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Investment control strategies in smart construction of hydropower projects

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Abstract: Smart construction has become a transformative trend in the development of large-scale hydropower projects. This study investigates the investment control mechanisms enabled by smart construction within hydropower projects. A comprehensive framework is proposed to support full-process cost management, incorporating dynamic monitoring, real-time analysis, and predictive decision-making. Furthermore, an engineering case study is presented to validate the framework's practical applicability and performance. Based on these findings, the paper outlines several strategic recommendations for optimizing investment control under smart construction paradigms, providing theoretical insights and technical references for future applications.

Keywords: hydropower project; smart construction; investment control; building information modeling (BIM); cost management; Internet of Things (IoT); digital engineering.

1. Introduction

Hydropower, as a key component of China's clean energy portfolio, plays a fundamental role in achieving the national goals of carbon peaking and carbon neutrality [1]. In recent years, the commencement of numerous large-scale pumped storage power stations and hydropower projects in Southwest China's clean energy bases has significantly increased the complexity of project construction, investment intensity, and associated risks [2]. These evolving challenges urgently call for a transformation in project management approaches.

Traditional investment management in hydropower engineering has largely relied on manual record-keeping, periodic reporting, and on-site inspections. This mode suffers from issues such as delayed information flow, lagging decision-making, and unclear accountability, which often lead to cost overruns and resource inefficiencies [3]. Smart construction, a new paradigm that deeply integrates and optimizes construction processes through digital technologies [4,5], offers a viable pathway toward establishing an investment control system characterized by data-driven decision-making, dynamic regulation, and full-process traceability. This approach enables real-time sensing, analysis, and decision-making throughout the entire construction lifecycle, significantly enhancing both the quality and economic performance of hydropower projects.



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2. Key technologies of smart construction and their roles in investment management

Smart construction, by integrating digital technologies with engineering construction processes, fundamentally transforms project implementation methods. In terms of investment management, it demonstrates the following key contributions:

2.1. Building information modeling (BIM): investment visualization and full-cycle cost management

BIM integrates design, construction, and budgeting into a unified platform through 3D visualization models [6], offering several advantages:

- (1) Automated Quantity Extraction: BIM models can accurately extract quantities, dimensions, and properties of components, providing a high-precision basis for budget preparation.
- (2) Dynamic Budget Tracking: By combining construction progress with payment milestones, the system dynamically generates budget execution reports and assesses remaining funds.
- (3) Change Impact Analysis: In the event of design modifications or material substitutions, the system rapidly evaluates their impact on total investment and suggests alternative plans.

2.2. Internet of Things (IoT): real-time cost sensing on construction sites

By deploying sensors, RFID tags, and cameras in critical structures such as dams, high slopes, underground powerhouses, and access tunnels [7], IoT enables:

- (1) Material Inflow and Consumption Monitoring: Automatically records the status of materials such as aggregates, cement, and steel, allowing real-time comparison between planned and actual usage.
- (2) Equipment Runtime Statistics: Operating data from excavators, concrete batching plants, and other machinery are uploaded automatically to support equipment depreciation and energy cost calculation.
- (3) Labor Resource Optimization: Through the integration of GPS and attendance data, the system analyzes labor cost structures and productivity to minimize redundant workforce deployment.

2.3. Digital twin: visual decision support for investment control

By constructing a digital twin of the hydropower project, real-time mapping between the physical project and its virtual counterpart is achieved [8], enabling:

- (1) Visualized Investment Schedule Presentation.
- (2) Cost Simulation of Engineering Modifications via Scenario Modeling.
- (3) Asset Valuation and Maintenance Cost Forecasting during the Operational Phase.

3. Construction of an investment management system for smart construction in hydropower projects

3.1. Objectives and principles of investment control

The core objective of investment management in smart construction is to achieve comprehensive control over fund utilization across the entire lifecycle, all elements, and all processes. The fundamental principles include:

- (1) Pre-Planning: Setting investment redlines and risk thresholds based on model-driven data analysis.

(2) Real-Time Control: Utilizing on-site data for continuous monitoring, deviation analysis, and corrective action during construction.

(3) Post-Event Traceability: Enabling traceable analysis of decision pathways and cost flows after project execution.

3.2. System architecture design

The smart construction investment control platform is structured in hierarchical layers:

(1) Data Acquisition Layer: Includes on-site sensors, RFID devices, video surveillance systems, and BIM models.

(2) Data Integration Layer: Establishes a unified data platform for the standardized processing and fusion of multi-source data.

(3) Business Logic Layer: Integrates functional modules such as budget control, contract management, material tracking, and cost-schedule coordination.

(4) Visualization and Decision-Making Layer: Presents key performance indicators (KPIs) through dashboards, supporting project managers in efficient and informed decision-making.

3.3. Control content and indicator system

A multi-dimensional investment control index system is established, including:

(1) Investment Execution Rate: Ratio of funds used to total budget.

(2) Unit Construction Cost Deviation Rate: Measures variance from expected cost benchmarks.

(3) Material Loss Rate and Abnormal Fluctuation Detection: Identifies overconsumption and anomalies in material usage.

(4) Integrated Evaluation Index of Cost-Schedule-Quality (CPI-SPI-QPI): A composite metric linking cost performance (CPI), schedule performance (SPI), and quality performance (QPI) for comprehensive assessment.

4. Engineering application

4.1. Project overview

The engineering application was implemented at the Kala Hydropower Station, located in the Yalong River basin in the mountainous canyon area of Southwest China. Situated in Liangshan Prefecture, Sichuan Province, it is the seventh hydropower station on the middle reaches of the Yalong River. The station has an installed capacity of 1.02 million kilowatts, with a normal reservoir level of 1987.0 meters and a total storage capacity of 237.8 million cubic meters, classifying it as a large-scale (Class II) project. The key structures include a concrete gravity dam, spillway and energy dissipation works, and an underground powerhouse.

Due to its location in a remote mountainous canyon with poor geological conditions and challenging transport access, the project presents high technical complexity and large-scale construction requirements. During the construction phase, an integrated smart construction system—"1+1+4+1"—was developed to align with the full-business, full-process, and all-element digitalization goals, ultimately achieving a complete digital handover for safer, more efficient, and precise construction

and management. The system, known as the Kala Smart Construction Platform, consists of 1 set of infrastructure, 1 unified data platform, 4 smart applications, and 1 decision-making and command module.

4.2. Implementation of smart construction investment management

(1) BIM Modeling

Full BIM coverage was achieved across all major structures in the dam area, integrating lifecycle data—from preliminary design and construction drawings to as-built models—including schedule, quality, and investment data (displayed in Figure 1).

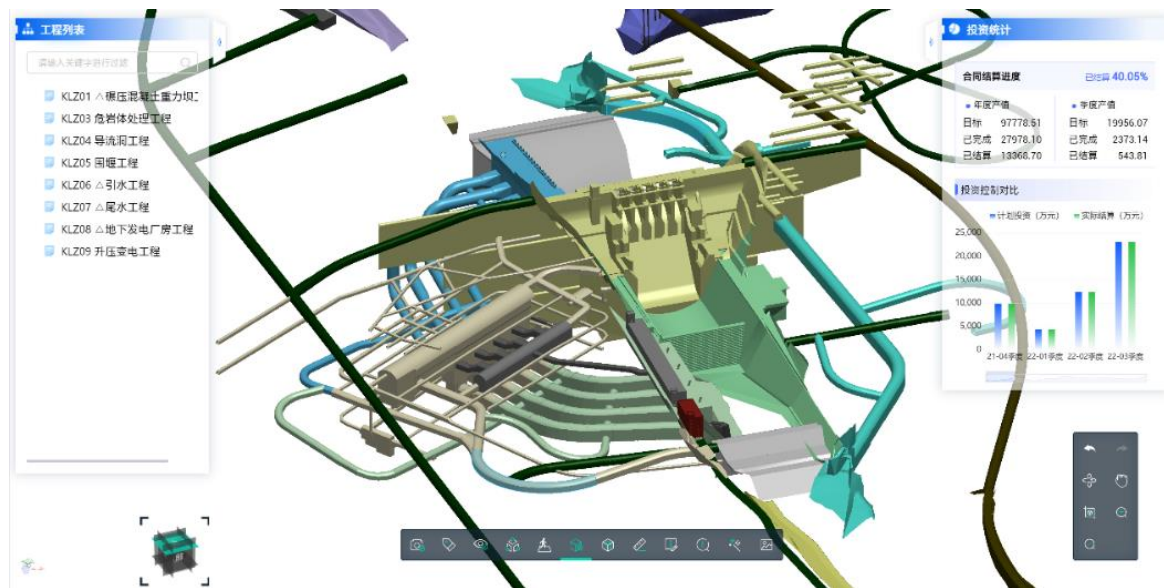


Figure 1. BIM model for the full lifecycle of project construction.

(2) IoT Deployment

Over 2,100 sensor points and video surveillance units were installed to provide real-time monitoring of key processes such as underground powerhouse excavation, concrete production and pouring, temperature control, and strength development. Figure 2 displays a typical IoT deployment. Figure 3 displays the intelligent concrete temperature control system for the dam based on IoT monitors and AI algorithm.

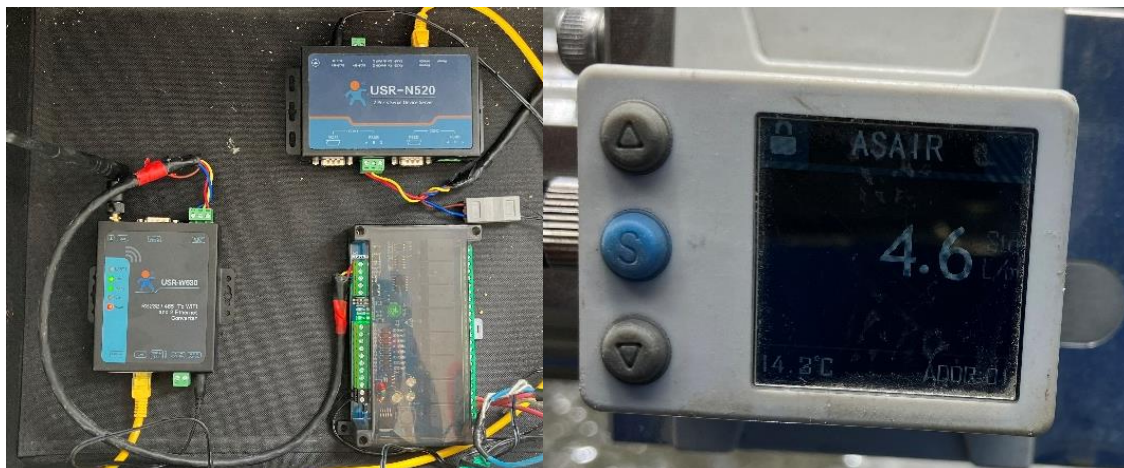


Figure 2. IoT deployment overview.

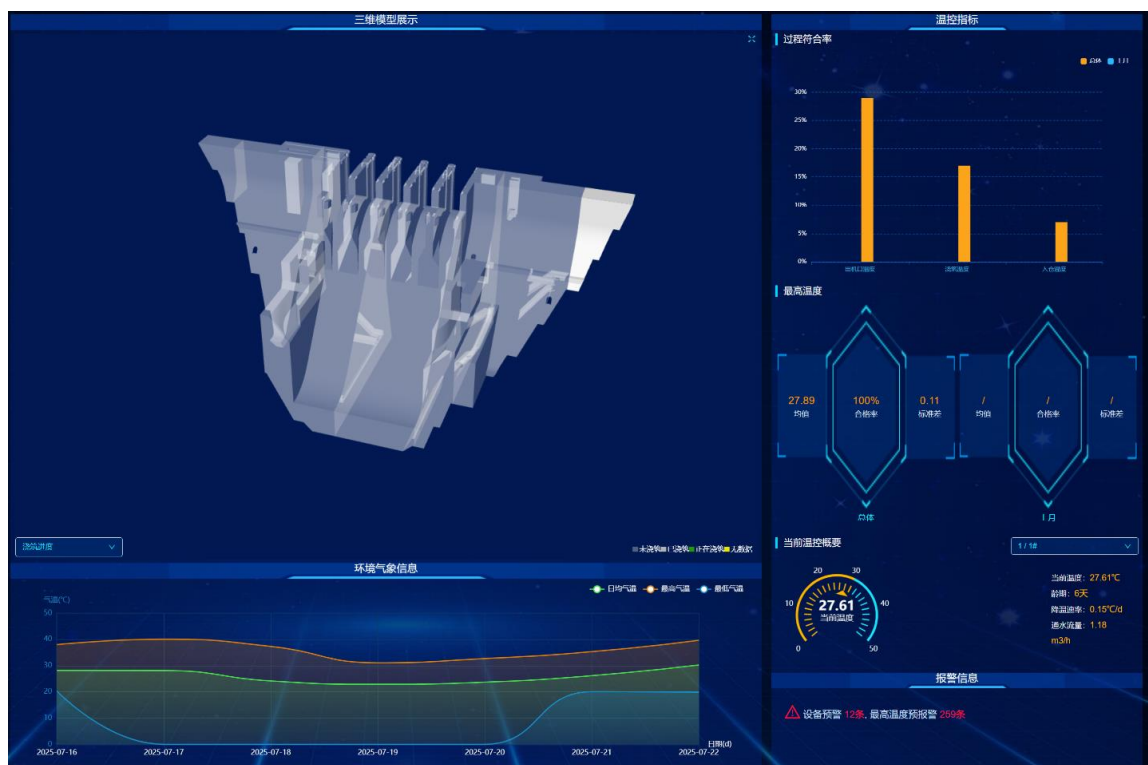


Figure 3. Intelligent concrete temperature control system for the dam.

(3) Investment Data Analysis

Automated weekly generation of investment comparison charts and execution reports, linked with construction progress, enabled the identification of deviations at both project and subcomponent levels. Figure 4 displays a typical investment comparison chart.

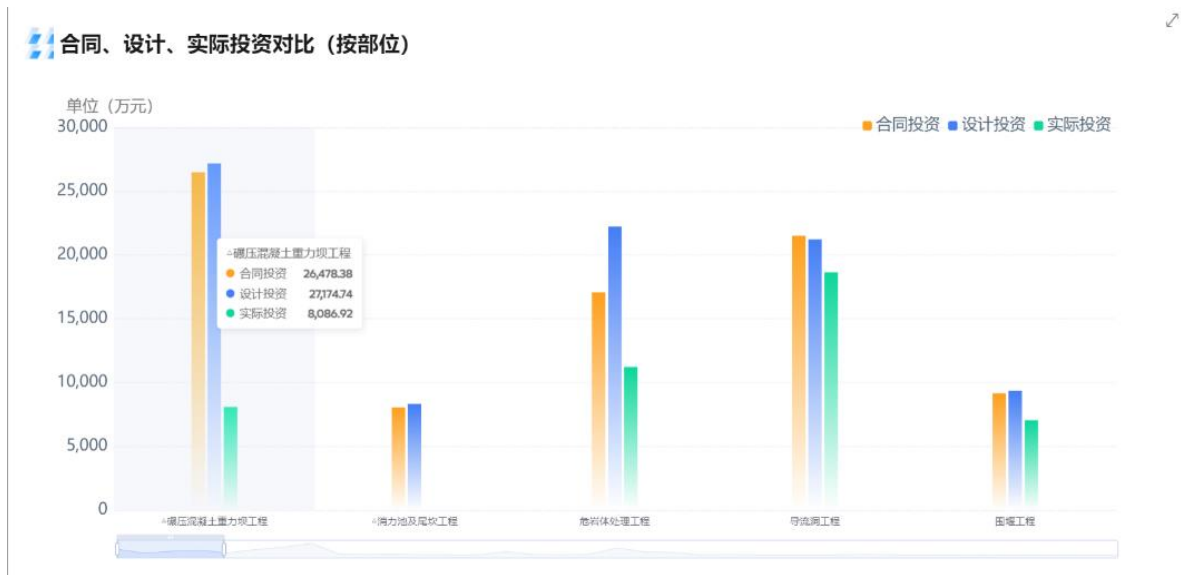


Figure 4. Investment data comparison report.

(4) Visualization Dashboard

A command center dashboard displayed a real-time “investment heatmap” to visualize fund usage across various construction segments (Displayed in Figure 5).



Figure 5. Visual dashboard of investment control system.

4.3. Implementation outcomes

Investment deviation rate reduced from $\pm 8.5\%$ to $\pm 2.7\%$:

- (1) Material wastage rate decreased by 15%.
- (2) Project settlement cycle shortened by approximately 28%.
- (3) Information approval cycle reduced from an average of 5 days to less than 1 day.

5. Future development directions

5.1. Establishing unified industry data standards

It is recommended that relevant government ministries take the lead in formulating standards such as the *‘‘Data Interface Standard for Smart Construction in Hydropower Projects’’* and the *‘‘Technical Guidelines for Investment Control Models’’*, thereby promoting cross-platform interoperability and collaborative application.

5.2. Strengthening interdisciplinary talent development

By fostering integrated expertise in cost management, engineering, and information technology, a new generation of professionals can be cultivated who are proficient in both investment control and digital platforms.

5.3. Advancing lifecycle intelligent management

Investment control should be extended beyond the construction phase into the operational period, enabling analysis of lifecycle equipment costs and dynamic asset value management throughout the entire project lifespan.

5.4. Building a digital twin system for hydropower investment

Develop a comprehensive ‘‘investment digital twin’’ system that enables dynamic simulation and real-time feedback across the entire project chain—from virtual design and construction modeling to cost estimation and long-term operation and maintenance.

6. Conclusion

As a forward-looking paradigm in construction, smart construction has brought unprecedented technological and managerial innovation to investment control in hydropower projects. By building an intelligent investment management system that integrates technologies such as BIM, IoT, and artificial intelligence, project teams can significantly improve the transparency, accuracy, and efficiency of capital utilization, ensuring both the quality and cost-effectiveness of engineering outcomes.

Looking ahead, efforts should focus on promoting standardization, platform integration, and professional talent development, in order to accelerate the transition of smart construction from technical pilot to mainstream systematic practice within the hydropower sector.

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Authors' contribution

Formal analysis, Jincheng Li, Shuai Zhang; investigation, Jincheng Li; resources, Chengjia Huang; data curation, Shuai Zhang; writing—original draft preparation, Jincheng Li; writing—review and editing,

Shuai Zhang visualization, Chengjia Huang; supervision, Shuai Zhang. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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