Journal of
INTELLIGENT
CONSTRUCTION

Research Article
https://doi.org/10.26599/JIC.2023.9180014

HydroBIM—Digital design, intelligent construction, and smart operation

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Received: 2023-06-14 ***Revised:*** 2023-07-06 ***Accepted:*** 2023-07-08

ARTICLE INFO

Keywords
water conservancy
hydropower engineering
life cycle
building information modeling (BIM)
digital design
intelligent construction
intelligent operation

ABSTRACT

Improving the design efficiency of hydropower hub buildings and promoting the application of intelligence in engineering construction and operation management have been critical issues in hydropower engineering construction. The major challenges are mainly reflected in the difficulties of multidisciplinary collaboration and the inefficient coordination of work involving multiple parties. This paper proposes a building information modeling (BIM)-based technology system architecture for digital design, intelligent construction, and intelligent operation, which combines BIM technology with geographic information system (GIS), computer aided engineering (CAE), internet of things (IoT), artificial intelligence (AI), and other technologies. The proposed system includes a BIM-based multi-professional forward collaborative design method, a BIM-based engineering construction management model, and a real-time safety analysis and evaluation technology system based on actual measured safety information and construction. The hydroelectrical engineering BIM (HydroBIM) comprehensive control platform is developed. In the planning and design stage, the platform enables the whole process and full-professional collaborative digital design. In the engineering construction management stage, it supports the whole process and all-round information management and control of contract, schedule, quality, safety, and investment. In the operation management stage, the platform facilitates the integrated management of engineering safety evaluation, early warning, and emergency plan based on monitoring data and the consistency criterion of positive and negative evaluation. The application of this technology in more than 20 engineering, has proven to improve the efficiency of design and analysis of hydropower hub buildings and the intelligence level of engineering construction and operation management, and overcome the difficulties of multi-professional collaboration in the design stage and low efficiency of multi-participant coordination in the construction stage.

1 Introduction

The building information modeling (BIM) technology originated in USA has been widely adopted in the water conservancy and hydropower engineering industry in China. Domestic scholars have extensively researched the BIM technology and its application in the entire life cycle of water conservancy and hydropower engineering.

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Citation: Zongliang Zhang, Sherong Zhang, Zhiyong Zhao, et al. HydroBIM—Digital design, intelligent construction, and smart operation. *J Intell Constr*, 2023, 1, 9180014.

During the design phase, Zhang et al. [1] proposed an extended industry foundation classes (IFC) export method based on Autodesk Revit software and data exchange from extended IFC to batched three-dimensional (3D) tiles. Mao et al. [2] applied the BIM technology to carry out online collaborative design, achieving the design of multi-specialty in the same platform by using the geological model, hydraulic model, electrical equipment model, building structure model, and metal structure model. In the construction phase, Zhang et al. [3] developed a collaborative management system for the construction period of hydropower engineering using BIM + geographic information system (GIS) fusion technology and web graphics library 3D (Web-GL3D) graphics technology. The system provides a collaborative and open platform for all participants. Yi et al. [4] combined BIM with the internet of things (IoT) to control the whole process of engineering construction safety, quality, and progress using whole process visualization, real-time transmission, intelligent processing, and business collaborative management as the basic operation mode. Wang et al. [5] utilized the BIM technology to control the construction schedule of dam engineering. During the operation and maintenance phase, Zhou et al. [6] combined the BIM technology with ontology-based knowledge management, developing a dam safety monitoring technology. The method allows for BIM model visualization and monitoring management. Overall, the application of BIM technology in water conservancy and hydropower engineering has shown significant potential in improving the efficiency and quality of engineering design, construction, and operation management.

In recent years, scholars have been exploring the integration of BIM across various stages of engineering, including planning and design, construction, and operation management. For instance, the 3D modeling technology has been utilized to visualize building materials, real-time monitoring information, and engineering business data [7–9]. Four-dimensional (4D)-BIM has been employed to correlate BIM with time [10–12]. Additionally, GIS has been combined with BIM to overlay BIM into GIS scenes, facilitating engineers' work in areas such as environmental analysis, cost calculation, and flood evaluation [13–15].

After conducting investigations on over 200 water conservancy and hydropower engineering design and construction operation models both domestically and internationally and reviewing relevant literature, it was discovered that the development and construction model for water conservancy and hydropower engineering in China has shifted from the traditional construction model, where design, construction, and operation are conducted independently, to a new model based on BIM technology. This model emphasizes digital design, intelligent construction, and intelligent operation, with integrated control throughout the entire life cycle [16–20].

This paper proposes a BIM-based technology system architecture for digital design, intelligent construction, and intelligent operation. Additionally, it proposes a BIM-based multi-professional forward collaborative design method, a BIM-based engineering construction management model, and a real-time safety analysis and evaluation technology system based on actual measured safety information and construction. Finally, a hydroelectrical engineering BIM (HydroBIM) comprehensive control platform is developed.

2 HydroBIM system architecture

To address the challenges in managing the entire life cycle of water conservancy and hydropower engineering design, construction, and operation, the interdisciplinary research and innovation have been carried out in digital design, intelligent construction, and intelligent operation using BIM. We developed the HydroBIM system architecture with independent intellectual property rights, as shown in Fig. 1, which summarizes "one platform, two methods, three stages, four major engineering, five in one, and six-party harmony".

The HydroBIM system architecture comprises:

- One platform: the entire life cycle management and control platform of water conservancy and hydropower engineering under the integration of multi-system and multi-software.
- Two methods: conventional analysis and cloud computing.
- Three stages: planning and design stage, engineering and construction stage, and operation and management stage.
- Four major engineering: hub project, electromechanical project, reservoir project, and ecological project.
- Five in one: design quality, project quality, construction management, project safety, and comprehensive benefits.
- Six-party harmony: government agencies, owner units, design units, construction control units, construction units, and manufacturing units.

The HydroBIM system architecture provides an integrated management and control scheme for hydropower engineering planning and design, engineering construction, and operation management (Fig. 2). It enables the management and control of water conservancy and hydropower engineering throughout the entire life cycle under the integration of multi-system and multi-software.

The HydroBIM system framework is designed to cover the entire life cycle of water conservancy and hydropower engineering, allowing for complete and interdisciplinary collaborative digital design during the

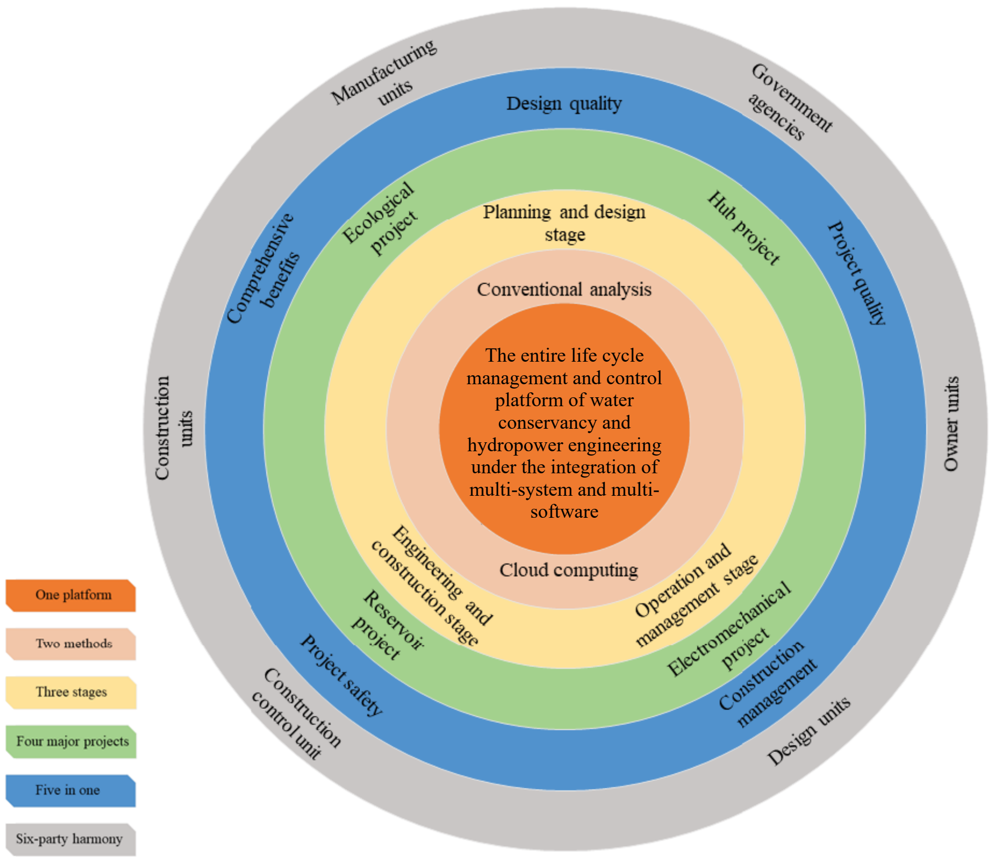


Fig. 1 Core concept of HydroBIM.

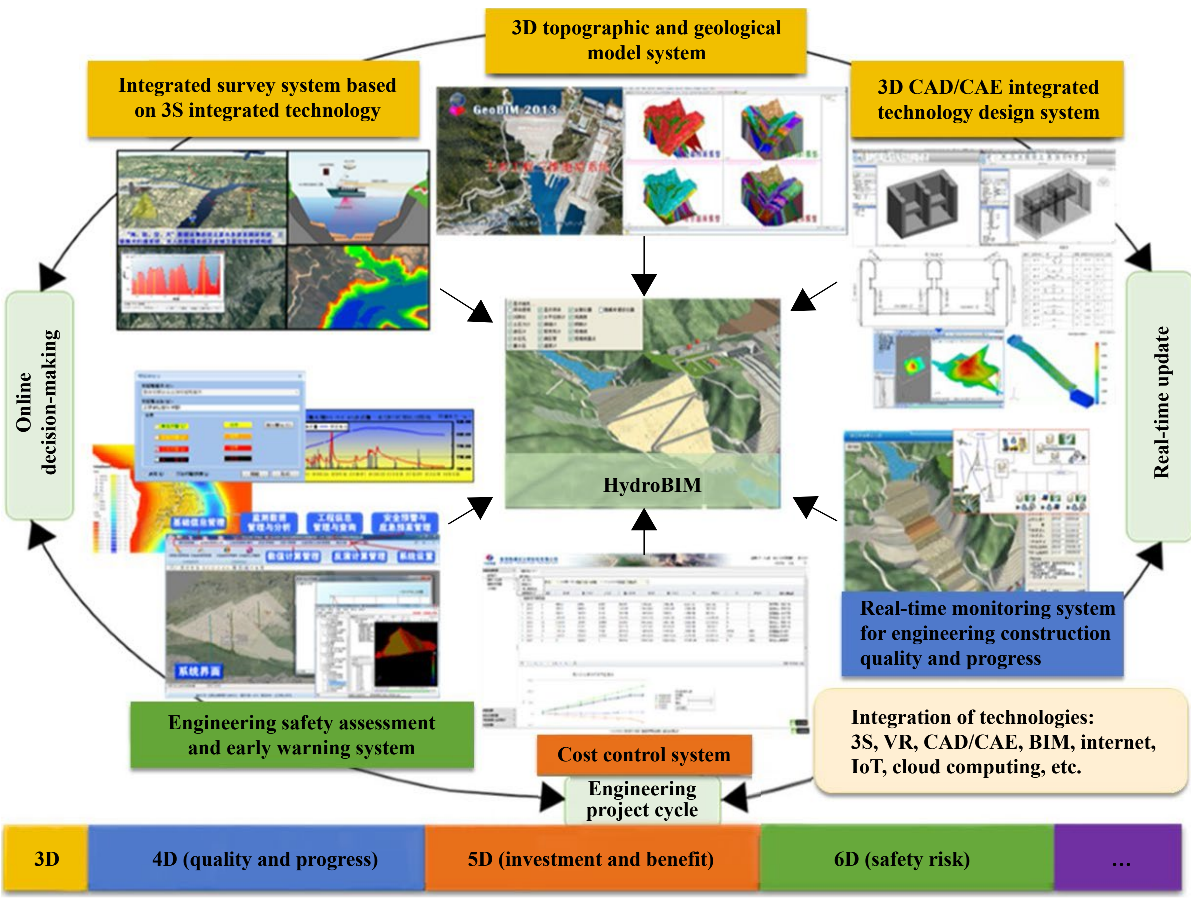


Fig. 2 Integrated solution scheme of hydropower engineering planning and design, engineering construction, and operation management (5D: five-dimensional; 6D: six-dimensional).

planning and design stage. The engineering construction management stage enables full information management and control of contracts, progress, quality, safety, and investment. In the operation management stage, the system provides integrated management of engineering safety evaluation, early warning, and emergency planning through monitoring data and consistent guidelines for positive and negative evaluations. Additionally, the HydroBIM management and control platform allows for the integration of multi-dimensional BIM information throughout the entire engineering life cycle.

3 Key technologies of HydroBIM system

3.1 BIM plus GIS

Water conservancy and hydropower engineering can vary in size and scope, including larger individual, long-distance linear, and large-scale regional engineering. These engineering requires a combination of regional macro management and individual refinement management throughout their entire life cycle. In addition, these engineering involves using both geospatial data and engineering management data.

The GIS technology allows for acquiring, storing, managing, calculating, analyzing, and displaying various data related to the earth's surface in an intuitive geographic graphic format. It enables the digitization of geographic information and provides a valuable tool for managing large-scale engineering. On the other hand, BIM technology provides a technical route and method for digitizing buildings.

Integrating GIS and BIM technologies can achieve macro-to-micro integration and complementarity. This integration allows for the integration of spatial information and model information across fields, display and comparison of design solutions in GIS large scenes, optimization of designs and data analysis based on BIM models, and reduction of errors and omissions. Ultimately, integrating and applying BIM + GIS can comprehensively improve the level of engineering refinement management and the degree of informatization, leading to more efficient and effective water conservancy and hydropower engineering.

3.2 BIM plus virtual reality (VR)

The VR technology is a computer simulation system that can create and provide an immersive experience of a virtual world. BIM technology provides the graphics and basic data for 3D models applied in VR. The integration of BIM and VR technologies includes virtual scene construction, simulation analysis, construction progress simulation, complex local construction plan simulation, construction cost simulation, operation monitoring simulation, and interactive scene roaming. The integration of BIM and VR technologies can enable the construction, integration, simulation, and interaction of virtual scenes in the construction and operation of water conservancy and hydropower engineering. This provides a new perspective and approach for communication, discussion, and decision-making in the engineering design, construction, operation, and maintenance processes and improves communication and decision-making efficiency. Additionally, it offers a new interactive working mode for visual disclosure, construction simulation, production management and control, simulation training, virtual inspection, and operation monitoring.

3.3 BIM plus IoT

The IoT collects real-time data from objects or processes that need to be monitored, connected, and interacted with through various sensors such as information sensors, radio frequency identification technology, global positioning systems, infrared sensors, and laser scanners. It collects information such as sound, light, heat, electricity, mechanics, chemistry, biology, and location and uses network access to connect things and intelligent perception, identification, and management. The integrated application of BIM and IoT is the visual integration and fusion of information in the engineering process. The BIM technology plays a crucial role in upper-level information integration, interaction, display, and management, while the IoT technology undertakes the functions of underlying information perception, collection, transmission, monitoring, feedback, and application.

The integrated application of BIM and IoT can play a significant role in the construction, operation, and maintenance of water conservancy and hydropower engineering. It can realize the visual integration, fusion, and decision-making processing of engineering information, build a dynamic perception and intelligent monitoring system with visualization of the whole process, form an organic integration between virtual information and physical hardware, and ultimately achieve intelligent construction, operation, and maintenance.

3.4 BIM plus cloud computing

The integration of BIM and cloud computing technology benefits the water conservancy and hydropower industry. For example, it can provide efficient and flexible collaboration and communication among engineering participants, enable real-time access to engineering information from anywhere, and ensure data security and reliability. It can also support the development of digital twin technology, which involves creating a virtual replica of a physical asset or system and using it to simulate, monitor, and optimize performance. With BIM-based data centers and cloud computing capabilities, digital twins can be created for water conservancy and hydropower engineering, allowing for real-time monitoring of performance and enabling predictive maintenance and other advanced analytics. Overall, integrating BIM and cloud computing technology can improve engineering efficiency, reduce costs, and enhance the quality and safety of water conservancy and hydropower engineering.

3.5 BIM plus digital twin

The concept of the digital twin involves creating a dynamic virtual model of a physical entity with multi-dimensional, multi-spatiotemporal scale, multi-discipline, and multi-physical quantity, to simulate and describe its properties, behaviors, rules, and more within its real environment. The primary task of digital twin implementation is to create the digital twin model of the application object, which can be achieved through BIM technology constructing a 3D virtual space and entity. By combining BIM and digital twin technologies, the physical entities of water conservancy and hydropower engineering and elements such as people, machines, objects, environment, and information within the virtual space can be mutually mapped and interactively integrated. This enables the dynamic simulation of the entire life cycle status of water conservancy and hydropower engineering, leading to intelligent operation, precise control, and reliable operation and maintenance.

4 HydroBIM integrated platform

A technical system architecture based on BIM was created using various technologies, including IoT, GIS, computer aided engineering (CAE), IFC, cloud computing, and database management. This architecture enabled digital design, intelligent construction, and intelligent operation of water conservancy and hydropower engineering. A complete database framework and workflow were developed, as well as BIM and IFC data structure standards specific to water conservancy and hydropower engineering. The HydroBIM integrated management and control platform was developed, with BIM as the core, data-driven, and network collaboration as the means, to support the entire life cycle of water conservancy and hydropower engineering (Fig. 3).

The HydroBIM integrated management and control platform is based on traditional management modes, taking the main focus of hydrological and geological conditions as preconditions and core management elements. It combines BIM integration, dynamic design, online analysis technology, and engineering construction processes to create a multi-dimensional BIM information fusion and stage optimization scheme for the entire life cycle of the engineering. This has resulted in a comprehensive engineering construction management mode that covers all stages, from planning and design to construction and operation and maintenance, incorporating multiple dimensions of engineering management elements such as engineering planning, contract, bidding and procurement, design, schedule, cost, quality, resources, finance, environment,

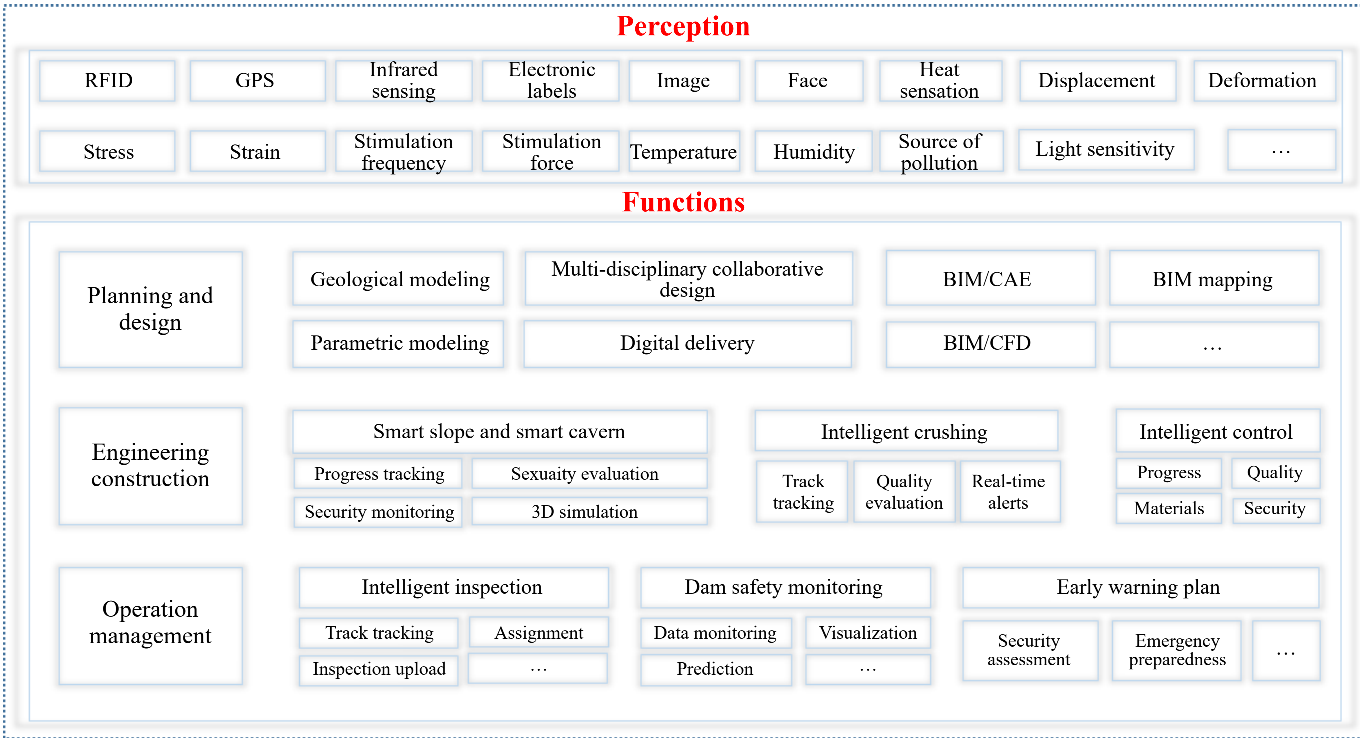


Fig. 3 Functions of management system and HydroBIM integrated management and control platform of water conservancy and hydropower engineering (RFID: radio frequency identification device; GPS: global position system; and CFD: computational fluid dynamics).

safety production, risk, trial operation, archives, and more.

With the entire life cycle multi-dimensional BIM model established under this mode, the HydroBIM integrated management and control platform provides data visualization for the entire life cycle of water conservancy and hydropower engineering. This technical support allows for all-around, refined, and high-quality construction and management of the engineering.

The HydroBIM integrated management and control platform comprises three components: HydroBIM-collaborative design and analysis integrated platform, HydroBIM-engineering construction management information platform, and HydroBIM-dam safety operation management information platform.

4.1 BIM-collaborative design and analysis integrated platform

The HydroBIM-collaborative design and analysis integration platform has been developed to achieve collaborative digital design across the entire process and all professions, improving the design efficiency of water conservancy and hydropower engineering and reducing unnecessary repetitive work. The pre-survey and design technology for poor information conditions, the multi-disciplinary forward collaborative design process and method based on BIM, and an integration of geoinformation with BIM (GeoBIM) 3D geological modeling system were proposed through research conducted on this platform. Four sub-results are described below:

(1) The proposed pre-survey and design technology under poor information conditions aims to address the challenge of conducting pre-survey and MOU design in remote areas and certain international engineering with insufficient basic information. To manage the survey and design process of water conservancy and hydropower engineering, remote sensing, GIS, and GPS (3S) integrated technology is utilized, leveraging its strengths in processing and applying basic geospatial information. The implementation process involves data collection and compilation of poor information data and the application of result data, with 3S integrated technology serving as the guiding factor and the data application process as the core. It caters to all professions involved in poor information surveys and achieves a closed loop of the entire survey and design process under poor information conditions.

(2) The proposed multi-disciplinary forward collaborative design process and method based on BIM aim to improve design efficiency and quality for water conservancy and hydropower engineering. A five-in-one collaborative model was developed, integrating specialty, phase, technical, construction participants, and off-site collaboration. The collaborative design process between specialties is based on data, while collaboration between enterprises, owners, suppliers, or subcontracting design units mainly occurs outside the specialty. This allows all parties involved in the design process to keep track of progress and communicate and modify designs in real time, ensuring that the design is guided in the correct direction. Additionally, professional partitions were set up, providing each participant with their own independent design space while relying on the integrated platform for large-scene progress control.

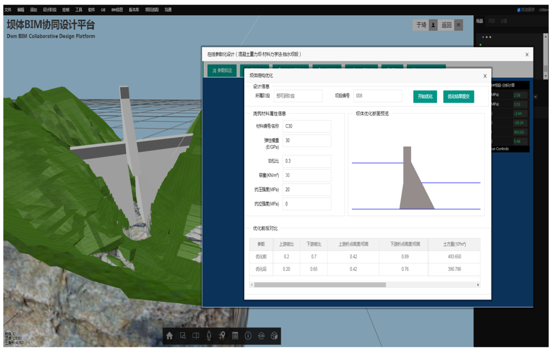
(3) The proposed method aims to facilitate collaborative design in water conservancy and hydropower engineering, focusing on coordinated design and comprehensive data flow integration during the design phase. The method is based on the water conservancy and hydropower IFC standard and web lightweight display technology, which converts different commercial software formats into a circulation format to ensure smooth data flow among different disciplines. The HydroBIM-collaborative design and analysis integrated platform was developed by integrating BIM, CAE, cloud computing, and visualization engine technologies. The platform enables BIM model collaborative design, BIM/CAE integrated analysis, and feedback optimization design, as shown in Fig. 4.

(4) A GeoBIM 3D geological modeling system was developed to enable rapid and accurate modeling of geological objects and customize the output of geological engineering drawings. Additionally, it opened up data interfaces with upper- and lower-order majors to realize the integrated application of geological and building models. GeoBIM collects and organizes 3D topographic data and stores geological exploration data in a database. The 3D geological model is then created by acquiring geological data from the database and constructing standardized geological model nodes.

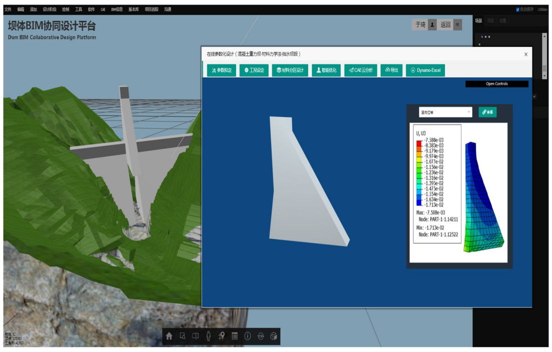
4.2 HydroBIM-engineering construction management information platform

The HydroBIM-engineering construction management information platform (Fig. 5) was developed to cover the entire process of HydroBIM planning, delivery, collaboration, and general control, enabling efficient, unified, standardized, and coordinated information control of the engineering procurement construction (EPC) engineering of water conservancy and hydropower engineering, including contract, schedule, quality, safety, and investment.

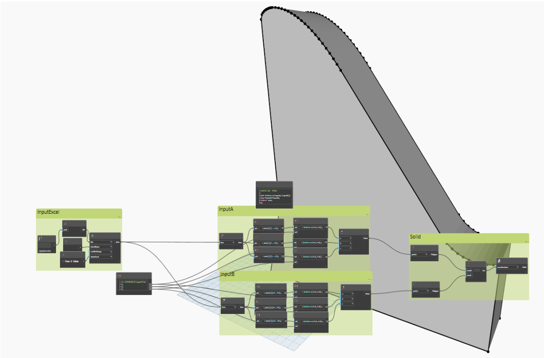
The platform proposed a BIM-based engineering construction management mode, which combined the HydroBIM engineering information model and EPC engineering general contracting model with cloud platform construction, database design, and other key technologies to achieve the integration of various technologies in HydroBIM engineering construction

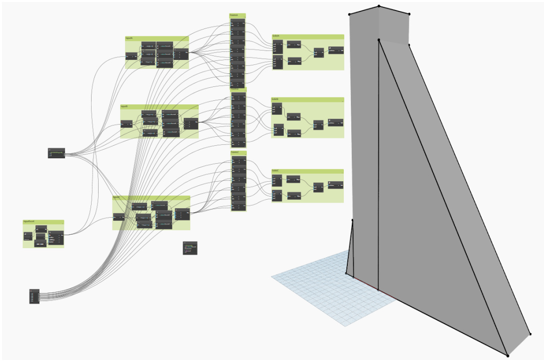


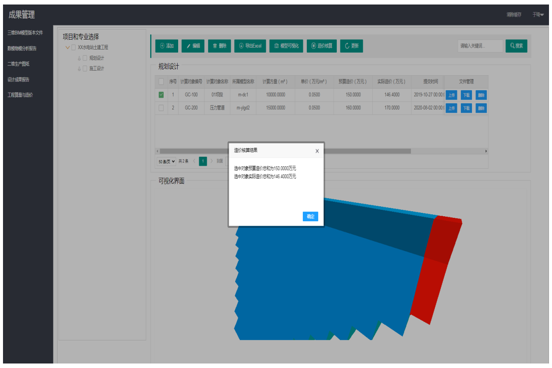
(a) RCC online design



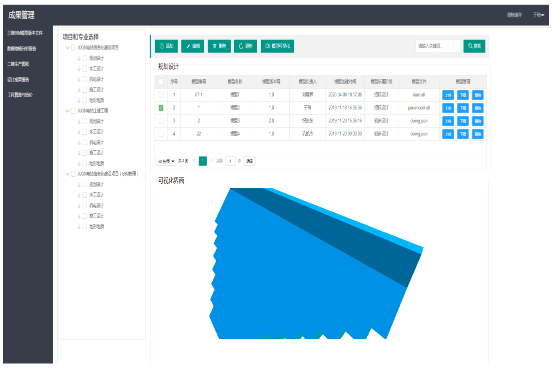
(b) Online design and analysis


(c) Programming design

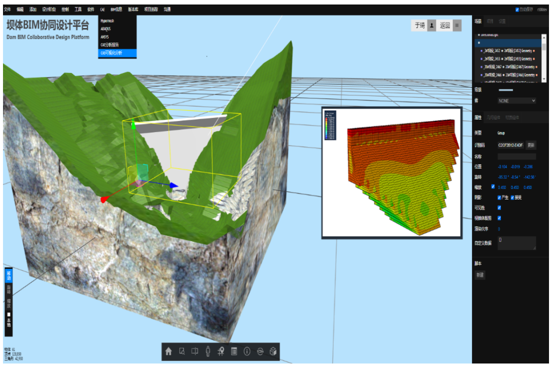

(d) Programming design



(e) Quantity analysis



(f) Design management



(g) BIM/CAE system

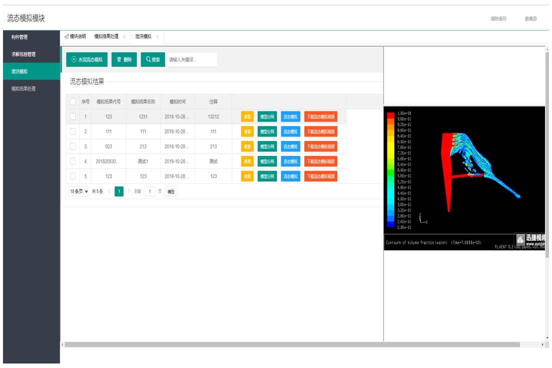
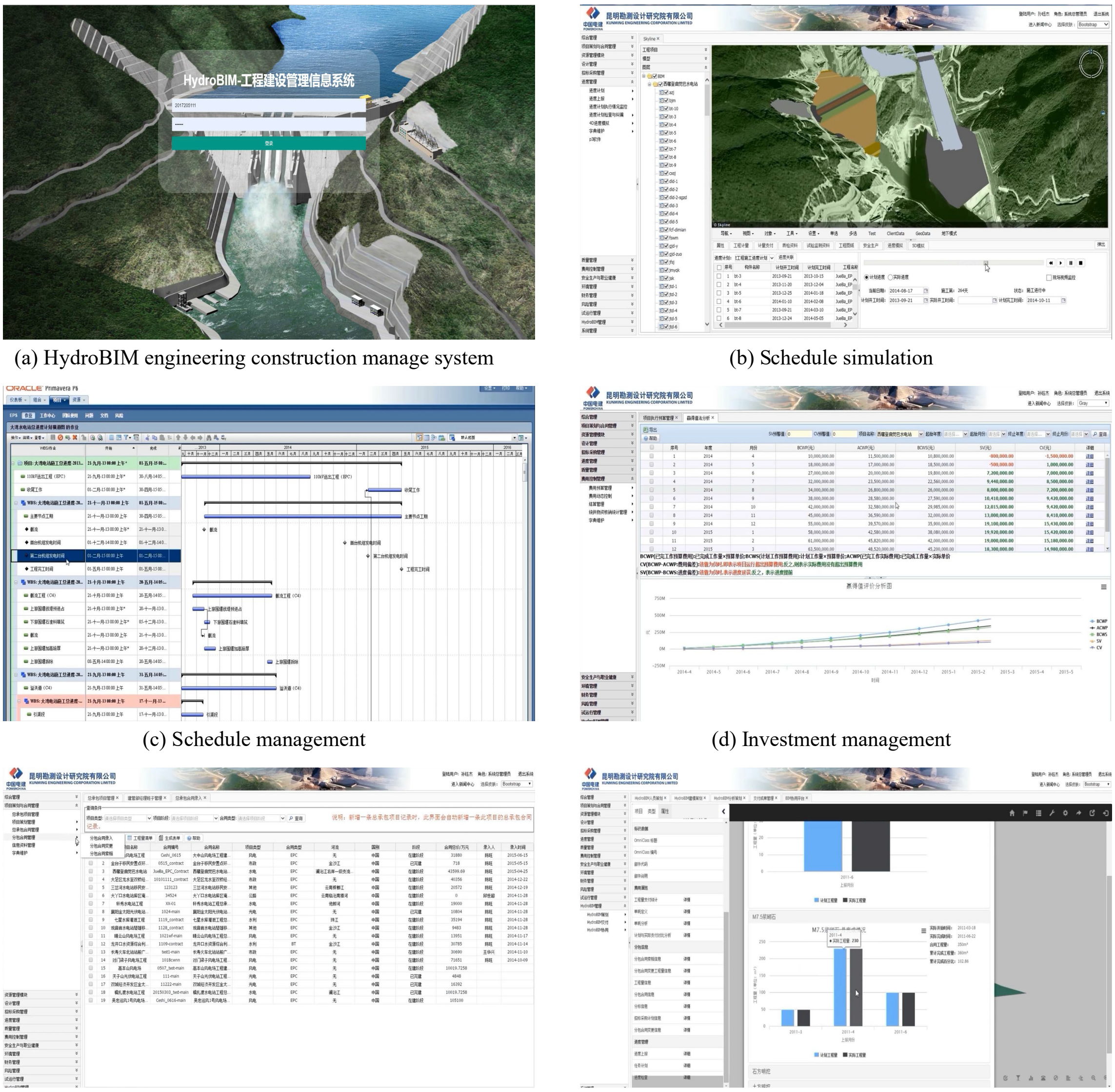

(h) BIM/CAE system

Fig. 4 HydroBIM-collaborative design and analysis integration (RCC: roller compacted concrete).

management. It established a standardized data center based on BIM to enable the collaborative sharing of multi-dimensional data (e.g., contract, schedule, quality, safety, and investment) of the entire profession and eliminate information silos.

Moreover, the platform proposed a BIM model data and EPC engineering information coupling technology to break the traditional mode of EPC engineering management as solely business information management and control. It achieved real-time linkage between the BIM model and EPC engineering management system by coupling and associating the



(a) HydroBIM engineering construction manage system (b) Schedule simulation

(c) Schedule management (d) Investment management

(e) Contract management (f) Quantity management

Fig. 5 HydroBIM-engineering construction management information platform.

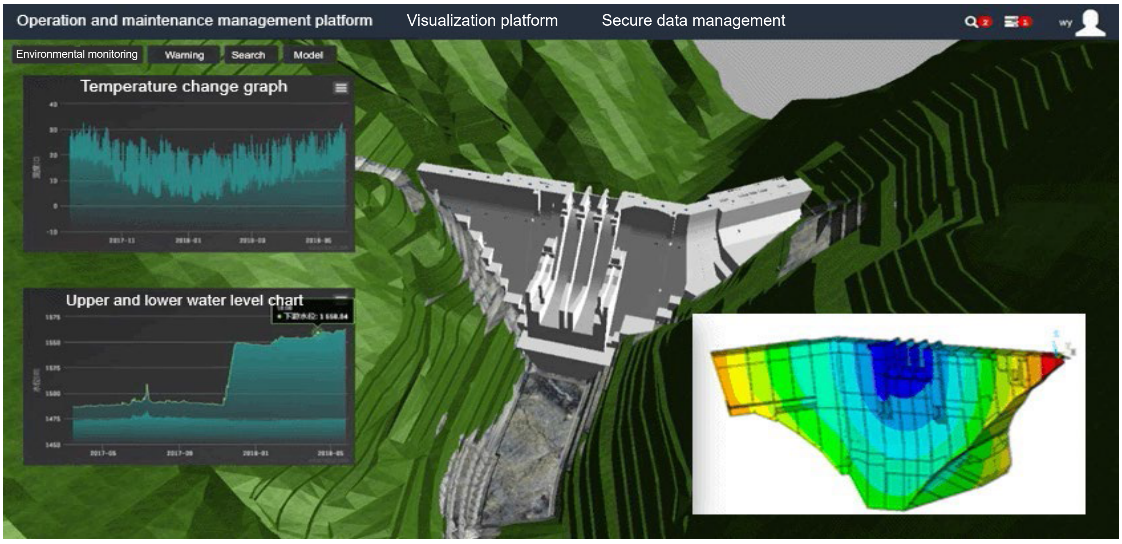
ever-growing BIM model with the real-time information of the EPC engineering.

4.3 HydroBIM-dam safety operation management information platform

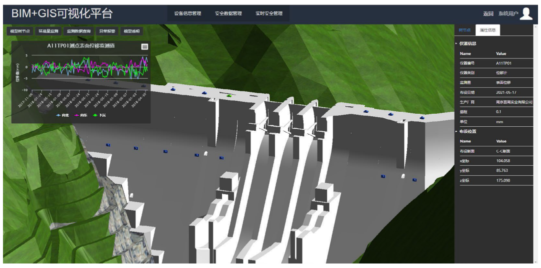
The HydroBIM-dam safety operation management information platform is a comprehensive system for the integrated management of engineering safety evaluation, early warning, and emergency plans (Fig. 6). Its development was based on the monitoring data and the positive and negative evaluation consistency criterion.

In order to perform engineering safety analysis and intelligent evaluation within the platform, a safety risk index system for water conservancy and hydropower engineering was constructed and integrated with real-time safety analysis and evaluation technology. The technical system applied to build the platform is based on BIM-integrated information integration, monitoring and inspection data processing, morphological numerical calculation, and parameter inversion analysis. The structural analysis is performed during operation based on monitoring data and parametric inversion analysis tools. The inversion analysis obtained refined forward simulation results based on a 10^8 degree of the freedom 3D finite element overall model, which compensated for the deficiency of numerical differential accuracy of stress deformation in key parts of conventional 3D finite element calculation. This enabled the comparison of the calculated results with the corresponding parts of the completed monitoring volume to achieve the operational safety evaluation of the dam structure under the consistency criterion of forward and inverse evaluation.

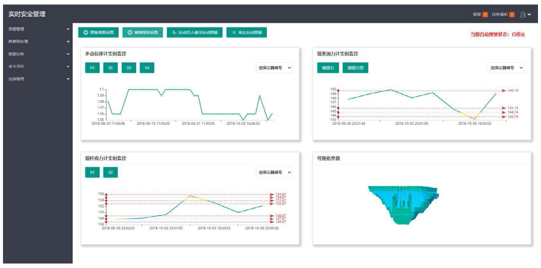
In addition, the HydroBIM was developed by combining multi-source monitoring and inspection data with measured safety information. The system provides a full range of engineering safety monitoring and early warning services. Through the deep mining of multi-source monitoring and detection data and artificial neural network simulation and prediction, the real-time



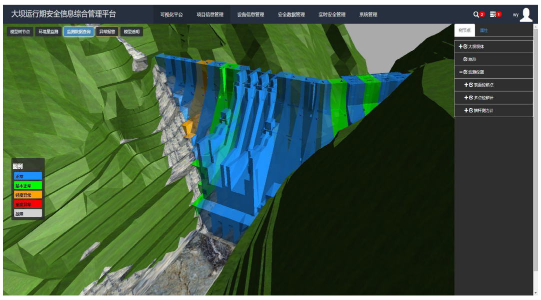
(a) Operation and maintenance management platform



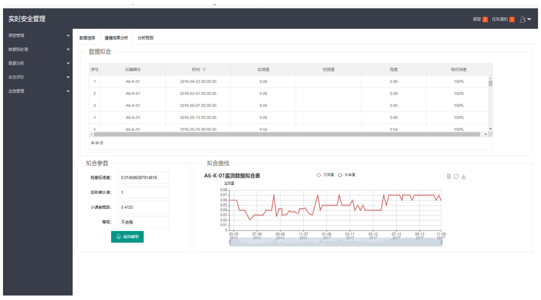
(b) Monitoring information retrieval



(c) Automatic analysis andearly warning



(d) Early warning evaluation of dam body



(e) Output early warning result

Fig. 6 HydroBIM-dam safety operation management.

analysis and rapid prediction of engineering risk level were realized.

5 Engineering applications

The HydroBIM series platform has been successfully implemented in over 20 water conservancy and hydropower engineering, including Nuozadu, Huangdeng, Guanyinyan, Jueba in Tibet, Luanping pumping and storage, Hongshiyan barrier lake, Dianzhong water diversion, Beiben in Laos, and Kluet1 in Indonesia. By utilizing the HydroBIM platform, the efficiency of design and analysis for water conservancy and hydropower hub buildings has been improved by 1.5–2 times in terms of time compared to conventional methods.

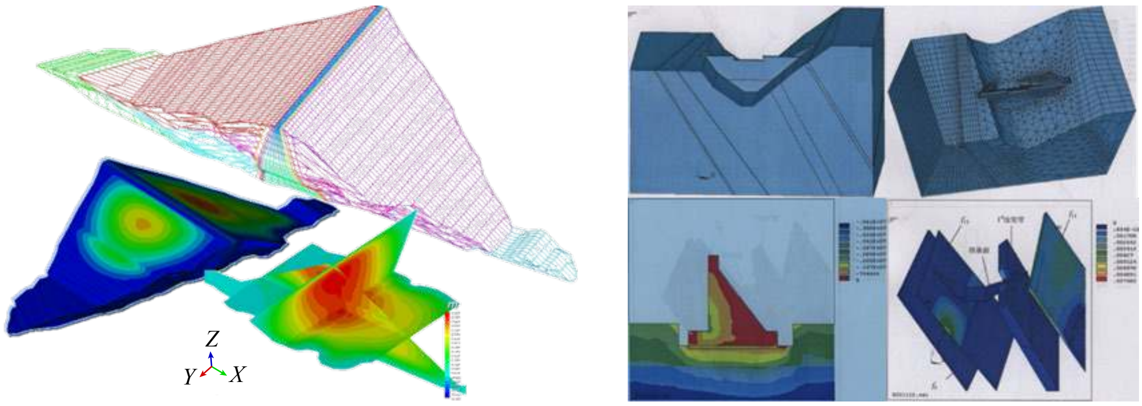
As an example, the Nuozadu hydropower station located in Puer City of Yunnan Province, with an installed capacity of 5.85 × 10^6 kW, has successfully applied the HydroBIM platform to its heart-wall rockfill dam, open spillway on the left bank, flood-discharge tunnels on both banks, underground water diversion and power generation system, and other buildings.

5.1 Planning and design phase

During the feasibility study of the Nuozadu hydropower station, various software such as autodesk computer aided design (AutoCAD) and 3D studio max (3DS Max) was utilized in combination with multidisciplinary applications to achieve 3D visualization of layout patterns and dam type selection (Fig. 7). This facilitated the exchange of design ideas among different disciplines and allowed decision-makers to evaluate design schemes rapidly. Furthermore, static and dynamic numerical simulations were conducted separately for both concrete gravity dam and heart-wall rockfill dam types to aid in their comparison and

(a) Heart-wall rockfill dam scheme (b) Gravity dam scheme

Fig. 7 3D visualization simulation of hub arrangement scheme.

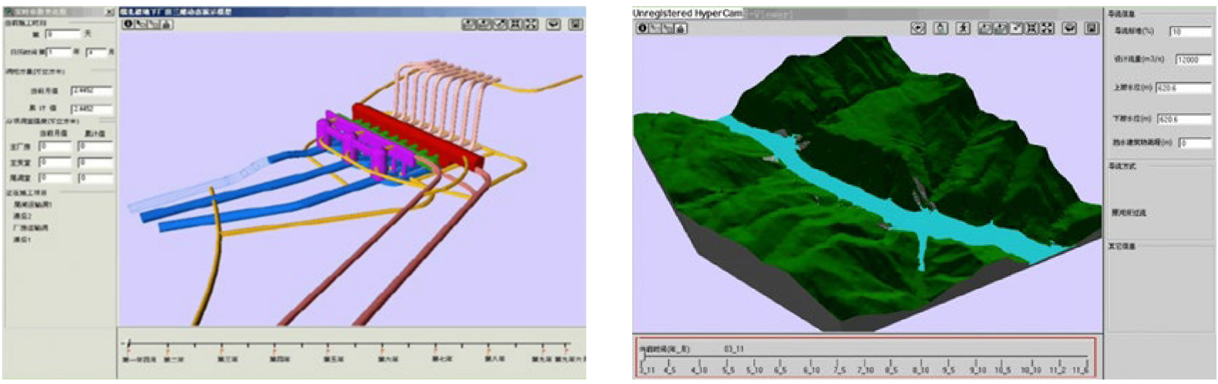


(a) Heart-wall rockfill dam (b) Gravity dam

Fig. 8 3D numerical simulation.

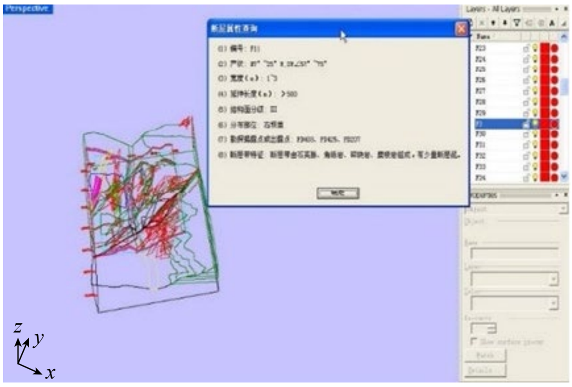
selection (Fig. 8). The BIM + GIS technology was also implemented to simulate and optimize the 3D visualization of the dam, underground cavern group, and diversion and interception construction (Fig. 9). In addition, a 3D geological model of the hub area was established by combining geological exploration and experimental analysis, thereby improving construction design efficiency.

During the bidding and construction drawing phase, the team developed NZD-VisualGeo, a system for 3D visualization modeling and analysis of geological information. This system allowed for the dynamic updating of the geological information model based on the latest geological conditions, providing an interactive platform for design and construction and improving work efficiency and quality (Fig. 10). Using the reverse engineering technology, the GIS 3D geological model was materialized. The various teams then used software such as Civil3D, Revit, and Inventor to carry out 3D design directly, and Navisworks software was used for intuitive model integration review, support design, model profiling, 4D construction, and other tasks (Fig. 11). This provided a complete 3D design review scheme for the hub and electromechanical engineering design. By combining the geological conditions revealed during construction with 3D CAD/CAE integrated analysis and monitoring information feedback, the team was able to dynamically adjust and optimize the underground cavern

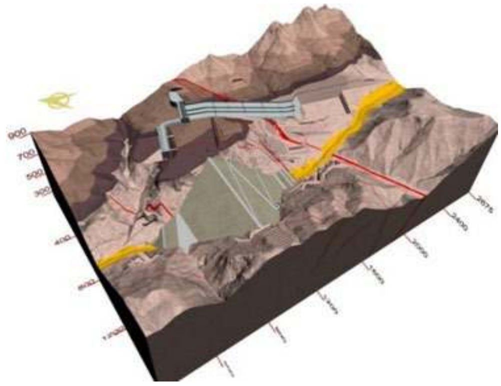


(a) Dam and underground cavern group (b) Diversion and interception construction

Fig. 9 3D visualization simulation and optimization.

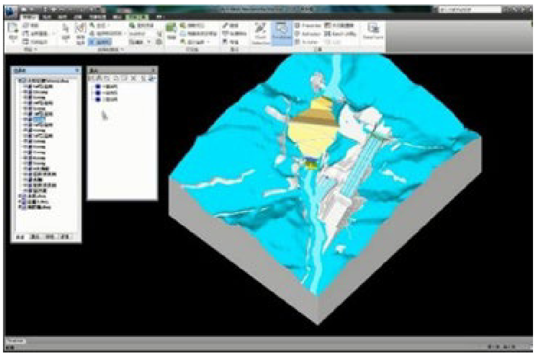


(a) Interactive platform

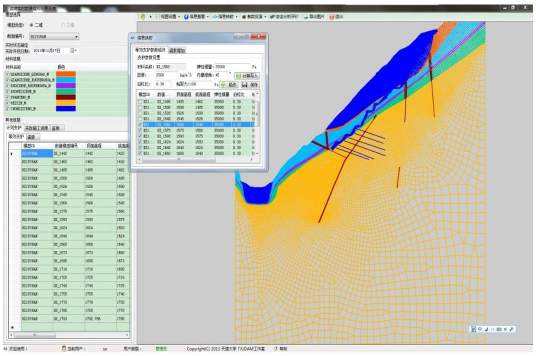


(b) Geological model

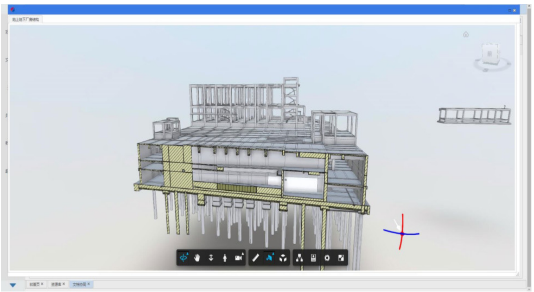
Fig. 10 Geological information model of hub area.



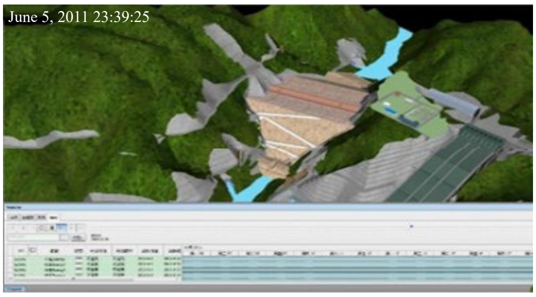
(a) Integrated review



(b) Support design



(c) Model profiling



(d) 4D virtual construction of heart-wall rockfill dam

Fig. 11 Application of BIM in technology.

group and high slope support parameters, ensuring the safety and economy of the engineering.

5.2 Engineering construction phase

During the construction phase of the dam body, a real-time monitoring technology for the transportation of dam materials onto the dam was proposed (Fig. 12). An automatic collection device was developed to gather dynamic information on dam material transport vehicles, and a real-time monitoring system for the transportation process of dam materials onto the dam was established. This system facilitated the matching of material source and unloading material partition, as well as the dynamic monitoring of up-dam intensity and road traffic density, ensuring the accuracy of the dam material and the efficient scheduling of construction and transport vehicles.

In addition, a real-time monitoring system was independently developed to gather information on the rolling process of the dam surface. This system analyzes and judges in real-time whether the driving speed, excitation force output, number of rolling times, and compaction thickness exceed the standard and provides real-time alarms through the monitoring terminal personal computer (PC) and handheld personal digital assistant (PDA) to guide relevant personnel in making on-site adjustments (Fig. 13).

5.3 Operation management phase

Based on the planning and design results, a safety evaluation and early warning management information system for an ultra-high heart-wall rockfill dam based on cloud computing remote control was developed using integrated engineering safety comprehensive evaluation and early warning digital technology (Fig. 14). The system includes monitoring data collection and analysis

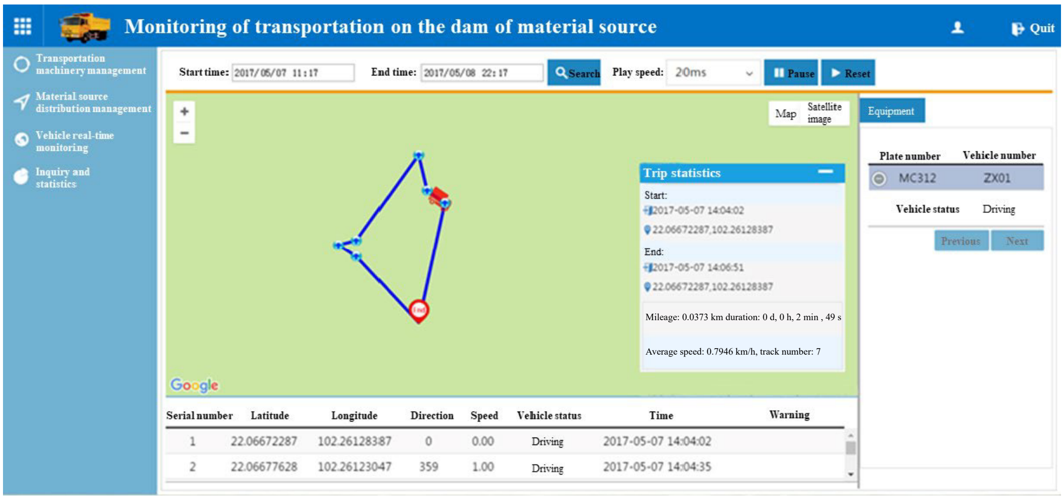


Fig. 12 Dam material transportation trajectory monitoring.

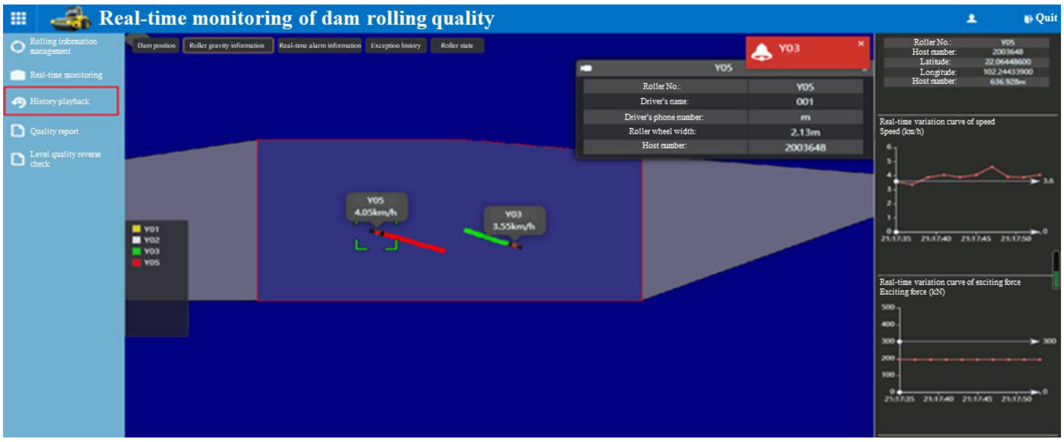
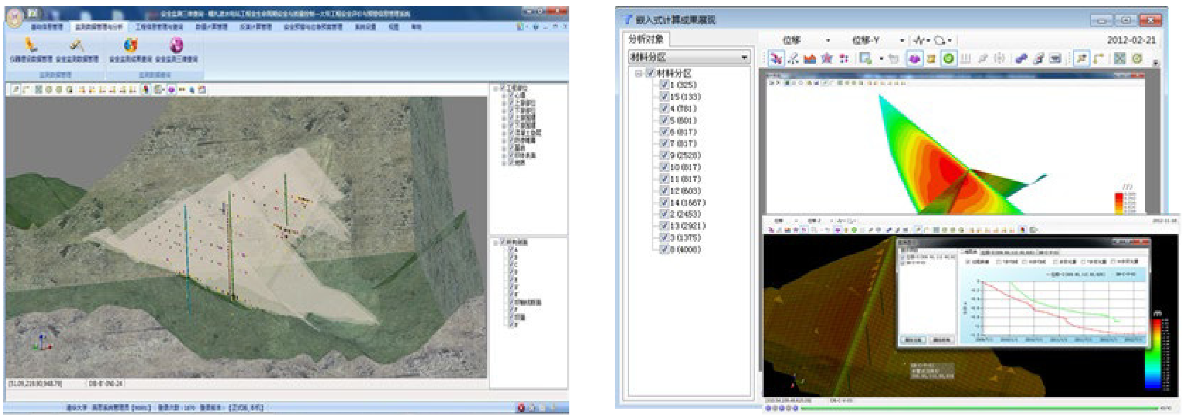


Fig. 13 Real-time monitoring system for the information of dam face rolling process.



(a) Visualization of monitoring point layout (b) Displacement monitoring and numerical calculation results

Fig. 14 Safety evaluation and early warning management information system.

management, dam numerical calculation and inversion analysis, safety comprehensive evaluation index system, early warning system, inspection records, and document management. It integrates all these functions to play an important role in the monitoring information management, behavior analysis, safety evaluation, and early warning of the dam.

6 Conclusions

In conclusion, this study presents a comprehensive approach to digital design, intelligent construction, and smart operation of hydropower engineering based on the HydroBIM series system platform. The HydroBIM technology system, standard system, IFC data standard, GeoBIM 3D geological modeling software, collaborative design and analysis integrated platform, engineering construction management system, dam safety operation management information platform, and the life cycle HydroBIM control platform were developed and applied.

The results demonstrate that the HydroBIM series system platform can significantly improve the cooperativity of all participants, work efficiency, and information integration and ensure the quality and safety of the life cycle of hydropower engineering. Additionally, the potential of emerging technologies such as artificial intelligence (AI), knowledge graphs, digital twins, VR, blockchain, meta-universe, and others should be explored further to innovate the working mode of the water conservancy industry and improve its efficiency.

Overall, the HydroBIM system platform represents a promising approach to the digital transformation of hydropower engineering and has significant potential for future development and application.

Acknowledgments

This work is supported by The National Key R&D Program of China Project “Research and Development of Technology and Equipment for Landslide Dam Danger Management and Exploitation” (No. 2018YFC1508500), Yunnan Province Science and Technology Innovation Talent Program Project “Science and Technology Leading Talent: Zongliang Zhang” (No. 2016HA004), Yunnan Provincial Key R&D Program Project “R&D of BIM Integration Technology for Long-Distance Banded Composite Buildings in High Mountain Canyon Area” (No. 2018BA066), etc.

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