieve remote monitoring and operation regulation between the power plant and power grid, as well as information interaction and data transmission between power plants.

d) Variable-speed pumped storage technology. The conventional pump turbine units are generally fixed-speed units, featured by a slow regulation speed and a small operating efficiency. But with these units the pumping can only be at full load and the pumping power cannot be adjusted according to the demand of the power grid. It therefore cannot meet the requirements of a fast and accurate load regulation of the power grid.

With the development of power electronic technology, pump turbine units with variable speed technology have become an effective means of accommodating a higher proportion of new energy consumption in the power grid.

Compared with conventional pump turbine units, variable-speed pump turbine units can flexibly change the active power under pumping cases, quickly adjust the active power and reactive power under power generation cases, improve the stability of the system and its rapid response capability, effectively control the frequency of the grid load, balance the frequency fluctuations caused by renewable energy, and improve the utilization efficiency of new energy.

The variable-speed units in pumped storage power stations can be roughly divided into two types: one is speed regulation by level, including variable-pole speed and double rotor and double stator speed; a second is continuous speed regulation, including full power frequency conversion speed regulation on the stator side and AC excitation frequency conversion speed regulation on the rotor side. The full power variable frequency speed regulation on the stator side is a full size converter (FSC) with the same capacity as the synchronous motor in series on the stator side of the conventional pumped storage synchronous generator motor. The AC excitation frequency conversion speed regulation on the rotor side uses the double-fed generator motor during installation. At present, continuous speed regulation is widely used, and AC excitation frequency conversion speed regulation is being rapidly developed. AC excitation variable speed pump turbine units are suitable for pump turbine units with large capacity, while full power variable speed pump turbine units are suitable for pump turbine units with a medium and small-sized capacity.

The full-power variable-speed pump turbine unit connects a frequency converter, with the same capacity as that of the generator motor, between the generator motor's stator and the power grid. In the power generation mode, the power with different voltage and frequency from the generator is transformed into the power with the same voltage and frequency as that of the power grid after frequency conversion and voltage transformation and is fed into the power grid. In the electric mode, the power flow reverses, with the unit operating as an electric motor that absorbs power from the grid.

The AC excited variable-speed pump turbine unit adopts an AC excited motor as the generator motor and uses a frequency converter to provide AC excitation for the rotor. With AC excitation, the frequency and amplitude of rotor current can be adjusted. To get a more efficient working condition, the AC excited variable-speed pump turbine unit allows the motor speed to change and realize variable-speed and constant-frequency operation of the motor by adjusting the frequency of the rotor when the speed changes.

The AC excitation system control of variable-speed unit in pumped storage power stations needs to be coordinated with the governor control to meet the operation and control requirements of variable-speed units under various operating conditions. Through AC excitation, the variable-speed unit can adjust the speed and power in the pumping mode, allowing it to meet the requirement of fast and accurate frequency regulation of the power grid better than the conventional fixed-speed unit does. Considered from the operation of the power plant itself, the variable-speed unit has the advantages of improving the efficiency and stability of the unit, improving the cavitation performance, and possessing the power

regulation function, etc. From the perspective of the power grid, the variable-speed pump turbine unit enables the rapid and precise response to the grid's needs, enhancing both grid stability and electric power quality.

4.7.3 Challenges

Due to the important role of pumped storage power stations in the clean and low-carbon zero-carbon power system, these stations have ushered in the opportunity of vigorous development. Pumped storage operating enterprises have started the construction of new power plants on a large scale and are generally facing great pressure on the infrastructure control of these plants. The plants already in operation face challenges of safe and efficient operation, as well as problems of deficient human resources and insufficient O&M capacity.

Challenges for the pumped storage plants in the current development opportunities include:

- Design and construction of high-head, large-single, large-capacity units for pumped storage
- Control technology for variable-speed units of pumped storage
- Joint control technology for hybrid pumped storage power stations
- Construction of a high-precision, real-time sensing system for pumped storage power stations
- Development of a standardization system for the installation and commissioning of pumped storage power stations
- Digital twin technology for pumped storage power stations
- Troubleshooting technology for equipment of pumped storage power station
- Auxiliary decision-making technology for maintenance of pumped storage power station equipment

4.8 Hydro-wind-solar hybrid power generation

4.8.1 General

Hydro-wind-solar hybrid power generation system refers to a regional energy system that can accommodate the input of various renewable resources such as hydro, wind and solar energy, and the organic collaboration and coordination of various energies, as well as the output of various energies. It is not a simple superposition of multiple energies, but a comprehensive hybrid and mutual coordination in accordance with the levels of different energies, as well as an overall arrangement of the organic relationship between the various energies and the conversion and utilization of energy. The goal is to achieve the most reasonable energy utilization benefit, and a continuous and stable power supply. This three-source hybrid system will contribute to the low-carbon transformation of global energy, support structural reform of the energy supply, and enhance both economic efficiency and the comprehensive utilization efficiency of the energy system.

4.8.2 Key technologies

a) Dynamic capacity planning. Dynamic capacity planning refers to the process of rationalizing the timing and capacity ratios of various energies, while considering a variety of factors such as natural resources, grid-connection requirements and power supply loads in the design of system. The system may be jointly planned and constructed by power generation enterprises, power grid enterprises, power equipment companies, design institutes, etc. Such collaboration involves multi-dimensional issues of economy, environment and society. There is, therefore, an urgent need to study the scientific ratio of installed capacity of hydro-wind-solar hybrid systems in different regions and development sequences and to formulate a synthetic evaluation index system

and a benefit compensation mechanism for the market players.

- b) Multi-timescale optimal dispatch.** Multi-timescale optimal dispatch includes mainly short-term real-time dispatch and medium-term and long-term dispatch. Short-term real-time dispatch means that the system carries out hourly or minute-by-minute optimization dispatch based on real-time weather conditions, energy demand and market power tariffs, etc. It needs to solve the problems of load distribution of the generating units within the plant and operation dispatch among the plants to ensure both the stability of the system operation and the high efficiency of the generating unit operation. Medium-term and long-term optimal dispatch refers to seasonal planning and annual optimization of the system by using historical data and meteorological forecasts, while considering the energy dispatch, supply, storage and trading among power plants, in order to both maximize the comprehensive utilization rate of energy and the economic efficiency of the system and solve the problem of compensating and distributing the benefits among different market players. Therefore, the optimal dispatch of multi-energy hybrid system at multiple time-scales needs to consider technical, economic and policy factors from the perspective of generating unit operation, power plant deployment and market level. It also needs to develop innovative algorithms and optimization models and formulate efficient and precise optimal dispatch strategies for hydro-wind-solar hybrid system to maximize the overall performance of multi-energy hybrid system.
- c) System operation stability.** The operational stability of the multi-energy hybrid power generation system includes three types of stability: energy stability, grid stability and generating unit stability. Energy stability mainly focuses on the continuous supply and resource

utilization efficiency of hydro, wind and solar energy under different climatic and weather conditions. Grid stability mainly focuses on the impact of uncontrollable and intermittent energy on the system voltage, frequency stability and power balance. Generating unit stability mainly focuses on the generating unit: power response capability, stability margin and equipment operation status during the actual operation process. The wind energy and solar PV power generation in the system have strong randomness and fluctuation, and lack the stable frequency support and dynamic reactive power support capacity, weak anti-interference ability and rotational moment of inertia characteristics of conventional power plants. This presents the system with many obstacles to safe and stable operation.

d) Dynamic risk assessment system. With hydro/wind/solar energy hybrids, the dynamic risk assessment system is to dynamically quantify, evaluate and predict the various factors that may affect the stability of the system, and thereby take measures to reduce or avoid these risks, guaranteeing safe, reliable and economic operation of the system. In addition to examining these system stability risks, the dynamic risk assessment system also looks at economic, technological, environmental, policy, market competition and cross-field cooperation. However, the complexity of different energy coupling within the hydro-wind-solar hybrid power generation system, the uncertainty of multi-time-space effects, and the high-dimensional nonlinearity of the hybrid system model fundamentally increase the difficulty of establishing a dynamic risk assessment system of the hybrid power generation system.

4.8.3 Challenges

The hydro-wind-solar hybrid system plays an important role in maximizing the comprehensive benefit of the basin and in accelerating the energy transition. Such hybrids are also internationally recognized as one of the feasible ways to solve the problem of new energy consumption. However, the coupling of multi-energy flows in the system will bring new challenges to the dynamic capacity planning, optimal dispatch and safe and smooth operation of the system.

Under current development opportunities, the challenges for hydro-wind-solar hybrid power generation include:

- Dynamic capacity planning for hydro-wind-solar hybrid system for multi-market players
- Optimal dispatching of hydro-wind-solar hybrid system on multiple timescales
- Operational stability of hydro-wind-solar hybrid system
- Dynamic risk assessment indicator system

Section 5

Application cases

5.1 Investigation, planning and design application cases of hydropower projects

The dam of Huangdeng Hydropower Station is a roller compacted concrete (RCC) gravity dam with a maximum height of 203 m, see Figure 5-1. It is the highest RCC gravity dam built or under construction in China and gives full play to the role of BIM as a link between the previous and the subsequent designs in the engineering construction.

Here we examine that role starting by looking first at BIM generally. During the design stage, construction requirements are introduced, and a BIM model of the whole site of the entire project layout is created to enable engineering design visualization. Relevant parameter information is queried through the BIM model of main buildings to fully understand the design intent, supporting comprehensive control by all parties involved in the project construction. The engineering design, built on a unified platform, features strong collaboration, high efficiency, and integrated information, effectively reducing coordination cost between various disciplines. The design scheme simulation is achieved through the BIM model, with different simulation schemes compared using computer-aided engineering (CAE) and other integrated analysis tools. 3D numerical structure analysis and hydraulic analysis are conducted using existing models, and the design is optimized based on the analysis results.

At Huangdeng during the construction stage, the BIM design model was repurposed to build a “Digital Huangdeng” and to develop the dam

construction quality monitoring system of the hydropower station, the slope safety evaluation and warning decision-making system, and the dynamic feedback analysis and safety warning system for the rock stability of the underground caverns. Topographic and geological information, construction progress information, monitoring information, numerical simulation information and safety evaluation information and other extensive information related to the project are integrated. In sum, the BIM model has played a large role in construction Huangdeng’s simulation, safety monitoring, quality control and other fields, strengthened the information management of the construction process, provided solutions to the construction difficulties of the project, and provided strong technical support for the construction of a high-quality hydropower project.



Figure 5-1 | Huangdeng hydropower project

5.2 Application cases of intelligent construction of hydropower projects

5.2.1 Normal concrete arch dam

Since 2017, in conjunction with the initiation of Baihetan Ultra-High Arch Dam, the theory of intelligent construction closed-loop control has been utilized as a guiding theoretical framework, see Figure 5-2. This approach involves seamless integration of engineering spatial models with information alongside ongoing refinement and advancement of such as sensing technology, data processing, and information systems. Through this framework, the hydropower industry has conducted research and developing technological practices pertaining to the intelligent construction theoretical system. The objective is to develop innovative models for engineering intelligence and precision management, as well as a business architecture that is centred on the workflows and processes of engineering construction.

The first aspect is construction process management, which is based on the dam information model (DIM) platform. This management includes excavation support, consolidation grouting, concrete pouring, temperature control, joint grouting, curtain grouting, HSSs fabrication and installation, organized around unit engineering and its associated processes and workflows.

The second aspect involves intelligent production management and control, encompassing a set of technologies for concrete pouring monitoring, concrete block spreading and vibration monitoring, intelligent water supply, intelligent spray, intelligent grouting and others. This enables intelligent production management and control through online acquisition, background processing, remote monitoring, warning and forecasting, and intelligent regulation.

The third aspect is scientific research and simulation services. The scientific research institutions can conduct construction progress

simulation and scientific research simulation services for the operational behaviour of the entire lifecycle, encompassing excavation, construction, impoundment, and operation. The simulation entity has the capability to retrieve data from the platform online and publish the results of scientific research simulations in real-time on the platform.

The fourth aspect is professional services. On the basis of the professional service, the related subsystems can be developed. These subsystems are capable of functioning autonomously and performing a variety of tasks, such as quality management, safety management, safety monitoring, test and inspection management, survey management, measurement of works, acceptance of works, hydrometeorology, and work area management. Furthermore, technical services for the intelligent construction system are provided through data interfaces.

The fifth aspect is technical management. Design outcomes, construction proposals, detailed supervision rules, and standardized construction management, regulations and specifications have all been integrated to allow for efficient digital management of technical document information, as well as for sharing and utilization by all construction parties. The Baihetan and Wudongde intelligent construction management platforms developed 22 subsystems and fundamental modules, such as a concrete pouring system that integrates 17 systems or datasets like intelligent water supply. Additionally, these platforms have developed six modules for predictive warning and query analysis, encompassing big data analysis. This integration enables comprehensive data management and information query, analysis, and display across multiple platforms and levels. After nearly five years of operation, a large amount of business data has been accumulated, forming a complete engineering database that can provide support for engineering big data analysis and data mining.

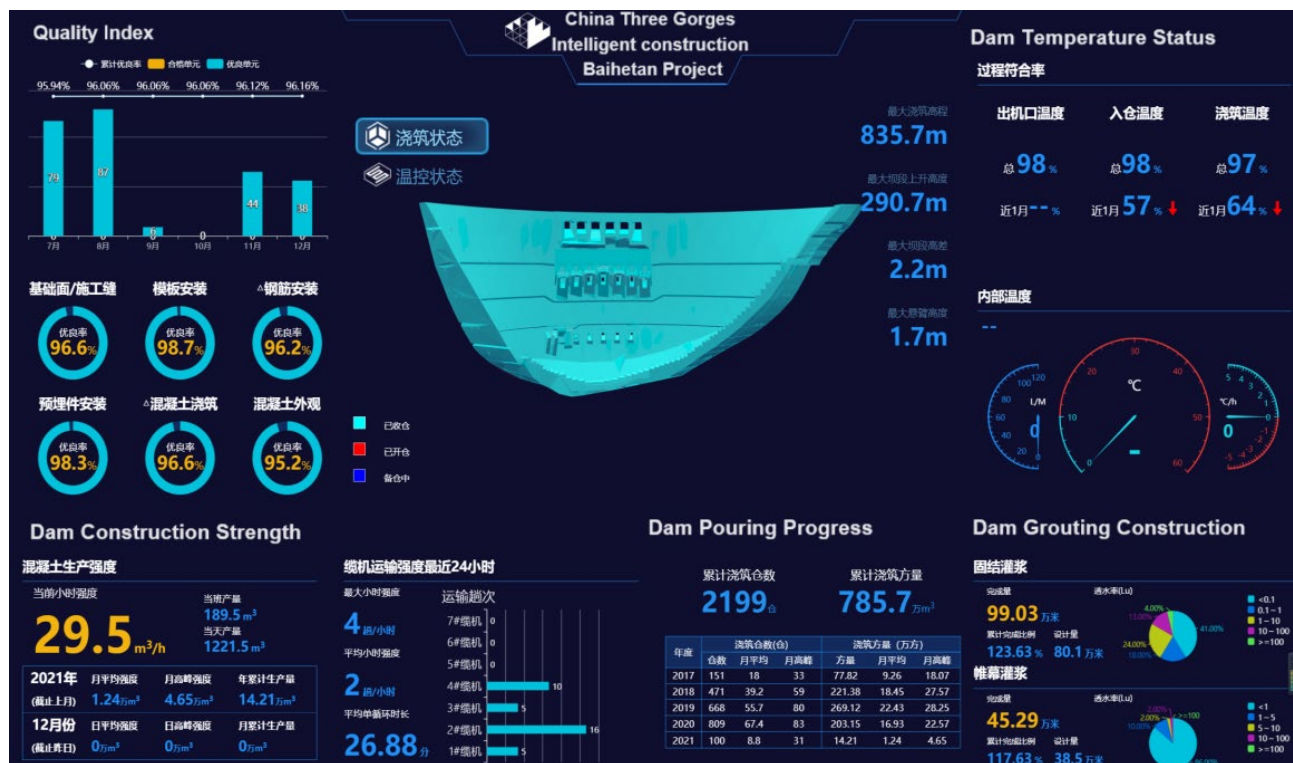


Figure 5-2 | Intelligent construction system (Three Gorges Baihetan Project)

5.2.2 Roller compacted concrete gravity dam

When concrete is poured for an RCC dam by rolling construction workmanships of embankment dam, there arise three coupling control problems of the rolling quality, mass concrete temperature control and crack prevention, and bonding between lifts. Under the traditional manual control mode, it is difficult to accurately control the pouring quality and temperature of mass RCC because the time interval for pouring of different lifts is too long and the cement slurry of the upstream impervious layer is rough, leading to large leakage after impoundment and other problems. The problems have restricted development of this advantageous dam type. For construction of Huangdeng RCC dam, Huaneng Lancang River Hydropower Inc. (Huaneng Hydropower) developed a complete set of technologies and basic theory for intelligent construction of high RCC dams. In concrete

pouring of high RCC dam, the intelligent monitoring technology system was created, and the intelligent analysis theory and technology of high RCC dam were developed, in which the prediction accuracy of the intelligent rolling quality analysis model of high RCC dam reached 99%. For comprehensive intelligent temperature control of high RCC dams, the intelligent temperature control method and model for the whole process of crack prevention during construction were put forward. A method of temperature control tracking inversion simulation analysis was also proposed. The maximum temperature control standard was optimized by 2 °C through real-time fine simulation, saving significant water supply costs. For efficient, large-scale application of intelligent construction of high RCC dam, full-process intelligent monitoring equipment for construction and the closed-loop control system for construction information in all links under complex conditions has been

developed. This achievement provided advanced technical means for high standard construction of high RCC dams and played a significant role in ensuring engineering construction quality, improving efficiency and saving investment, which was then applied to eleven large RCC dams, including Huangdeng and Fengman, see Figure 5-3. In sum, significant social and economic benefits have been achieved.

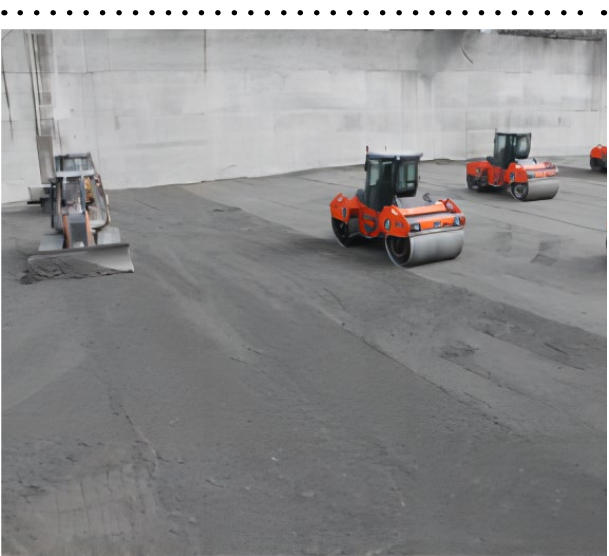


Figure 5-3 | RCC dam

5.2.3 Core embankment dam

For the high-core embankment dam, the quantities of work are large, the construction stage and zone division are complex, and the dam filling and rolling quality requirements are high, as it is difficult to accurately control construction quality by conventional quality control (QC) method. For construction of Nuozhadu Ultra-high Core Embankment Dam, Huaneng Lancang River Hydropower Inc. developed a real-time monitoring “digital dam” system for the construction quality of ultra-high embankment dams and proposed real-time monitoring technology for the transportation of dam materials to the dam to realize full-process positioning of transport vehicles from the material source to the dam face, as well as the monitoring

of loading and unloading materials, see Figure 5-4 and Figure 5-5. The real-time monitoring technology of dam filling and rolling quality was developed to realize all-weather, real-time, refined and remote monitoring of dam face filling and rolling quality. Construction quality dynamic information PDA real-time collection technology was developed to gather information on dam filling and rolling quality as well as information on vehicles transporting materials to the dam. The integrated visualization technology for digital dams under network environment has solved the difficulty in dynamic integration of comprehensive engineering information characterized by large amounts of data, diverse types and high real-time. All-weather, refined and online real-time monitoring of the whole process of dam construction has been realized by using a “Digital Dam” system. The latter is a major innovation among QC methods of dam construction in the world.

5.3 Application cases of intelligent production in hydropower plants

5.3.1 Intelligent management platform for hydropower plants

A layered “End-Edge-Cloud” architecture is adopted for smart hydropower plant platforms. Within this architecture, infrastructure resource pooling is managed through a hyper-converged cloud platform, while shared components support the development of top-level applications, forming intelligent applications for operation, maintenance and overhaul. Real-time, online monitoring of the hydroelectric units’ operating status, water inflow and energy output in the whole basin of the Lancang River is achieved using the “drainage map”. Additionally, real-time monitoring and closed-loop response to industrial Internet alarms and smart application warnings are also attained. A “plant-side dynamic portal” provides a full panoramic view of the hydropower plant and the smart hydropower plant. An integrated smart

hydropower plant management platform is built on three levels to realize integrated monitoring of multi-source data with business. This overcomes the problem of poor interactivity of a traditional static data dashboard. The smart hydropower plant

data dashboard is built in the form of visualization charts + a detailed dynamic window, so that real-time monitoring of the operation of each intelligent application and warning situation of the power plant is possible.

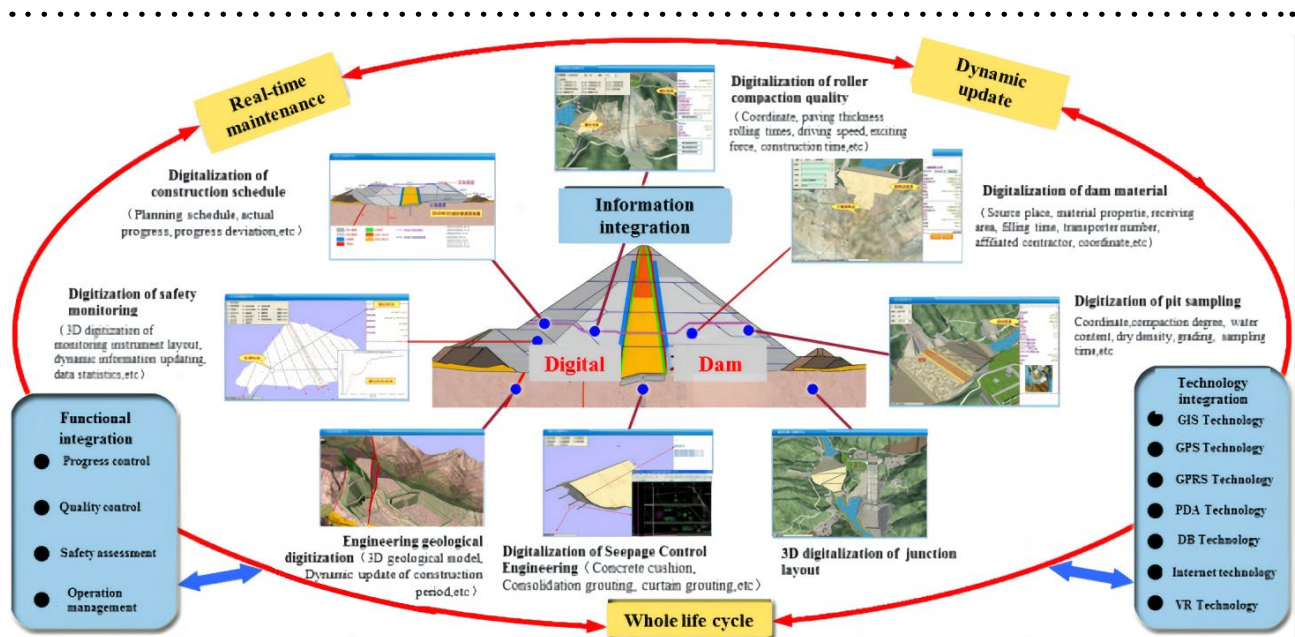


Figure 5-4 | Digital dam system



Figure 5-5 | Intelligent management system for hydropower plants

5.3.2 Intelligent monitoring of hydroelectric units

As the main body of energy conversion equipment, the hydroelectric unit is usually provided with a stability status monitoring system focused mainly on frame vibration, large shaft swing and pressure pulsation. At present, the status monitoring of hydroelectric units is changing from traditional local special monitoring to on-line intelligent monitoring of overall real-time sensing, see Figure 5-6. In addition to the hydroelectric unit stability status monitoring, the monitoring contents are expanded to cover monitoring and analysis of hydroelectric unit energy and cavitation, generator air gap, gas content in the main transformer oil, partial discharge of generator, vibration at generator stator end, magnetic field strength of generator, top cover bolt stressing and other technical parameters. Besides pressure sensors, vibration sensors, displacement sensors and other instrumentation, current monitoring equipment includes acoustic sensors, infrared temperature sensors, video equipment, gas sensors, ultrasonic

sensors, and stress-strain sensors. Thus, the acquisition of state characteristics of main and auxiliary machines of hydroelectric units can be realized, and an intelligent state sensing system can finally be built for hydroelectric units.

The intelligent monitoring system acquires real-time sensor data for state characteristics analysis and alarm. It conducts real-time analysis and evaluation by using the hydraulic, mechanical and electrical coupling model. It obtains the deterioration trend and alarm of the hydroelectric unit in operation and finds fault in advance by applying data mining and fault diagnosis technology. The traditional diagnostic method adopted in the past is based on expert knowledge and experience but can no longer meet the requirements for safe, efficient and stable operation of a hydroelectric unit. In the intelligent monitoring system of hydroelectric units, the operation normality/abnormality assessment diagnostic theory/method is adopted, and a model for multi-dimensional hydroelectric unit operation state assessment and for abnormality detection and performance degradation prediction

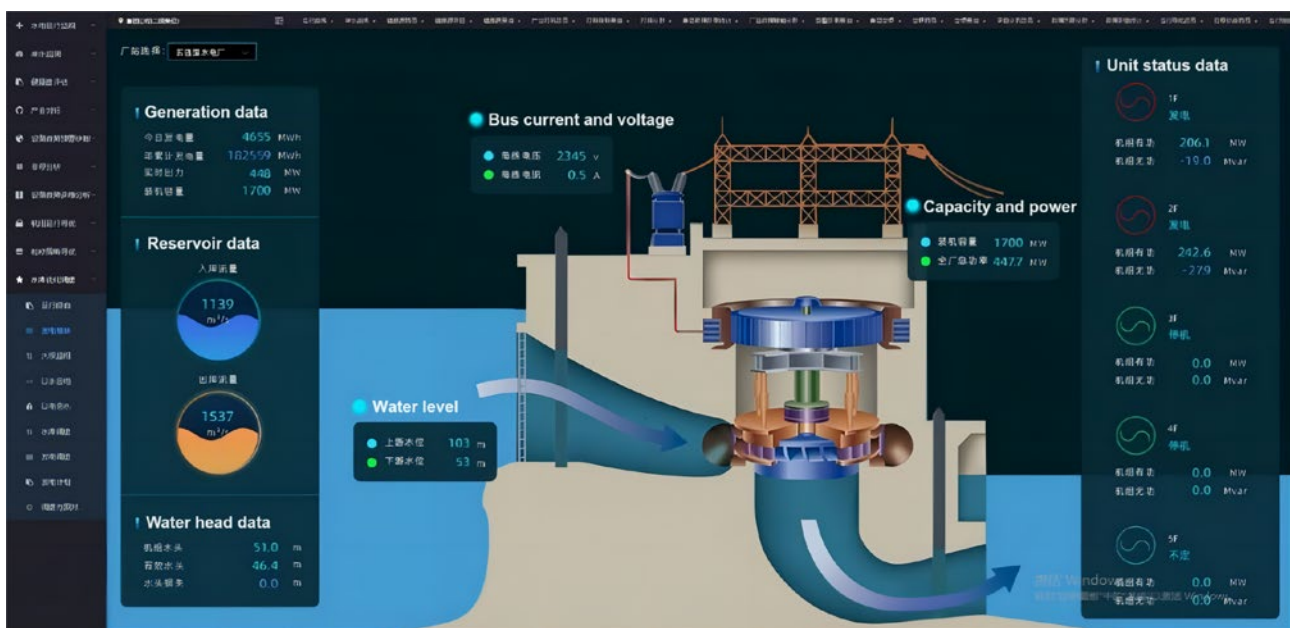


Figure 5-6 | Intelligent monitoring of hydroelectric units

are established. In this way, real-time operation state assessment and prediction of performance degradation of the hydroelectric unit are realized, improving accuracy of the abnormality diagnosis. Additionally, further fault cause analysis is conducted and suggested solutions are generated automatically through an intelligent expert diagnosis knowledge base built on deterioration assessments and fault warnings.

5.4 Application cases of intelligent regulation and utilization of water resources

5.4.1 Cascaded regulation in the Lancang River basin

As its objective, Lancang River Basin Intelligent Cascaded Dispatching supports the deep integration of hydrological data acquisition and transmission in Lancang River basin. This consists of long-, medium- and short-term meteorological and hydrological forecasting, joint optimal regulation of reservoirs in the basin, intelligent regulation and control of flood gates, self-learning and evolution of system regulation mode, and 3D visualization.

An intelligent water regulation decision-making system covering flood forecasting, an optimized intelligent regulation and intelligent decision-making for flood control is built in. Four centres for intelligent water regulation decision-making have been constructed in Lancang River basin.

The first is the meteorological and hydrological forecasting centre, comprehensive sensing is carried out for the meteorological and hydrological information of each province in Lancang River basin, in the regional power grid and in the Mekong River basin; they serve as meteorological and hydrological forecasting centres to provide the integrated long-, medium- and short-term meteorological and hydrological predictions of each reservoir in Lancang River basin and those

of other basins of the region, allowing for intelligent regional energy prediction.

Second, is the joint optimization regulation centre and carries out intelligent analysis and conducts cascaded reservoirs optimization regulation and flood optimization regulation while considering the following: the operation of cascaded power stations on the Lancang River, the system supply and demand, the power market, the multi-energy hybrid, the equipment maintenance and other complicated factors. It these functions to realize both joint optimization regulation centre with efficient use of water resources and maximized power generation benefits for the power stations.

Third, is the emergency commanding decision-making centre that provides intelligent warning for heavy rainfall, large-scale floods and geological disasters in the Lancang River basin. It can intelligently operate and control flood gates of a cascaded power plant. Using 3D visualization technology, it can display the evolution of rainfall and floods in the basin, the operation of reservoirs and the manipulation of gates and can serve as an emergency commanding decision-making centre to provide intelligent decision-making on flood control and emergency regulation for disasters in the basin.

Fourth, is the Lancang-Mekong cooperation demonstration centre and gives full production to the regulation role of cascaded reservoirs in the basin, considering demands for ecological water, production and living water, and shipping water in combination with the meteorological and hydrological characteristics of the Lancang-Mekong River, see Figure 5-7.



Figure 5-7 | Intelligent cascaded regulation of the river basin

5.4.2 Cascaded regulation in the Yangtze River basin

The intelligent Three Gorges cascaded dispatching system is used to carry out intelligent sensing, analysis and judgement for the massive information of water resources system with hydropower stations as the core. It does this by relying on cloud computing, big data and other advanced technologies, focusing on the two core functions of forecasting and dispatching. It also provides intelligent forecasting, dispatching, decision making and evaluation. In recent years, a series of forecasting and dispatching technology support systems have been developed and applied in the Three Gorges system, enabled by the improved water resource utilization in the basin and the comprehensive benefits of the cascaded reservoirs.

With the complete set of leading meteorological business systems in China having been built, a system covering the real-time monitoring of the water and rain regimes of the entire

Yangtze River basin, a short and medium-term refined precipitation grid forecast, the extended precipitation process forecasts, and a long-term precipitation trend prediction was developed, see Figure 5-8. Also developed was a hydrological forecasting system adapted to the characteristics of cascaded reservoir regulation in the basin, whose forecasting contents include those required for annual, monthly, ten-day, weekly and daily forecasting of the long, medium and short term; the accuracy of this forecasting is at the leading level in the industry. Additionally, an automatic water regulation system, an automatic power dispatching system and other production business system have been successively built for the production dispatching of Yichang, Chengdu, and Kunming, etc. Finally, developed, too, is a water resources decision-making support system of complete independent intellectual property rights with well-known scientific research institutes of China for Yangtze River Power providing key technical support for the joint regulation of six reservoirs.

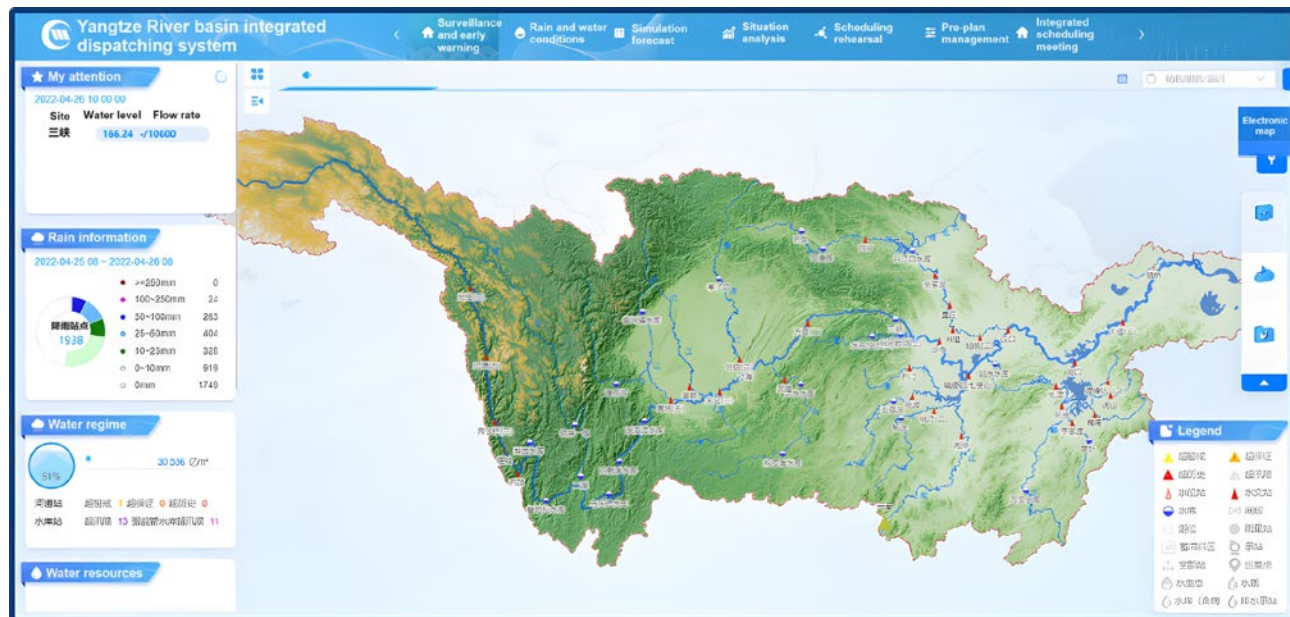


Figure 5-8 | Integrated integration system of Yangtze River basin

5.4.3 Efficient utilization of hydro energy example from Brazil

Since the end of 1990s, Brazil has suffered from drought all the year round, and water resources are scarce. Therefore, the efficient utilization of water resources is very important for national power supply in Brazil. Each day, the operators of national power system of Brazil send out the demand for power supply for the next day to the energy operators, and most of the operators responding to these demands are the owners of hydropower plants. Indeed, annually more than 66% of electric power comes from hydropower. The national energy operators comprehensively consider such factors as reservoir water level, inflow, downstream discharge when supplying power. Without affecting the social demand and environment, providing the best power is one item of work that needs to fully mine and utilize available data.

Aiming to simplify power dispatching work for power plant operators, a software developed by Optimal Energy of Brazil called Hydropower

Optimizer provides operators with solutions to optimize power dispatching according multiple internal and external constraints, see Figure 5-9. Hydropower Optimizer has been used in 18 power plants in Brazil that accounts for 10% of the installed capacity of the country. The software can simulate the power generation operation of the power plant in combination with the flow, output and other parameters of the turbine, and can provide better operation suggestions in each given hour and at different water levels of the reservoir. In addition, one key function of Hydropower Optimizer is providing a visual warning system to alert of potential violations of restrictions and also provide the options for correcting actions and ensuring compliance. Optimal Energy estimates that 46.7 hm³ of water and about 500 000 dollars can be saved per month by making use of their software in 387 MW Tres Maria Hydropower Station.



Figure 5-9 | Brazil's Hydropower Optimizer software interface [15]

5.5 Application cases of safety monitoring and risk prevention and control in hydropower projects

5.5.1 Intelligent online monitoring platform for dams in the basin

In long-term operation of reservoirs and dams, the safety problems encountered include dam safety, safety of underground works, slope safety, and water environment safety. In the dam safety arena, Huaneng Lancangjiang Hydropower Inc. has, after technical breakthroughs over the years by others, inherited special scientific research achievements including intelligent diagnosis of dam operation and safety, dynamic control of underground works, rapid assessment of high dams and strong earthquakes, and warning and prevention and control of slope hazards. The company has built the first basin-level intelligent online monitoring

platform for dams in China (see Figure 5-10) and realized cascaded dam safety control in the basin with one network and dam information display on a single screen, a dam information “one-screen overview”. In terms of intelligent dynamic control of large underground caverns, the company has constructed a long-term safety dynamic evaluation system of “multi-source integration and all-round evaluation” for large underground works and developed a digital twin control module for large underground caverns, which integrates visualization twin of geological and engineering structures, synchronous interaction of monitoring information, dynamic evaluation of safety status of caverns, long-term safety collaborative control and decision-making as a whole.

As for the rapid assessment of the risk of strong earthquake of high dams, Huaneng Hydropower has put forward rapid analysis methods for seismic



Figure 5-10 | Intelligent online monitoring platform for dams in the basin

intensity, modal parameters, stress response, etc., and achieved comprehensive earthquake hazard assessment for high-concrete dams in a “regional-integral-local” way. With monitoring and risk prevention and control of geological hazards on bank slopes, the company has developed the air-space-ground-depth integrated safety monitoring technology of large-scale general investigation, regional inspection, detailed investigation at key positions for geologic hazards control on bank slopes of the basin. The accuracy for identifying landslide risk points at the basin level has reached 92%, and the accuracy for monitoring the continuous deformation of key landslides reaches up to the millimetre level.

5.5.2 Laser 3D inspection for dams

Hydropower plants can be in service for a long time. Many hydropower plants built in the early 20th century are still in normal operation. Timely and effective identification of problems and repairs in aging hydropower infrastructure and equipment is helpful in further extending the service life of hydropower plants. Over time, the flood gate of a hydropower plant may jam, and the performance of the control elements used to regulate the downstream water level may degrade, resulting in peak water level of the reservoir, which in extreme cases may lead to dam failure. The timely detection and fixing of equipment and facilities aged or damaged helps to reduce the O&M costs of the power plant, but it is not easy to carry out such detection for underwater structural elements, where the detection accuracy is particularly essential. The traditional method of gate inspection

is by underwater human divers. But only a limited number of data can be acquired by this method, and data analysis usually takes a long time.

Hydro Quebec, the largest power company in Canada, has developed a laser scanning tool called WireScan, which can carry out accurate, real-time, high-precision 3D scanning for vertical surfaces of hydropower facilities, see Figure 5-11. The plumb line is taken as the benchmark. WireScan can be used in places where the underwater visibility is greater than 1 m. It is suitable for narrow spaces, work sites and various harsh environments. It can obtain reliable flatness and perpendicularity measurements at any height, and the maximum vertical coverage is up to 30 m. It is less affected by surface waves or changes in water level and can automatically generate detection result graphs. Since 2020, WireScan has been used by more than 100 facilities owned by Hydro Quebec, British Columbia Hydro (BC Hydro) and NB Power.



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Figure 5-11 | Scanning by WireScan [16]

5.6 Application cases of ecological environment monitoring and evaluation

5.6.1 Monitoring of water environment in deep and large reservoirs

The construction of giant cascaded hydropower stations can effectively improve to an excellent level regulation and control of water resources and realize significant energy and socio-economic benefits. However, such stations do significantly affect the hydrological process of natural rivers and the attributes of river water bodies and create a plateau-cascaded artificial “lake-reservoir”. Therefore, water environment monitoring of these deep and large reservoirs has become an important issue. Huaneng Hydropower carried out research, development and integration demonstrations of key technologies for water environment monitoring and assessment in the deep and large reservoirs formed by development of Lancang River basin and the cascades. They developed three sets of layered sampling and online monitoring devices for water environment with a depth of more than 200m, including a deep water-chemical stratified sampling device for reservoir water and an in-situ partial pressure equilibrium dissolved gas sampling device for water body. In addition, the company has developed a floating platform for online monitoring of water environment of deep and large reservoir, see Figure 5-12. They have formulated the optimal layout and control technology of monitoring station network for deep and large reservoirs and formed a sound technical system for monitoring and evaluation of water bodies of deep and large reservoirs in the basin. They also realized a technical breakthrough in monitoring and evaluation of water environment under ultra-deep and ultra-large conditions and improved the real-time dynamic monitoring capability of the water environment in the basin under conditions of cascaded hydropower development.



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Figure 5-12 | Floating platform for online monitoring of water environment

5.6.2 Intelligent dredging of reservoirs

Reservoir sediment management is an important challenge for hydropower industry because the accumulation of sediment will affect water quality and reduce energy output of power plants. To maintain the health of the water body when a reservoir's sediment accumulates, it is usually cleaned by manual dredging. The cost of dredging is very high, and the power plant must often reduce its power generation during large-scale dredging in the reservoir. Nessie is a pioneering reservoir cleaning robot (see Figure 5-13), jointly developed by a French company Watertracks and the French power company Electricité De France (EDF), that removes sediments and debris from the bottom of reservoirs and lakes. In November 2020, EDF approved the operation of this product. Nessie dredged 14 000 m³ of sediment of Sautet Dam at a depth of 54 m. Nessie is not limited by the depth of water and can dredge in both fresh water and saltwater. Importantly, because it copies the natural process of the river in removing reservoir sediments, Nessie's work does not interfere with normal operation of the hydropower station.



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Figure 5-13 | Nessie robot [17]

5.7 Application cases of pumped storage

5.7.1 Variable-speed pump turbine units

Because power generation by wind power, solar energy and other new energy is intermittent and variable, their large-scale integration will impact the grid. Such energy sources needs to be used together with an energy storage regulation system. The pumped storage is one kind of energy storage mode that can provide power grid-level energy storage with ultra-large capacity. Variable-speed pump turbine units can change the rotor speed, and flexibly and quickly adjust the power, so that new energy can be connected to the power grid in a more stable way. At present, most variable-speed pump turbine units in the world are located in Japan and Europe. Japan is currently the country with the largest number of variable-speed pump turbine units. Since the 1990s, variable-speed pumped storage technology has been applied to achieve power grid frequency control in Japan. Variable-speed pump turbine units have been successfully used in Okinawa, Shiobara, Okukiyotsu, Komarukawa, Kazunogawa and other pumped storage power stations, with a total installed capacity of more than five million kilowatts, including Komarukawa pump turbine units with a maximum speed of 600 rpm and

Kazunogawa pump turbine units with a maximum capacity of 475 MVA/460 MW, a maximum rated head of 714 m and a rated speed of 500 rpm.

Komarukawa pumped storage power station is located in Miyazaki, Kyushu Region, see Figure 5-14. There are four pump turbine units in the power station, two fixed-speed and two variable-speed. The capacity of the fixed-speed units are each 300 MW with a rated head of 646.2 m. With high efficiency and miniaturization of pump turbine as the goal, the unit has a rated speed of 600 rpm. The units of Komarukawa pumped storage power station can respond rapidly to demand. For example, the time required from standstill to full-load operation was shortened from 5 min to 2.5 min, while the time required to reach the rated speed is shortened by 47 s, and the opening time of ball valve is shortened by 10 s, reaching the leading level in the world. The variable speed range of the two variable-speed pump turbine units are each 576-624 rpm. Each unit can change the input of 100 MW within 15 s under pumping condition. As a result, the automatic frequency tracking range under pumping condition

expanded from 270 MW-340 MW to 240 MW-340 MW, and the minimum input under pumping condition was also reduced from 252 MW to 224 MW. Since the generator-motor can operate at any speed within the allowable range, the grid-connection time can be significantly shortened after the unit startup, and fast power regulation can be achieved.

5.7.2 Hybrid pumped storage power station

A hybrid pumped storage power station is a hydropower station with pumped storage and run-of-river power generation. With sufficient natural runoff recharging the upstream reservoir of the hydropower station, a hybrid pumped storage station can not only undertake conventional power generation and comprehensive utilization of hydro energy by using natural runoff, but it can also increase the peak shaving and valley filling, emergency reserve and others. Because the upper reservoir of a hybrid pumped storage power station makes use of the existing reservoir, it has such advantages over a conventional pumped storage



Figure 5-14 | Application of variable-speed units for Komarukawa pumped storage power station in Japan

power station as low project investment (cost), small reservoir inundation loss, no resettlement, a small environmental impact and a short construction period. It also has better economy and market competitiveness. The Lianghekou Hybrid Pumped Storage Power Station on the Yalong River in China, for instance, uses the reservoir of Lianghekou Hydropower Station as the upper reservoir and the reservoir of Yagan 1 Hydropower Station, connecting the cascaded hydropower downstream, as the lower reservoir, see Figure 5-15.

The capacity expansion of reversible hydroelectric units has dual regulating roles of pumping and power generation, allowing peak shaving and valley filling for the power grid. The power gap is supplemented by power generation and peak shaving, and surplus power is consumed by pumping and valley filling. The grid is supplemented by means of power generation when the power generation of new energy is insufficient and electric power is in short supply. In such instances, the reserved hydro energy is converted into electric energy. When the power generation of new energy is sufficient and the power is in abundance, the surplus power of the grid will be consumed by pumping, and corresponding electric energy is reserved as hydro energy.



Figure 5-15 | Lianghekou hybrid pumped storage power station on the Yalong River

5.8 Application cases of power generation of hydro-wind-solar hybrid project

5.8.1 Power generation of hydro-solar hybrid project

Longyangxia Hydro-Solar Hybrid Project (see Figure 5-16) was the first hydro-solar hybrid project in the world. A 320 MWp grid-connected PV power station was built in the first phase. It uses the storage and regulation performance of hydropower, as well as the characteristics of convenient startup and shutdown and rapid regulation of hydroelectric units to allow hydropower to support PV by providing capacity, PV to support hydropower through energy output and optimization of the PV power generation output curve to deliver high-quality electricity for the grid. When the concept of “virtual hydropower” is applied, the PV station and hydropower station operate in hybrid mode, allowing the power grid to dispatch them as one power plant according to the hydropower dispatching mode. The new energy power station functions as a base load unit of the hydropower station, participating in system load balancing and peak shaving, so the power grid will no longer need to provide reserve capacity for it. Through the hydro-solar hybrid, the annual utilization hours of the transmission line (TL) of Longyangxia Hydropower Station can be increased from 4 621 h to 5 019 h, boosting economic benefits for the power grid. The operation of the Longyangxia Hydro-Solar Hybrid Project demonstrates that hydro-solar hybrids can fully utilize the rapid regulation capacity of water hydroelectric units and the energy storage function of reservoirs. This coordinated approach enables PV power stations to smooth their power generation curve, improving energy quality and efficient dispatch. Seasonally, solar and hydropower outputs complement each other, potentially enhancing hydropower’s peaking capacity.



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Figure 5-16 | Longyangxia hydro-solar hybrid project

5.8.2 Power generation of hydro-storage hybrid project

Located on the bank of the Rhine River, Vogelgrun (see Figure 5-17) is a 142 MW run-of-river hydropower station in France on the German border. The project, which began operation in 1959, had four 39 MW low-head Kaplan turbines. With the operation of XFLEX HYDRO Project, one of the turbines in Vogelgrun Hydropower Station was used together with battery energy storage system (BESS). As an auxiliary device of the turbine, BESS can effectively increase the energy storage capacity and share the response ability with the hydraulic device. The flexibility of the hydropower system is also enhanced, and the hydroelectric unit wear impact is reduced through the optimization of the main control system. The integrated operation of Vogelgrun with the BESS has greatly improved the utilization rate of renewable energy and provided more flexible regulating ability for a power plant.

This hybrid mode enables the hydropower station to better adapt to changes in grid demand, meet power demand in peak load periods, and store

excess energy in low load periods. The innovative application at Vogelgrun has been an important way of promoting development of clean energy and renewable energy. It has provided more reliable, flexible and efficient power supply for local and regional power grids and promoted the application and development of energy storage technology.



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Figure 5-17 | Vogelgrun hydropower station [18]

Section 6

Standardization analysis

6.1 Present standardization work

Currently, IEC, ISO, IEEE and some countries have carried out standardization exploration in smart hydropower and its supporting technologies, but they have faced problems such as insufficient technical standards, incomplete coverage, lack of consensus among countries on the concept, scope and demands of smart hydropower.

6.1.1 IEC

IEC TC 4 (Turbine) has carried out standardization work related to smart hydropower, established WG 14 (Hydroelectric power plant automation and turbine governing systems), and issued, in 2023, the important deliverable IEC/IEEE 63198-2775, *Technical guidelines for smart hydroelectric power plant*. The scope of their standards includes smart hydropower plant system architecture, equipment configuration and functions, network security, commissioning operation and maintenance services, mainly for the smart production of hydropower plants, but only involving a part of the scope of smart hydropower. The standards belong to the general standards in content and put forward the basic requirements for the smart production of hydropower plants. The standards for all aspects of smart production need to be supplemented.

IEC's other technology-related TCs are the following: TC 2 (Rotating machinery), TC 57 (Power system management and associated information exchange), TC 65 (Industrial automation), ISO/IEC JTC 1 (Information technology) and its following SCs: SC 6 (Telecommunications and information exchange between systems), SC 7 (Software and systems engineering), SC 24 (Computer graphics,

image processing and environmental data representation), SC 31 (Automatic identification and data capture techniques), SC 32 (Data management and interchange), SC 38 (Cloud computing and distributed platforms), SC 41 (Internet of things and digital twin), and SC 42 (Artificial intelligence).

6.1.2 ISO

ISO TC 108/SC 5 (Condition monitoring and diagnostics of machine systems) develops ISO 13374, *Data processing, communication and presentation*, ISO 13379, *Data interpretation and diagnostics techniques*, ISO 13381, *Prognostics*, a series standard to construct a technical system for condition monitoring and diagnostics of machine systems.

ISO's other technology-related TCs are the following: TC 71 (Concrete, reinforced concrete and pre-stressed concrete), TC 113 (Hydrometry), TC 131 (Fluid power systems), TC 147 (Water quality), TC 182 (Geotechnics), TC 207 (Environmental management), and TC 339 (Small hydropower plants).

6.1.3 IEEE-SA

The ongoing project IEEE P2413.3, *Guide for Hydropower Energy Internet of Things*, describes mainly the technical system used for intelligent analysis and application. According to the guide, each distributed hydropower station achieves extensive involvement of terminal equipment of each hydropower station, data interconnection sensing, mass data acquisition, and forms cross-

basin optimal regulation, remote intelligent O&M, and virtual power plants by making use of big data, cloud platform, IoT and other technologies. The guide also defines the data interconnection between hydropower stations and the IoT and mines the value of data to provide technical support for power data, virtual power stations, remote maintenance, etc.

Other standards projects supporting smart hydropower include:

- IEEE P2807, *Framework of Knowledge Graphs*
- IEEE P2841, *Draft Framework and Process for Deep Learning Evaluation*
- IEEE P3110, *Draft Standard for Computer Vision (CV) – Technical Requirements for Algorithms Application Programming Interfaces (APIs) of Deep Learning Framework*, and *IEEE P3123, Standard for Artificial Intelligence and Machine Learning (AI/ML) Terminology and Data Formats*
- IEEE P3142, *Recommended Practice on Distributed Training and Inference for Large-scale Deep Learning Models*
- IEEE IC20-012, *Roadmap for the Development and Implementation of Standard-Oriented Knowledge Graphs*

6.1.4 International institutions

Here are three important international institutions and their latest main work:

- The International Association for Hydro-Environment Engineering and Research (IAHR) has issued a White Paper, *Artificial Intelligence. How can water planning and management benefit from it?*
- The International Commission on Large Dams (ICOLD) has issued a series of bulletins in recent years, including *Dam Surveillance – Lessons learnt from case histories*, *Operation of Hydraulic Structures of Dams*, *Dam Safety*

Management: Pre-operational Phases of the Dam Lifecycle, Integrated Operation of Hydropower Stations and Reservoirs, and Aging of Concrete Dams

- The International Hydropower Association (IHA) has issued recommendations for industrial deployment of hydropower flexibility technologies in two guides: *IHA Good Practice Guide: Hydropower and Protected Areas*, *Innovative Pumped Storage Hydropower Configurations and Uses*, and *How-to Guide: Hydropower Downstream Flow Regimes*

6.1.5 Relevant countries

Europe: XFLEX HYDRO project is developing a white paper on intelligent technologies for hydropower. The project was completed by 19 leading utilities, equipment manufacturers, universities, research centres and consulting companies working over four years. The white paper will demonstrate how hydropower stations can provide better flexibility and system support to balance the power grid and adapt to more renewable energy connection.

United States: National Institute of Building Science (NIBS) has developed National BIM Standard-US, whose main content framework includes three levels: standard reference layer, information exchange layer and BIM Standard implementation layer. NIBS formed a set of feasible BIM standards systems. The American Society for Testing and Materials (ASTM) developed ASTM D6224-98, *Standard Practice For In-Service Monitoring of Lubricating Oil for Auxiliary Power Plant Equipment*, which covers the requirements for effective monitoring of mineral oil and phosphate ester fluid lubricating oils in service auxiliary (non-turbine) equipment used for power generation. The American Society of Mechanical Engineers (ASME) developed ASME PTC 29, *Speed Governing Systems for Hydraulic Turbine Generator Units*, which guides the machinery

that converts the energy of flowing water, steam, or wind into mechanical energy, and then into electricity.

China: The Standardization Administration has formulated a series of national standards around the integrated management and control platform of smart hydropower plants, the maintenance of unit conditions, and the linkage of safety protection, etc. Table 6-1 lists some Chinese national standards related to smart hydropower.

6.2 Standardization requirements

Standards are the essence refined from advanced technology and practical experience, and they play both a supporting and a leading role in industrial development. Smart hydropower involves a wide range of professional fields, covering project development, production and operation of

hydropower plants, regulation of water resources, basin-wide ecological and environmental protection etc. The focus of research varies among the different international standards organizations and countries. Only certain sub-fields or specific application cases in the field of smart hydropower have been addressed by several standards, either released or being prepared.

Further standardization demands for smart hydropower are as follows:

- Unify the concept of smart hydropower and define the technical scope of smart hydropower
- Establish technical framework and standards system for smart hydropower
- Carry out research and development of needed standards regarding the eight technical subfields of smart hydropower proposed above in Section 4

Table 6-1 | Series standards for intelligent hydropower plants

No	Standards
1	Technical specification for unified management and control platform of smart hydropower plant (GB/T 39264-2020)
2	Technical guide for main equipment condition-based maintenance decision support system for smart hydropower plant (GB/T 39324-2020)
3	Technical specification of flood control emergency command system for smart hydropower plant (GB/T 39565-2020)
4	Technical specification of intelligent measurement and control devices for smart hydropower plant (GB/T 39627-2020)
5	Technical requirements of security and protection system linkage for smart hydropower plant (GB/T 39629-2020)
6	Specification for economic operation system of smart hydropower plant (GB/T 40221-2021)
7	Guide for smart hydropower plant (GB/T 40222-2021)
8	Technical requirements of common information models for smart hydropower plant (GB/T 40234-2021)
9	Technical specification for dam safety analysis and evaluation system of smart hydropower plant (GB/T 40285-2021)

Section 7

Conclusion and outlook

7.1 Summary

With the challenge of global warming and energy crisis, construction of a zero-carbon power system has become an important way to solve energy and environmental problems and promote sustainable development. Hydropower, as a clean and low-carbon power supply mode with significant economic benefits and good regulatory performance, is playing an important role in the global transformation to low-carbon energy. At present, the global hydropower inventory is large and the newly installed capacity is growing rapidly. In order to cope with the development of a zero-carbon power system and new demand, hydropower technology innovation is imperative. That imperative has led to the new concept of smart hydropower.

With the integration and development of hydropower and advanced information technology, new technology fields and new industries of smart hydropower have gradually emerged. Smart hydropower is a reliable force for promoting the construction of a zero-carbon power system, and smart hydropower's development prospects are broad and significant. Because of its characteristics of full sensing, real analysis, intelligent control, optimization and enhancement smart hydropower expands the function of traditional hydropower, carrying forward the latter's advantages and making up for its shortcomings. Smart hydropower can enhance the stability of the power system, guarantee the safety of project construction and operation, improve the economic benefits of power generation and accelerate the eco-friendly and environment-friendly development.

Smart hydropower includes many sub-technical fields, covering the whole lifecycle of hydropower projects. Significant progress has been made in the development of smart hydropower, a large number of key technical achievements have been accumulated, and a series of application cases have emerged, such as BIM-based hydropower project design, intelligent construction of multi-type large-scale hydropower buildings/structures, smart production platform and application of hydropower plants, intelligent monitoring equipment for the water environment of deep and large reservoirs. Smart hydropower also faces some technical challenges, which need to be solved by further integration with smart technology.

Standards play an important role in the development of smart hydropower. Standards can promote the construction of technical frameworks, accelerate the development of technical fields of smart hydropower and promote coordination and unification of technologies. At present, major international standardization institutions, academic institutions and some countries have carried out standardization explorations in smart hydropower and its support technologies. However, the standardization of smart hydropower is at an early stage, and little consensus has been reached on the concept and scope of smart hydropower on a global scale. The main work to be done involves technical framework research, , system research and other basic standards research. There is also imbalanced development of standardization in various technical fields and a lack of support from specific technical institutions in some areas. Therefore, there is, an urgent need to develop the standards of smart hydropower and its related

supporting fields to drive the rapid development of smart hydropower and its related industries and widen the intelligent boundaries of the power industry.

- Carrying out standardization activities and technical exchanges widely in the field of smart hydropower

7.2 Outlook

Globally, a consensus has not been reached on the basic concept of smart hydropower. But smart hydropower is inevitable, and it is a solid force in supporting the zero-carbon power system and promoting sustainable development. Its technology will rely on the rapid construction of a zero-carbon power system and new technologies to flourish, ushering in a new stage of development, to achieve the following goals:

- Deep integration and connectivity with advanced information technology
- Adequate coordination with traditional management modes
- Guarantee of an efficient, safe and sustainable supply of energy
- Reduction of carbon emissions from fossil energy consumption
- Provision of an effective path for comprehensive solution of multiple UN Sustainable Development Goals

Standards will become an important platform for the development of smart hydropower, leading the technical development of smart hydropower and related directions, regulating market order, and promoting sustainable development of the industry. Standardization of smart hydropower will develop rapidly and achieve the following goals:

- Reaching a consensus on the concept and scope of the smart hydropower field
- Establishing a sound standards system for smart hydropower
- Publishing related technical standards for smart hydropower

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