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Practice and prospects for intelligent construction and smart operation of Lancang River Hydropower Projects

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ABSTRACT

A hydropower project has four significant stages: artificialization, mechanization, automation, and digitization. Currently, it is in the intelligent stage and is advancing toward smartization. This study first briefly introduces the development process of intelligent construction and smart operation of the Lancang River Hydropower Project, and comprehensively summarizes the research, development, and practice in intelligent construction of the project and smart operation management of the reservoir dam. Then, the main functions and effects of digital construction of high earth–rock dams and intelligent construction of high roller compacted concrete (RCC) dams were elaborated. Special technologies and module functions such as intelligent diagnosis of dam operation safety, dynamic control of underground engineering, early warning and prevention of slope disasters, and online monitoring of the water environment of deep and large reservoirs were introduced. Finally, the future development trends of smart hydropower were discussed. The research can be used as a reference in the intelligent construction and smart operation of similar projects.

1 Preface

China is a major hydropower development country. By the end of 2022, China's hydropower installed capacity (including pumped storage) reached 414.00 million kW. In 2021, the State-owned Assets Supervision and Administration Commission of the State Council issued *Notice on Accelerating the Digital Transformation of State-owned Enterprises*, which requires accelerating the digital transformation of conventional industries in an all-round, all-angle, and all-joint way. Owing to their large scale, long cycle, complex construction technology, and many stakeholders, hydropower projects undergo four important stages: artificialization, mechanization, automation, and digitization [1], and are exploring the management mode of information and intelligence. Since the beginning of the "12th Five-Year Plan" period, Ma et al. [2] have pioneered the theory of digital dams and successfully applied it to the construction practices of Nuozhadu, Dagangshan, Xiluodu, Changheba, and other large hydropower projects. With the integration and development of the new generation of information technology and hydropower projects, hydropower construction and operation have gradually entered the intelligent stage. Zhong et al. [1], Lin et al. [3], Jia et al. [4], Fan et al. [5], Fan et al. [6], Wang et al. [7], and Minchin et al. [8] have explored the theory, method, and technology of intelligent hydropower construction, which have been applied and practiced in Huangdeng [9], Baihetan, Lianghekou, Shuangjiangkou, and other projects. Intelligent construction and management systems [10] for hydropower dams have been developed, with intelli-

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gent simulation, rolling, grouting, transportation, vibration, and temperature control as core technologies, and they are advancing toward amortization.

Smart hydropower has the typical characteristics of massive multisource data-driven, self-enhanced, and expanded learning ability, multifunctional coordination and unification, intelligent decision making, and overall utility optimization, which can ensure efficient, safe, and sustainable power supply. The Lancang River Basin can be called the library of dam. Major hydropower projects with milestone significance, such as the Xiaowan Concrete Arch Dam, Nuozhadu Core-Wall Rockfill Dam, and Huangdeng Roller Compacted Concrete (RCC) Gravity Dam, have been built successively. From the Nuozhadu Digital Dam [2] to the Huangdeng Intelligent Dam [9] to the integrated management of intelligent construction and smart operation of reservoir dams [11], we have always adhered to demand orientation, promoted the innovation and practice of smart hydropower technology, and achieved many influential scientific research results that provide important technical support for the construction and operation of hydropower projects.

2 Development and practice of intelligent construction of hydropower projects

Construction quality requirements gradually improve during the construction and development of hydropower projects as the scale and difficulty of dam construction increases. It is difficult to guarantee construction quality under the conventional manual control mode, which poses a severe challenge to dam safety. The Lancang River is a hydropower basin with several built cascade hydropower stations and is at the top scale of operation and installed capacity in China. Its total length is 2153 km, and 23 cascades are planned in the main stream. Currently, hydropower projects in the Yunnan section have been developed and completed, with 11 hydropower stations operational, totaling 21.35 million kW of installed capacity. To achieve full production by 2030, the development and construction of hydropower projects in the Tibet section will be accelerated [12]. The high-quality and efficient construction of super-large-scale cascade hydropower stations poses a significant challenge to the construction and management of hydropower projects. It is urgent to apply digital intelligent technology to improve construction and management levels. Hydropower projects in the Lancang River Basin have undergone intelligent construction, including the Nuozhadu Digital Dam, Huangdeng Intelligent Dam, and Toba green intelligent construction. Currently, integrated management planning and application exploration of intelligent construction of hydropower stations in the basin are being performed.

In the construction process of the Nuozhadu Earth–Rock Dam, digital monitoring technology is adopted to monitor various filling parameters in real time, realizing all-weather, fine, and online real-time monitoring of the entire process of dam construction. The construction of the RCC gravity dam at the Huangdeng Hydropower Station adopted comprehensive digital and partial intelligent monitoring technology. The entire process of digital and intelligent construction of the entire dam, including raw materials, concrete production and transportation, placement, rolling, thermal lifting, temperature control, impervious layer control, and grouting control, has been realized. The construction of the Toba Hydropower Station has also been upgraded on the basis of intelligent construction achievements from the Huangdeng and Baihetan Projects, realizing building information management (BIM), intelligent dam construction, intelligent underground powerhouse construction, intelligent management of electromechanical installation, general business management and decision support, and green construction archives at the same time.

2.1 Digital construction technology for high earth–rock fill dams

Earth–rock dams are the most extensively used dam types because of their strong adaptability to foundations, high seismic capacity, and low cost. The height of the Nuozhadu Core-Wall Earth–Rock Dam is 261.5 m. Compared with the highest earth–rock dam built in China at that time, its height increased by 100.0 m. The existing theory, technology, experience, and specifications cannot meet the needs of this dam construction. In terms of dam construction technologies such as artificial gravel mixed soil and soft rock rockfill dams, the Nuozhadu Core-Wall Earth–Rock Dam pioneered the construction and application of “digital dam” technology, as shown in Fig. 1, opened up a new mode of quality control for hydropower projects in the world, and promoted China’s high earth–rock dams from 150.0 to 300.0 m.

2.1.1 Research and development of digital dam system for high-core rockfill dams

High-core rockfall dams require extensive engineering, complex construction stage division, and high-quality dam filling and rolling. It is difficult to achieve precise control of construction quality using conventional quality control methods. To realize precise control of construction quality, it is necessary to establish a real-time monitoring mathematical model for the filling and rolling quality of high-core rockfill dams and the transportation process of dam materials and a real-time control mathematical model for the construction progress of concrete dams under complex constraints. A real-time construction control method based on a mathematical model is studied, which provides a theoretical basis for the real-time control of hydropower project construction. Second, on the basis of theory, real-time monitoring technology of

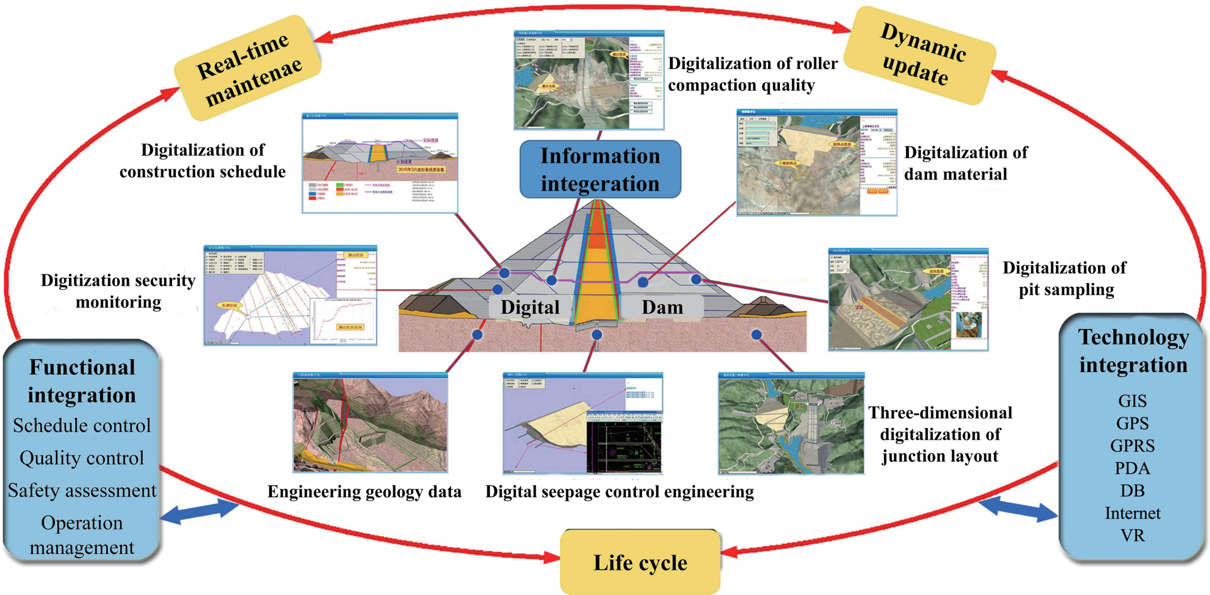

Fig. 1 Integrated digital dam model for high-core rockfill dam (GIS: geographic information system; GPS: global positioning system; GPRS: general packet radio service; VR: virtual reality).

construction quality of high-core rockfill dams is developed, including real-time monitoring technology of filling and rolling quality of high-core rockfill dams, real-time monitoring technology of dam material transportation process, and real-time personal digital assistant (PDA) collection technology of dynamic information of construction quality, to realize all-weather, fine, and online real-time monitoring of filling and rolling quality, ensure that construction quality of the dam is always under control, and realize dynamic monitoring of dam material unloading accuracy, loading strength, and traffic density. Finally, a digital dam system for high-core rockfill dams is developed to realize comprehensive integration of dynamic engineering information during dam construction, which provides technical support for real-time control of dam construction quality and progress and long-term safe operation of dams.

2.1.2 Application effects of digital dam system

For the first time, a digital dam system was used in the Nuozhadu Project to provide real-time monitoring and information feedback on dam material transportation, dam construction process, test results, and monitoring data. It realizes the entire process, including all-weather, fined, and online real-time monitoring of dam construction, and ensures the construction quality of more than 34.0 million m^3 of dam filling. It is a major innovation in the quality control method of dam construction in the world, leading and promoting significant progress in industry technology.

On the basis of the Nuozhadu digital dam technology, the Lianghekou and Shuangjiangkou Dams were intelligently upgraded, and intelligent project management and control modes were explored. Real-time monitoring was performed throughout the entire process of material source mining, blending, transportation, watering, paving, filling, testing, and evaluation, and an unmanned rolling machine fleet was adopted. Quality assurance and efficiency improvement of the efficient large-scale construction of high earth–rock dams under complex conditions were realized.

2.2 Intelligent construction of high RCC dams

An RCC dam has the advantages of fast construction and low cost and is one of the most competitive dam types. Critical points and difficulties in the construction control of this dam type include the seepage prevention of metamorphic concrete on the upstream dam face and the bonding quality of the rolling lifts of the dam body. The Huangdeng Dam, with a height of 203.0 m, is the highest RCC gravity dam in Asia. To overcome the weak links in conventional manual control and solve the problem of large leakage after impoundment of some high RCC dams in recent years, core scientific and technological problems in intelligent construction of high RCC dams have been solved in the Huangdeng Project, and a set of intelligent dam construction and management systems has been developed and practiced. The framework of the developed system is shown in Fig. 2. Its construction quality has set a new record in the same type and scale projects at home and abroad and has promoted the construction technology of high RCC dams to a new level.

2.2.1 Fundamental theory of intelligent construction of RCC dams

The intelligent construction of an RCC dam has the general features of integrity, collaboration, integration scalability, autonomy, and robustness. Based on these characteristics, the basic elements and control index

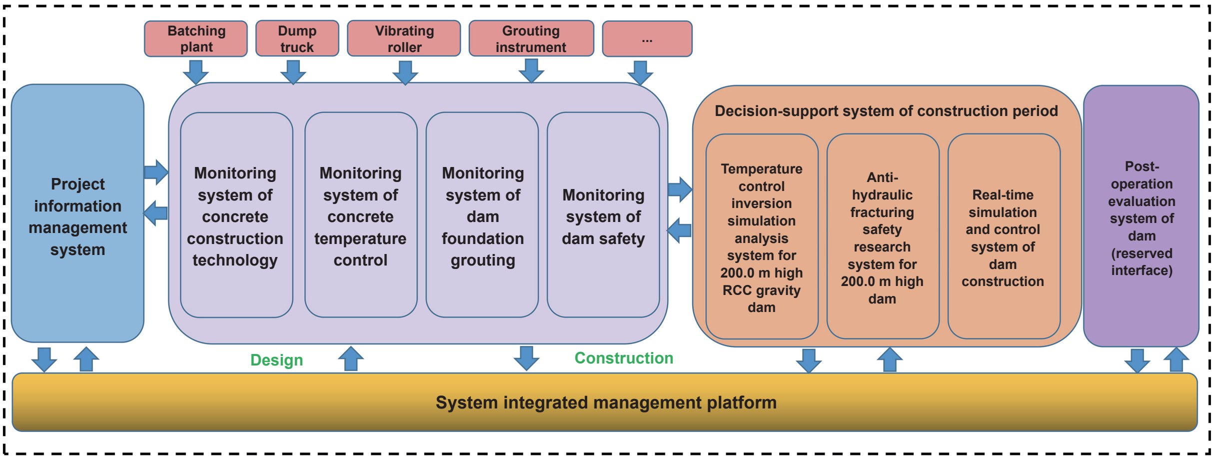

Fig. 2 Framework of intelligent monitoring and quality evaluation system for the construction process of high RCC dams.

system of intelligent construction of high RCC dams and the temperature control criterion of mass RCC under significant temperature differences were posited for the first time in the Huangdeng Project. An intelligent construction information model of high RCC dams was constructed, and construction technologies such as duration control on the coverage of the blank layer of high RCC dams and seepage control of manufactured metamorphic concrete were innovated, which laid the theoretical foundation and technical system for intelligent construction of high RCC dams.

2.2.2 Intelligent monitoring and analysis of placing quality

Conventional quality control for RCC dam placement relies primarily on manual inspection, side stations, and other methods. Intelligent monitoring methods of placement quality can perform fine and automatic management of construction quality. They mainly adopt Beidou satellite technology, real-time dynamic difference technology, wireless data transmission technology, database (DB) technology, real-time control feedback technology, graphic analysis technology, and the identification method of spreading and leveling operation of the spreading machine. Based on the intelligent analysis model of placement quality in a complex environment and multifactor coupling, the evolution rule of dam material performance under complex conditions is revealed through the complete sets of technologies, such as intelligent identification and rolling monitoring of the blank layer of a high RCC dam and intelligent monitoring of interlayer bonding and vibration, to realize real-time analysis and intelligent feedback control during the entire process of concrete placement of a high RCC dam.

The valley of the Huangdeng Dam is narrow, and the width of the dam sections is 20.0–27.0 m. However, its maximum length in the upstream and downstream directions is approximately 170.0 m, which is unsuitable for inclined rolling. This practice shows that, by considering the strong supply capacity of the mixing system, the use of flat rolling can ensure construction quality and is conducive to accelerating construction progress. Flat rolling has high requirements for the intensity of concrete placement, allocation of placement resources, rolling partition, and control of strip operation. By studying the initial setting time of the concrete and optimizing the concrete placement method, a thermal lift control method with dual control of the operation duration of the rolling strip and the coverage duration of the blank layer was proposed. During the construction process, by monitoring the thickness of the paving material, the duration of strip operation, and the coverage time of the blank layer, the concrete exposure time is calculated digitally in real time, and early warning is executed. By increasing concrete production and transportation intensity, a rapid and uniform rise of RCC is achieved to ensure bonding quality between the layers. The maximum placement surface area of the Huangdeng Dam is approximately 8800 m^2, the interlayer coverage time is not longer than 6 h, and the interlayer bonding quality is good.

2.2.3 Comprehensive intelligent temperature control and crack prevention analysis and intelligent decision-making

The Huangdeng Dam, with a bottom width of greater than 160.0 m, is the highest RCC dam in Asia, and it has a harsh construction environment and difficult temperature control during construction. The conventional problems in cracking factors of temperature control (large temperature difference, large cooling range, large temperature drop rate, and large temperature gradient) and in construction management (information acquisition was not timely, inaccurate, untrue, and unsystematic) were more prominent, and the two conventional "differences" (differences between design and actual situation and differences between construction and design) were more difficult to control. Aiming at the temperature control characteristics of a high RCC dam, the design criterion of "appropriate relaxation of foundation temperature difference and strict control of internal and external temperature difference" is adopted to establish a real-time acquisition method and intelligent prediction and early warning model of the entire process temperature control elements of the entire dam. A new method of inversion simulation analysis and a calculation analysis system for temperature control tracking are developed to realize intelligent temperature control analysis and precise crack prevention control of high RCC dams.

2.2.4 Efficient and scale application of intelligent construction technology

On the basis of the principle of "unified platform and module development", an intelligent monitoring system for the entire process of concrete placement of a high RCC dam and an intelligent temperature control system for the entire dam were developed. A complete set of equipment for intelligent monitoring, intelligent collection, and regulation of temperature control for the entire process of concrete placement of high RCC dams under complex conditions has been developed, and a full-link closed-loop information feedback and control platform has been constructed. The entire process of all dam sections of the Huangdeng dam is constructed and managed by intelligent monitoring and analysis technology. The concrete placement volume was 3.5 million m^3, and the longest perfect RCC core sample (24.6 m long) in the world was obtained. The leakage of the dam foundation is less than 8 L/s, and the construction quality control is good. The related technologies have been fully applied to the Fengman Reconstruction Project with an annual temperature difference of 80 °C. The temperature control and construction quality control of RCC are good, and efficient and scale application of intelligent construction technology in high RCC dams is realized.

Toba Dam under construction is comprehensively upgraded using intelligent construction technologies employed in Huangdeng and Baihetan Dams, focusing on improving the intelligent rolling and intelligent temperature control technology of the dam, breaking through the key technologies of intelligent foundation treatment, intelligent sand and gravel processing system, and intelligent dynamic management and control of underground engineering construction, improving the technical level and management efficiency of engineering construction, and developing a mature green intelligent construction technology system for RCC dams.

2.3 Integrated management of intelligent construction

With the gradual shift of the focus of hydropower development to Tibet, hydropower projects in the upper reaches of the Lancang River face a high-cold and high-altitude development environment. Common problems include poor construction conditions, technical difficulties, strict environmental protection requirements, and high development costs. Hydropower project construction management faces enormous challenges. To strengthen the integrity, coordination, pertinence, and applicability of intelligent construction work, an integrated management mode of intelligent construction is proposed on the basis of the characteristics and difficulties of hydropower project construction in the upper reaches of the Lancang River. The intelligent construction of hydropower projects will be upgraded from a single-project intelligent construction management mode to a basin-level, multiproject integrated management mode, covering various dam types and the entire life cycle of the project and supporting the "local + remote" front and rear collaborative management. This is a new goal, a new challenge, and a new journey in the field of intelligent construction of hydropower projects in the Lancang River Basin.

The integrated management platform for intelligent construction has the functional requirements of standard function replication, special module configuration, rapid development of special requirements, and seamless integration of heterogeneous systems, which primarily includes five modules, i.e., digital design, intelligent construction, intelligent management, integrated decision making, and digital handover, to achieve comprehensive data sharing, efficient business collaboration, and integration of integrated systems. It is capable of iterative technological upgrades and evolution and constant business expansion and optimization. Centralized + distributed data deployment is adopted. For data with high access frequency and timeliness, particularly data related to on-site control, on-site deployment and local control are implemented. For data related to daily business management, i.e., data with low access frequency and timeliness requirements, centralized deployment is adopted to transmit, store, and query these data in the cloud. The multiproject management mode is based on the development of standardized, normalized, process-oriented, and traceable project management work systems. Through smooth information communication channels, project information can be accurately, quickly, and efficiently summarized, approved, and shared between enterprises and various project organizations, thereby realizing interface, application, and data integration, breaking through project barriers, and integrating shared resources (Fig. 3).

3 Development and practice of smart operation management of reservoir dams

Lancang River Basin passes through the Hengduan Mountains and is located between the Nujiang and Jinsha River Basins of the "Three Parallel Rivers". There are dense mountains and canyons, developed geological structures, large-scale unfavorable geology, and frequent geological disasters in this area. Since the completion of the first cascade hydropower station in 1985, 11 large-scale reservoir dams have been constructed. The operation of reservoir dams is faced with issues of dam safety, un-

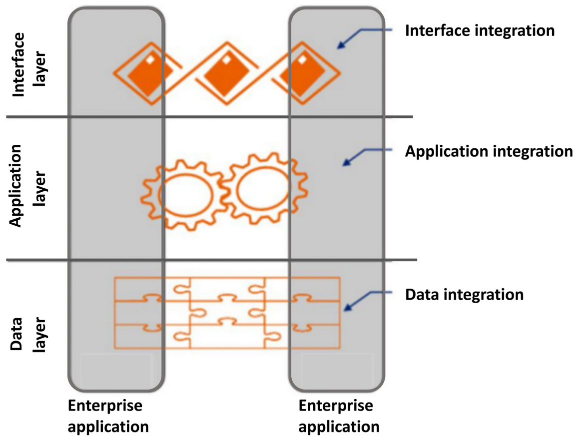

Fig. 3 Integration architecture.

derground engineering safety, slope safety, and water environment safety. Through years of technical research, the first basin-level intelligent online dam monitoring platform in China has been completed and put into operation. Important achievements have been made in intelligent diagnosis of dam operation safety, dynamic control of underground engineering, early warning and prevention of slope disasters, and online monitoring of the water environment of deep and large reservoirs, which provide technical support for the safe operation of reservoir dams.

3.1 Smart dam operation technology

3.1.1 Intelligent diagnosis technology for dam operation

(1) Digital dynamic simulation method for safety monitoring of dam operation.

Given the difficulty in safety monitoring during dam operation and the lack of an operation safety simulation method system, a digital real-time simulation method for dam safety monitoring is proposed, which includes engineering entity monitoring perception, feature data screening and extraction, accurate construction of a digital model, dynamic mapping of structural characteristics, numerical analysis of the engineering state, and digital simulation of the emergency scene. It provides a technical method for dam safety management based on state twinning. A digital simulation logic framework for dam safety monitoring is constructed, which includes a monitoring perception layer, data extraction layer, model calculus layer, scene service layer, and business application layer (Fig. 4). It provides a standard data model interface and application service specifications for monitoring information collection, data aggregation and fusion, model calculation and analysis, engineering performance evaluation, and working condition simulation. It also provides system integration and data fusion services for dam twin monitoring.

(2) Multidimensional full space–time perception technology for operation behavior of core-wall rockfill dams.

To solve the problems of significant differences in the mechanical properties of dam construction materials, uncoordinated settlement deformation of the dam body, and difficult tracking and monitoring of point seepage in core-wall rockfall dams, special monitoring devices such as settlement deformation of dam rockfall materials, interface displacement of core-wall cushion, and point seepage in weak parts are developed. The developed devices are shown in Fig. 5. Intelligent detection technologies, such as imagery recognition of the apparent characteristics of dam defects and nondestructive detec-

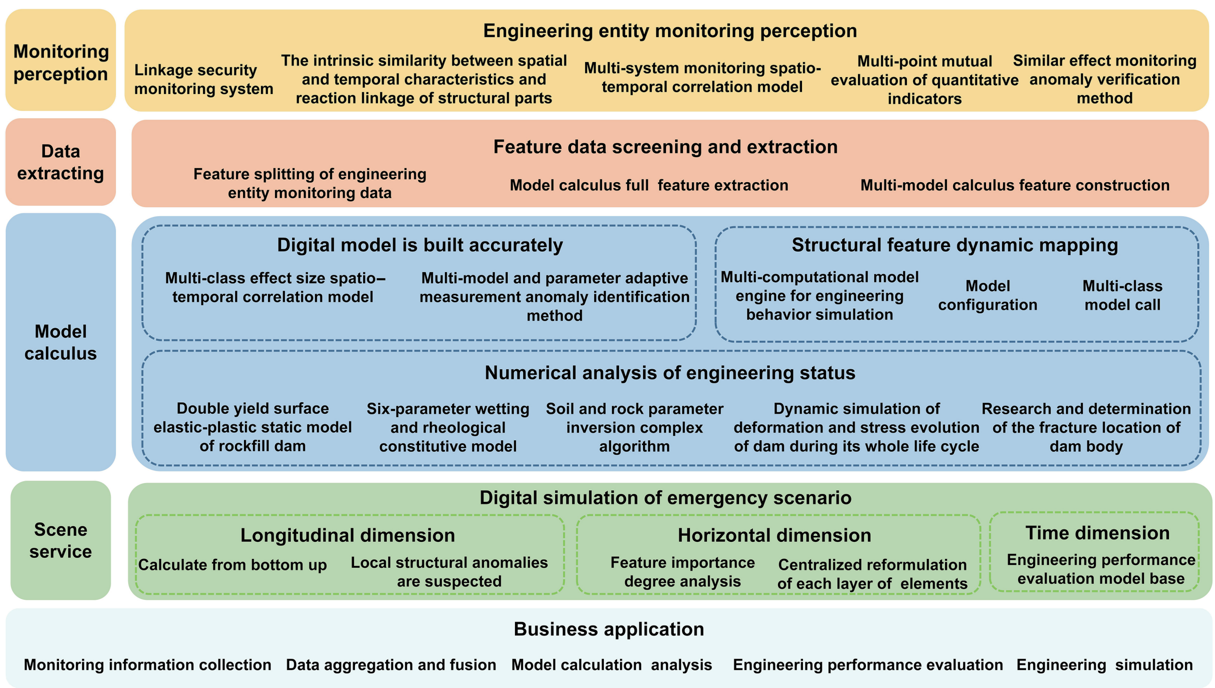

Fig. 4 Framework of digital simulation technology for dam safety monitoring.

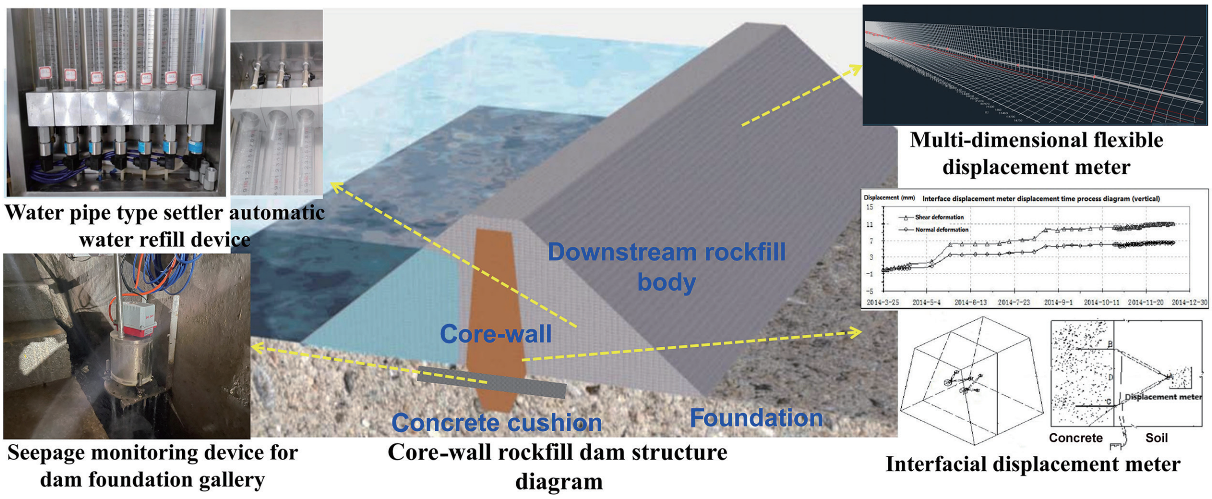

Fig. 5 Multidimensional intelligent monitoring apparatus for operation safety of core-wall rockfill dams.

tion of deep morphology, have been developed to provide accurate geometric dimensions for the construction of defect components. Rapid classification technology for multitype dam defects was developed to improve the efficiency and accuracy of defect classification. A sample library containing multisource data, such as defect images and monitoring sequences, is constructed. The comprehensive application of defect multidimensional perception and multisource data fusion realizes the full space–time accurate perception of digital scene data of the dam.

(3) Online diagnosis technology for operation behavior of core-wall rockfill dams based on multimodel fusion.

Aiming at the characteristics of frequent loss and multiple anomalies in the operation monitoring system of core-wall rockfill dams, a multimodel adaptive data analysis method based on machine learning is proposed, and a space–time correlation diagnosis model with multiclass monitoring effects is established to investigate and judge the structural behavior of the dam based on the measured data. An elastic–plastic static model of the double yield surface of the dam is constructed, and a composite algorithm of soil–rock material parameter inversion based on the measured data of the rockfill body and core wall upstream and downstream of the rockfill dam is developed. The entire cycle deformation and stress evolution law of the dam are dynamically simulated. The trend of uneven settlement and cracking on the dam crest is inverted. An interactive engine suitable for the digital simulation of engineering performance under multiple working conditions is developed to dynamically update the entity feature parameters and realize effective mapping of engineering structure features. The response relationship between the parameters of the mechanism model and the spatial and temporal characteristics of the monitoring data is determined. A multidimensional evaluation method system of engineering safety with horizontal coordination, vertical penetration, and full sequence coverage, which is illustrated in Fig. 6, is established to overcome the technical bottleneck of online evaluation of the service performance of core-wall rockfill dams.

(4) Integrated intelligent safety management and control technology for core-wall rockfill dams

To solve the problems of high failure risk, lack of authenticity of simulation, and difficulty in emergency decision making of core-wall rockfall dams under special working conditions, a similarity-matching method between twin-scene simulation of dam performance and emergency working conditions is proposed. A twin-scene simulation engine based on BIM is developed. Using the results of model calculation and analysis, the quantitative evaluation method of damage is integrated, and the evolution law of engineering performance is synchronously mapped in a three-dimensional digital scene, revealing the potential damage of the structure, deducing the development trend of risk, and supporting the emergency decision making of the project. By using the real-time aggregation technology of massive data for multi-monitoring systems, the knowledge of dam operation and maintenance management is mined, and a unified storage resource base of multimodal heterogeneous information is established. A similarity-matching method for the engineering operation state under special working conditions, such as strong earthquakes, floods, and rainstorms, is proposed. The microservice workflow engine is used to quickly push the early warning plan to establish an intelligent analysis and diagnosis system for the operation safety of core-wall rockfall dams and to form a new mode of dam operation safety management and control integrating online perception, in-depth analysis, and accurate decision making (Fig. 7).

3.1.2 Rapid assessment of the strong seismic risk of a high dam

(1) Seismic performance evaluation of the high dam.

Earthquakes frequently occur in Southwest China. To

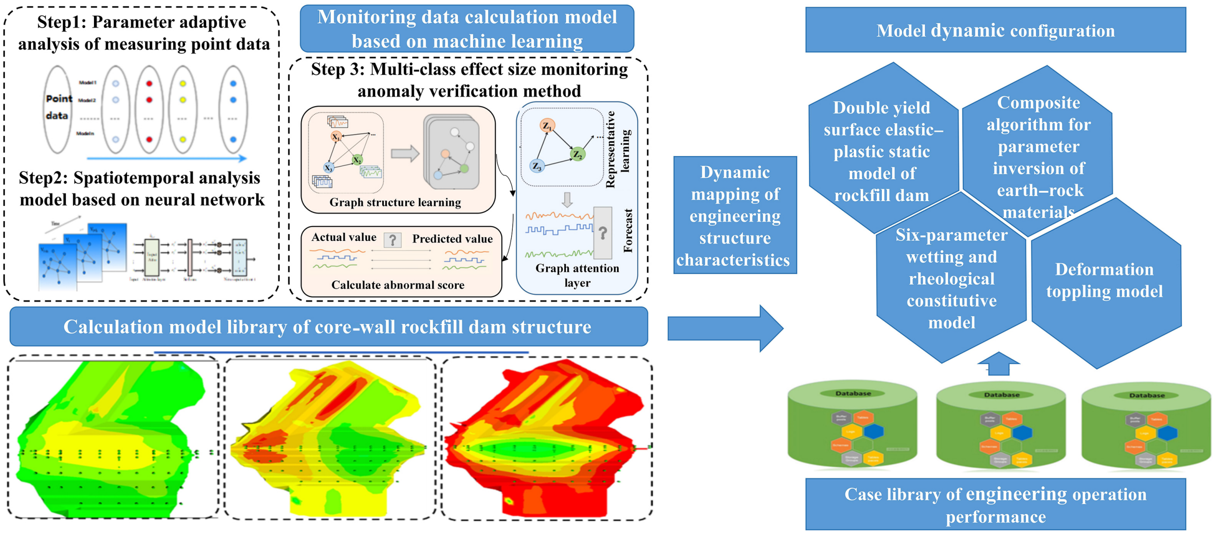

Fig. 6 Interactive model library for data analysis and structure calculation of dam safety.

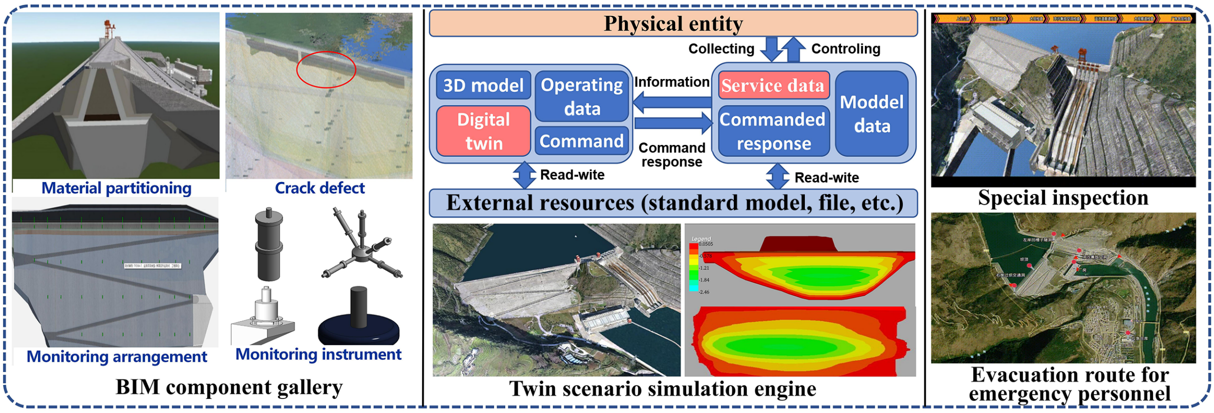

Fig. 7 Performance simulation and digital deduction technology of core-wall rockfill dam.

scientifically and quickly evaluate the seismic safety risk of high dams, the rapid assessment technology of seismic risk of high dams is investigated on the basis of measured seismic data by solving the problems of dispersion, singleness, and tediousness of seismic damage assessment of existing hydropower stations for two dam types: high-arch and high earth–rock dams.

Using the Xiaowan Ultrahigh-Arch Dam as a case study, the three-dimensional finite element method is used to perform the inversion of dam material parameters and stress simulation analysis. Meanwhile, on the basis of the measured seismic data, the seismic intensity of the dam area, the modal parameters of the dam body, and the deformation response of the dam foundation are analyzed in real time, and "regional–integral–local" rapid assessment and early warning of seismic damage of high concrete dams are realized. Modal identification of a high-arch dam is based on a combination of stochastic subspace identification (SSI) and the density-based spatial clustering of applications with noise (DBSCAN) clustering algorithm, which can realize automatic and accurate identification of the arch dam mode. Figure 8 shows the process to automatically identify the module parameter.

On the basis of the Nuozhadu Core-Wall Rockfall Dam, a double-mechanism proportional memory elastic–plastic constitutive model of rockfill material is adopted. According to the actual configuration and dam material partition of this earth–rock dam, a variable-scale modeling and analysis method of sparse-dense grid transition is adopted to establish a rapid fine analysis model of the earth–rock dam, and dynamic elastic–plastic analysis of the dam body is performed. A rapid seismic response analysis method for high earth–rock dams is proposed, which includes octet cross-scale modeling (Fig. 9), polyhedron–conventional element mixing, and similar element acceleration processing. The seismic subsidence rate and dam slope slip are taken as the non-failure dam index. This method has better analyticity, higher accuracy, and faster response speed, which can significantly improve the computational efficiency of the rapid safety assessment system for earth–rock dams.

(2) Rapid assessment module for high dam seismic risk.

The main functions of the rapid assessment module

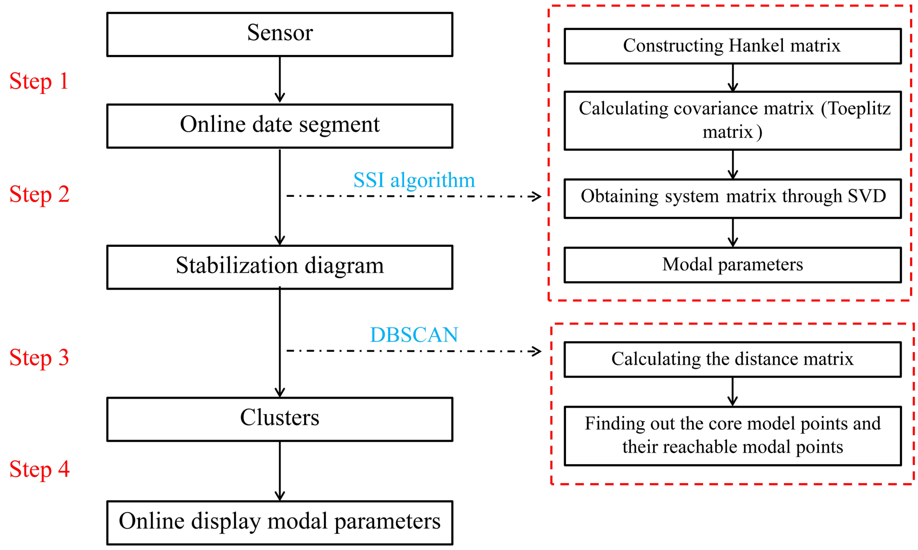

Fig. 8 Flow chart of automatic identification algorithm of module parameter (SVD: singular value decomposition).

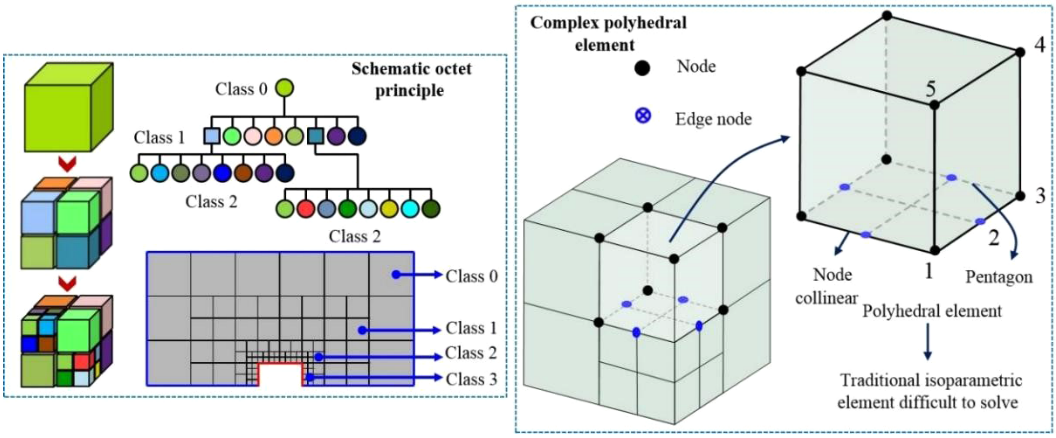

Fig. 9 Octet cross-scale discrete modeling.

for seismic risk of high dams are real-time monitoring of seismic data, research and judgment of seismic triggering mechanisms, rapid comprehensive analysis of seismic response, and automatic generation of seismic damage reports. This module has realized the integration and automation of the entire process and has been successfully used in Xiaowan and Nuozhadu Hydropower Stations. Currently, the strong seismic risk assessment time for high-arch dams is within 10 min, and that for high earth–rock dams is within 30 min, which provides a scientific and rapid basis for engineering seismic damage assessment.

3.2 Intelligent dynamic management and control of underground engineering during operation period

3.2.1 Multisource twin model fusion and lightweight technology for underground engineering

For the coupling and mutual feedback environment of various unfavorable factors such as complex geology, stress, and groundwater in the operation period of large-scale underground caverns in hydropower projects, based on the digital twin technology reflecting the entire life cycle process of the entity (system), photogrammetry, parameterization, database, and three-dimensional graphics library development modeling technology are integrated to establish a twin body (geological information, engineering structure, monitoring data, etc.) with back attributes and data support to realize the one-to-one mapping, co-growth, and collaborative reaction between real underground engineering (geology, engineering structure, environment, safety state, etc.) and three-dimensional digital twin underground engineering. On the basis of cutting-edge visualization technologies (graphics, data mining, web graphics library (WebGL), etc.), dynamic analysis and three-dimensional visualization interactive display of spatio–temporal information such as twin models, monitoring data, and security status are realized. In addition, mainstream vertex compression technologies (Draco compression and JavaScript decoding) and texture compression technology (Khronos texture (KTX)) are used to reduce the amount of data and video storage required. The data structure index reconstruction method based on the "pyramid" multilevel model is used to accelerate data reading and ensure a lightweight twin fusion model and fluency of access (Fig. 10).

3.2.2 Long-term dynamic safety evaluation method of underground engineering during operation period

Based on the expert investigation method, core factors affecting the long-term safety of underground engineering are identified, and the influence of the external geological environment (rainfall, water level, and earthquake), monitored status of surrounding rock (deformation, stress, and seepage), and internal environment (cracking, falling block, leakage of the tunnel wall, and drumming of surrounding rock) on long-term safety are considered. Principal component analysis is then used to evaluate the weight value of each influencing factor in the analytic hierarchy process theory, and the early warning and risk levels of each influencing factor are classified to realize the dynamic evaluation and prediction and early warning of the long-term safety state of underground engineering during the operation period. The proposed method is illustrated in Fig. 11.

3.2.3 Digital twin safety management and control module for large underground cavern group

The digital twin safety management and control module for a large underground cavern group is based on the long-term safety dynamic evaluation system of "multi-source fusion and comprehensive evaluation" of large underground engineering and web front-end development technology. It is an integrated management and control platform that integrates geological and engineering structure visualization twins, synchronous interaction of

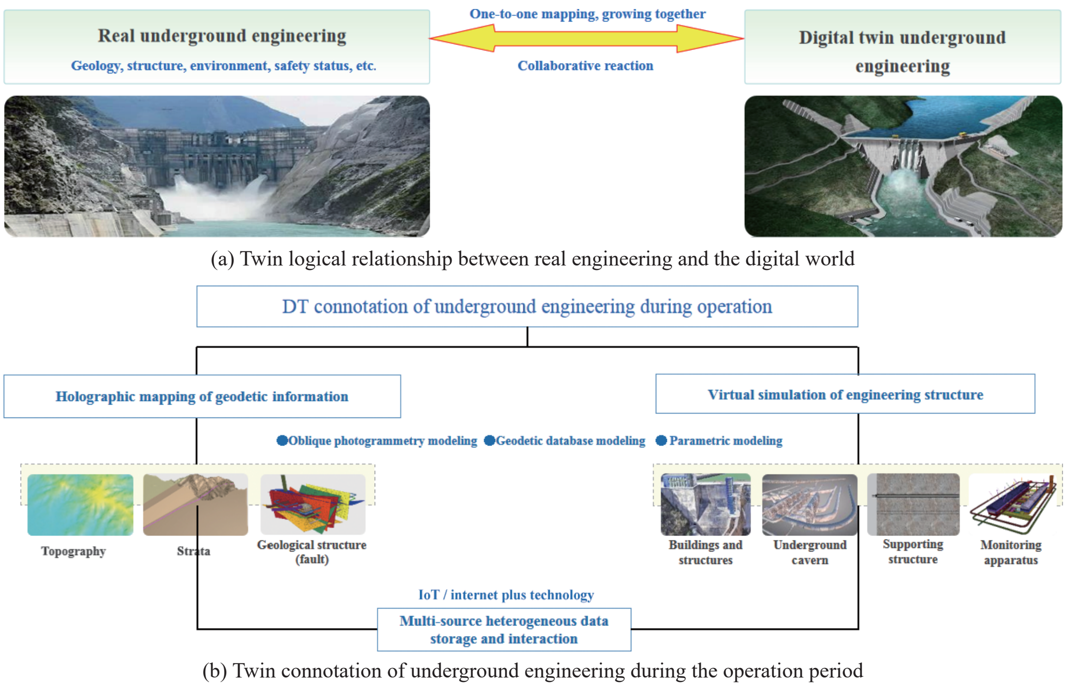

Fig. 10 Technology system for multisource fusion twin modeling in underground engineering (IoT: Internet of Things).

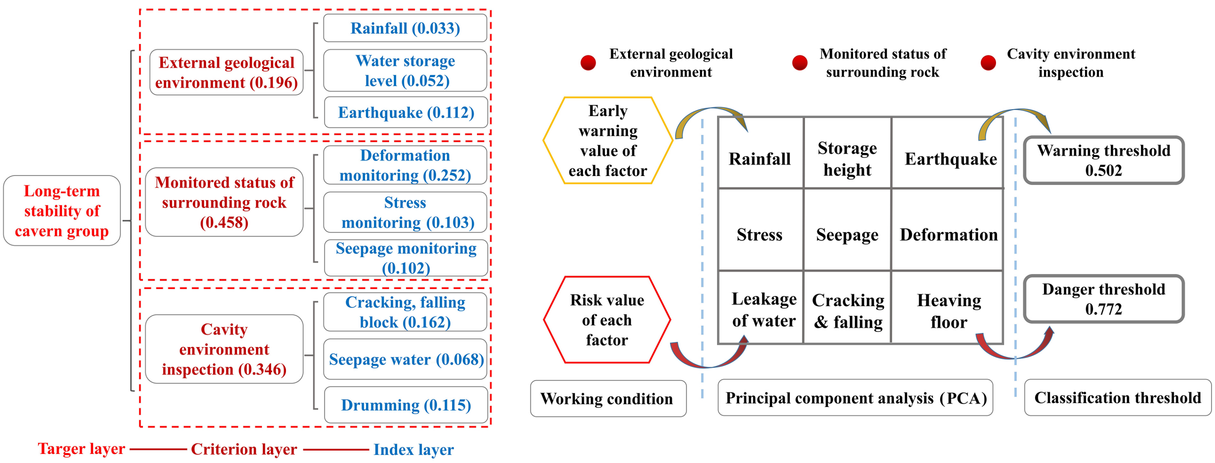

Fig. 11 Theoretical system for long-term dynamic safety evaluation of underground engineering during operation period.

monitoring information, dynamic evaluation of cavern group safety status, long-term safety collaborative management, and decision making. The module has the characteristics of a reliable core theoretical model, lightweight twin model, realistic visualization effect, fast loading access speed, intelligent analysis, and decision making. It can realize multisource twin model fusion, multisource data fusion dynamic analysis, and multidirectional safety state assessment and monitoring, which is convenient for front-line and rear management personnel to dynamically determine the safety state of the underground engineering of hydropower stations during operation. Simultaneously, it reduces the work intensity of technical personnel and improves the operation and management efficiency and level of large underground cavern groups.

3.3 Monitoring and risk prevention and control technology for reservoir bank slope geological disasters

3.3.1 "Space–air–ground" integrated safety monitoring technology

Conventional safety monitoring and management of hydropower projects are primarily based on the management of conventional sensor data and lack the processing, display, and integration of modern noncontact monitoring technologies; thus, they cannot adapt to the investigation and management of hidden danger points in various reservoir banks. Using spaceborne interferometric synthetic aperture radar (InSAR), vehicle/ship InSAR, unmanned aerial vehicle (UAV) tilt photography, fixed InSAR, throwing Beidou intelligent monitoring terminal, flexible intelligent displacement meter, and other monitoring methods, a "space–air–ground-in-depth" integrated safety monitoring technology, as shown in Fig. 12, of "large-scale survey, regional inspection, and detailed investigation of key parts" of geological disasters in reservoir bank slopes of river basins is developed and applied. The accuracy in identifying landslide risk points at the river basin level is 92%, and the accuracy of continuous deformation monitoring of key landslides reaches the millimeter level.

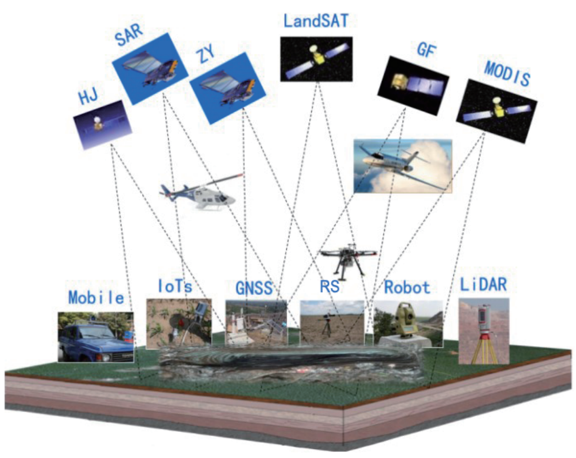

Fig. 12 "Space–air–ground" integrated safety monitoring system (GNSS: global navigation satellite system; RS: remote sensing; LiDAR: light detection and ranging).

3.3.2 Multisource data integration technology of digital twin reservoir bank

The reservoir shoreline of the Lancang River Basin is thousands of kilometers long, and the geological conditions of the slope are complex. The scale and number of hidden danger risk points are large, and safety monitoring and risk management are difficult. The digital twin has the advantages of multisource heterogeneous data fusion, data-driven precise mapping, and intelligent analysis-assisted decision making, and can realize synchronous mapping between the digital and physical worlds. By integrating the reservoir bank engineering survey and design data, multisource monitoring data, and a three-dimensional digital model, a digital twin model of the reservoir bank slope in a river basin is constructed, and a long-term operation safety assessment technology of geological hazard points based on a conventional rock mechanics model and a data-driven machine learning model is established to realize effective monitoring and rapid early warning of the geological hazard risk of reservoir dams and slopes.

Multisource data fusion to realize deformation field reconstruction is the key to slope digital twin technology. There are generally two methods for deformation field reconstruction. One is the interpolation algorithm based on monitoring data; however, there is a problem with the significant discreteness of measuring points and the limited accuracy of conventional interpolation technology. The other is a numerical simulation algorithm based on the finite element method; however, the simulation error is uncontrollable. In this study, combined with the multisource data obtained from the slope appearance monitoring system, the ensemble Kalman filter algorithm is used for data fusion. By considering the heterogeneity of multisource data in measurement accuracy and spatial–temporal scale, high-precision and high-resolution fusion deformation monitoring information is obtained. The deformation field calculated using the finite element method is a priori, and the prior data are corrected using the fusion deformation monitoring data. On the basis of the improved Bayesian–Kriging interpolation method, the multisubdomain data fusion strategy is used to generate the slope fusion deformation field. The overall prediction accuracy of the deformation field after correction and fusion is improved by approximately 50%, which is closer to the actual deformation distribution of the slope.

3.3.3 Intelligent analysis module for reservoir bank deformation monitoring

The main functions of the intelligent analysis module of reservoir bank deformation monitoring in the basin include automatic processing of InSAR data, intelligent identification of hidden danger points of geological disasters, automatic reconstruction and deformation detection of three-dimensional terrain of reservoir banks, multisource data fusion, and real-time release of major dangers. These functions realize the entire basin coverage of monitoring range, millimeter-level monitoring accuracy, and quasi-real-time monitoring frequency and comprehensively improve the fine management level and geological disaster prevention and control ability of reservoir banks in the basin (Fig. 13).

3.4 Wastewater environmental monitoring and evaluation of the deep reservoir

3.4.1 Three-dimensional monitoring and comprehensive evaluation of water environment in hydropower project reservoir

The water body of the Lancang River deep reservoir is stratified and the water environment is complex. Conventional sampling and monitoring methods cannot be fully applied to water environment monitoring in deep reservoirs. To realize real-time online monitoring of key water environment indicators from the surface layer to the water depth of 200.0 m, an online automatic monitoring technology (point) of the water environment of a 200.0-m deep reservoir and a three-dimensional remote monitoring technology (plane) of the water environment based on UAV and remote sensing images are developed and used to construct an "air–ground integrated" three-dimensional monitoring system of the deep reservoir water environment. Consequently, the characteristics and variation rules of the water environment of deep and large reservoirs are analyzed, and the evolution mechanism of hydrological physics and water chemistry, environment, and ecology of deep and large reservoirs is revealed. A technology system for optimizing and controlling the layout of water environment monitoring stations of deep and large reservoirs is established, and a comprehensive water environment quality evaluation technology, as shown in Fig. 14, suitable for the characteristics of deep and large reservoirs is developed.

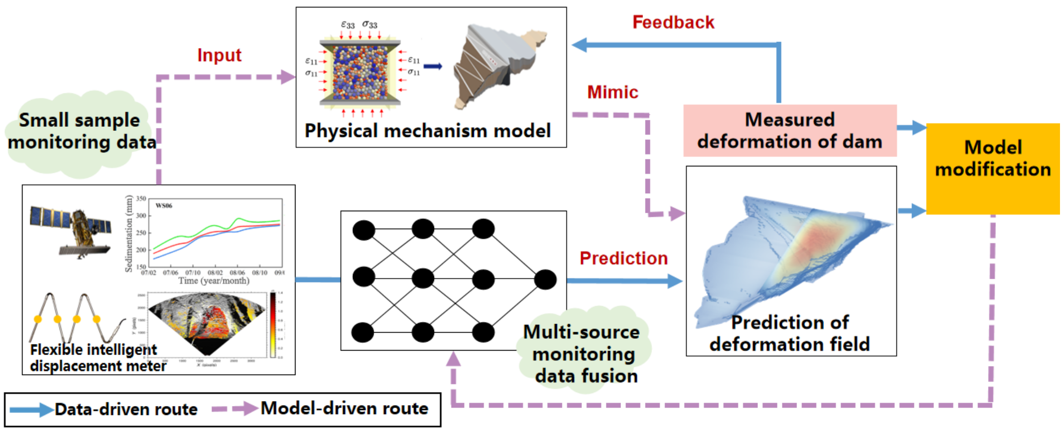

Fig. 13 Deep coupling model-driven and data-driven intelligent prediction method for reservoir dam deformation.

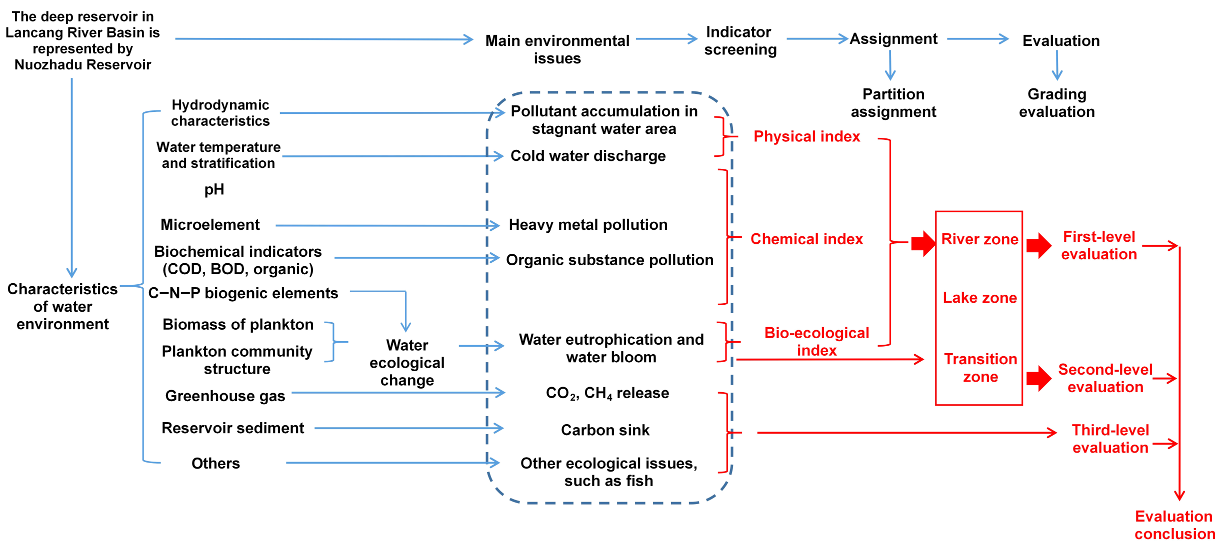

Fig. 14 Comprehensive evaluation of water environment quality.

3.4.2 Online monitoring module of deep reservoir water environment

The online monitoring module of the water environment of deep and large reservoirs exceeds the limit of super-deep water depth of 200.0 m and achieves real-time online monitoring of key water environment indexes, such as water depth, water temperature, dissolved oxygen, pH, conductivity, turbidity, and chlorophyll level, from the surface to 200.0 m deep bottom water, filling the gap of super-deep water environment monitoring at home and abroad.

4 Conclusions and prospects of smart hydropower

The following instructions are based on years of research, development, and practice in intelligent construction and smart operation of hydropower projects in the Lancang River Basin. First, adhere to demand-oriented and value-oriented principles, focusing on top-level planning and design. Second, establish a strong organizational implementation mechanism. Third, coordinate the relationship between the new technology and conventional management mode. Fourth, strengthen training and accelerate popularization and use efficiency of information technology. Fifth, attach significant importance to the improvement of the system and continuously improve the reliability and convenience of information technology.

The majority of China’s hydropower resources will be developed in the high-cold and high-altitude areas of Southwest China. Facing many challenges such as harsh natural conditions, complex geological conditions, fragile ecological environment, and backward infrastructure, construction of these projects is difficult. Smart hydropower technology is an inevitable trend in modern science and technology and industry development and will become a necessary means of hydropower project construction and operation management. The new concept of full life cycle development of “digital design, intelligent construction, and smart operation” should be fully implemented. Dam technology should adhere to the principle of “safe and efficient, green environmental protection, and intelligent interconnection”. Basin development should achieve “overall planning, common technology sharing, individual key breakthroughs, and coordinated development of the basin”. Based on the entire life cycle of engineering design, construction, and operation, key projects such as dams, factories, slopes, and units should be considered in all aspects, links, and elements. An information system and standards for the entire life cycle of hydropower stations should be proposed, and a method system for engineering intelligent perception, wireless transmission, professional analysis, dynamic monitoring, evaluation and early warning, decision support, terminal push, data mining, etc. should be established to form a set of green and intelligent construction technologies that lead the industry and achieve “digital, information, and intelligent” management of the entire life cycle of hydropower station engineering construction. After several generations of efforts and experience accumulation and through the combination of production, research, and application of science and technology, China’s smart hydropower technology will constantly make breakthroughs, leading the world’s hydropower development to achieve a new leap.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

Author contribution statement

All authors have given approval to the final version of the manuscript.

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