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Application and Development of Hydraulic Steel Structure Safety Information Management System in Pumped Storage Hydropower

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Abstract. In the context of the current energy structure transition and the rapid advancement of clean energy, the reliability of hydraulic steel structure equipment plays a crucial role in the stable operation and efficiency improvement of pumped storage hydroelectric power stations. With technological advancements, strengthening the digital management of hydraulic steel structures has become a focal point in the industry's development. This paper takes the "JinZhi" system developed by the PowerChina HuaDong Engineering Corporation Limited as an example to deeply explore the practical application of hydraulic steel structure safety information management system and its significant role in enhancing operational efficiency and safety. By analyzing industry development trends, the paper reveals the challenges and potential opportunities encountered during digital transformation and proposes targeted recommendations for future development direction. The research demonstrates that the integrated application of information technology can effectively improve the management quality and safety level of hydraulic steel structures, ensuring the efficient and stable operation of power stations, and providing valuable insights for similar industries aiming to achieve digital transformation.

1. Introduction

With the global energy structure transitioning and the rapid development of clean energy, pumped storage hydroelectric power stations, as the most effective energy storage method, play a vital role in regulating grid load, improving energy utilization efficiency, and supporting the stable integration of renewable energy[1,2]. Among the various components of pumped storage power stations, hydraulic steel structure equipment (i.e. gates and hoists) is responsible for several key functions, and its reliability is directly related to the safe and stable operation of the power station.

Currently, as China enters the peak period of pumped storage power station construction and development, addressing the challenges in the maintenance and management of hydraulic steel structures and enhancing their digital management levels has become an urgent issue. From the online monitoring of a few equipment parameters to a panoramic, comprehensive safety and operational information management system, not only can real-time monitoring of equipment status be achieved, but also potential risks can be predicted through data analysis. This evolution represents a significant leap in the technological capabilities of the industry, providing more reliable and efficient management tools. The "Hydraulic Steel Structure Intelligent Management System" (HSSIMS, JinZhi in Chinese) provides reliable technical support for the safe operation of power stations.

This paper reviews and discusses the application and development status of the hydraulic steel structure safety information management system in pumped storage power stations, focusing on analyzing the core functional modules of the system and their roles in improving operational efficiency and safety. By analyzing industry characteristics, summarizing the challenges and opportunities encountered in the digital empowerment process of the hydraulic steel structure industry, and providing suggestions for the further development of safety information management systems.

This comprehensive analysis aims to establish a framework for future innovations and adaptations in the sector. Furthermore, it emphasizes the importance of formulating clear digital development goals, forming a unified construction mechanism, and ensuring the orderly progress of information construction.

The key elements of this analysis are:

Data Aggregation: Consolidating data from various sources and in different formats to create a comprehensive dataset.

In-depth Analysis: Conducting thorough examination and exploration of the aggregated data to derive meaningful insights.

Quality Improvement: Leveraging the insights gained from the data analysis to enhance the overall management quality and decision-making processes.

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The goal is to provide a structured approach to facilitate future innovations and adaptations within the sector, while also emphasizing the criticality of establishing clear digital development objectives, implementing a unified construction framework, and ensuring the systematic advancement of information infrastructure.

2. Key Roles and Safety Manage-Ment Challenges of Hydraulic Steel Structures

Hydraulic steel structures, such as gates and hoists, are responsible for critical functions such as emergency flow cutoff and diversion discharge in pumped storage power stations. Any failure can lead to severe safety accidents and economic losses, requiring the equipment to maintain high reliability and rapid response capabilities. However, in many power station practices, the management of hydraulic steel structures is still relatively rough and traditional, unable to match the trend of comprehensive digitalization in engineering. The operational characteristics of power stations include relatively streamlined staffing, and there may be a lack of specialized technical personnel focused on hydraulic steel structures among the operation and maintenance personnel, posing challenges for daily maintenance management and emergency response.

- Shortage of Professional Personnel:

With the development of high-efficiency and streamlined operations in pumped storage power stations, there may be a lack of dedicated hydraulic steel structure maintenance personnel on site. Non-specialized personnel may find it challenging to timely and accurately identify and address structural issues, increasing operational risks.

- Increased Information Maintenance and Management Pressure:

Due to streamlined operation and maintenance personnel, higher demands are placed on the technical capabilities and maintenance efficiency of existing personnel. The low degree of digitalization of operational data, with various inspection records, operational data, and documentation managed separately or without digital storage, hinders efficient operation and maintenance and leads to a large workload in responding to safety inspections and other routine tasks.

- Lack of Monitoring Data:

Hydraulic steel structure equipment is generally not equipped with real-time monitoring and sensing equipment, making it impossible to track and record the operational status of the equipment. Problems can only be discovered through periodic inspections, making predictive maintenance management challenging.

Meanwhile, the integration of emerging technologies such as IoT and advanced data analytics has the potential to transform the monitoring and management landscape for hydraulic steel structures. The continuous emergence of new technologies, such as digital information platform technology, various sensor IoT, and modern detection technologies represented by artificial intelligence algorithms, has effectively applied these technologies to the maintenance and management of hydraulic steel structures, enhancing the overall performance and safety of the system[3]. This brings new solutions for the safety management of hydraulic steel structures. With the peak period of pumped storage power station construction in China[4], it is a rare opportunity to enhance the digital management level of hydraulic steel structure equipment.

3.definition and Development of Information Systems

Monitoring systems for hydraulic steel structures have always existed in the industry. These systems often cover individual equipment levels without involving unified information management across the entire power station. They can achieve online monitoring and status display of equipment, with some products performing preliminary fault diagnosis functions.

The author’s institute, the PowerChina Huadong Engineering Corporation, has developed and designed a product from the perspective of the overall hydraulic steel structure safety information management system for the entire power station. The original intention was to serve as a comprehensive assistant for hydraulic steel structure management personnel. After years of exploration with many owners through scientific research projects and engineering projects, the product has been defined into four major functional modules:

- Panoramic information management;
- Online monitoring;
- Digital operation and maintenance;
- Expert systems.

This system has been registered under the "JinZhi" trademark and implemented in Fuchunjiang Hydropower Station, Tongbai Pumped Storage Power Station, Panlong Pumped Storage Power Station, and many other water conservancy projects. Figure 1 shows the main interface of the Fuchunjiang information system.

FIG. 1. Homepage of Fuchunjiang system (The homepage features a 3D baseboard displaying the power station and geographical scene, partially achieving a digital twin. The dashboard shows important design parameters and real-time monitoring data of the gates. Additionally, it is equipped with tools for alarm alerts and video surveillance.)

Each project has iterated significantly on the exploration of information systems. From a product perspective, the definitions and designs of the functional modules have gradually become clear. The following is an introduction to each module's functions:

- Panoramic Information Management:

Uses visual methods such as sandbox models and real-time feedback to display the distribution and working status of the steel structures throughout the power station. It highlights key information at a glance. Simultaneously, it manages and maintains all types of operational data, inspection records, and document information from design to commissioning throughout the life cycle.

- Online Monitoring[5]:

Combines software and hardware to collect typical data of hydraulic steel structures through the addition of sensors and integration into the automatic control system, generating operational data of hydraulic steel structure equipment, which serves as a data source for health assessment and fault diagnosis. Reasonable setting of monitoring items and alarm rules.

Figure 2 shows the page of the online monitoring module.

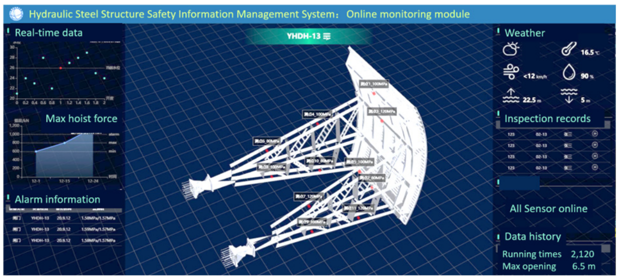

FIG. 2. Online monitoring module (In this module, a 3D model displays the sensor layout on the gate structure and the measured values. It also shows the process lines of the measurements and the comparison results of key data.

- Digital Operation and Maintenance[6]:

Achieves guided inspections through mobile software and convenient data synchronization and collection functions.

- Expert System[7]:

Includes advanced applications such as health assessment and fault diagnosis, providing macro overall health assessments and micro multidimensional operational status evaluations. Operational management personnel at all levels concerned with the status of hydraulic steel structures can obtain the required information.

By integrating these modules into a cohesive system, the management of hydraulic steel structures becomes more streamlined, allowing for real-time insights and proactive maintenance strategies that significantly enhance operational reliability and safety.

For empirical analysis, consider the use of mathematical models such as reliability indices and fault prediction algorithms. For instance, the health index HI of a steel structure can be defined as:

$$HI = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

where x_i represents the monitored parameter values, and w_i denotes the weights assigned to these parameters based on their importance.

Unlike the typical application of the Analytic Hierarchy Process (AHP) for comparing multiple alternatives, the safety assessment of structural equipment involves the quantitative evaluation of a single entity's performance over different time dimensions. This necessitates a tailored modification of the methodology. Specifically, monitoring indicators can be pre-converted into numerical values based on predefined thresholds to obtain corresponding weights.

Besides, for many indicators, expert judgment is required to establish scoring rules. Due to space limitations, some examples are provided as follows table 1:

Table 1. Evaluation indicator scoring examples of steel gate structure

	Good	Qualified	Basically Qualified	Unqualified
Major Component	$\sigma/[\sigma] < 0.85$	$\sigma/[\sigma] \le 1$	$\sigma/[\sigma] \le 1.05$	$\sigma/[\sigma] > 1.05$
Weld Quality	Good	Qualified	Basically Qualified	Unqualified
Main Beam Deflection	$\Delta l/l < 0.85/750$	$\Delta l/l < 1.0/750$	$\Delta l/l < 1.05/750$	$\Delta l/l \ge 0.85/750$
Arm Stability	$\sigma/[\sigma] < 0.85$	$\sigma/[\sigma] \le 1$	$\sigma/[\sigma] \le 1.05$	$\sigma/[\sigma] > 1.05$
Cavitation State	No cavitation	Mild cavitation	Cavitation damage	Severe cavitation damage
Maintenance Management	Regular maintenance	Basic regular maintenance	Irregular maintenance	Minimal maintenance
Corrosion Rate /mm·a^{-1}	≤ 0.03	≤ 0.05	≤ 0.08	> 0.08
Many other indicators				

Through practical application in typical projects, this evaluation system can achieve results similar to traditional safety inspection and assessment, and it can realize automated online operation.

4. Industry Characteristics Analysis

Hydraulic steel structure equipment includes mechanical structures, electrical equipment, and human-machine interaction usage and maintenance, making comprehensive evaluation and management a complex issue. This complexity is reflected in the wide range of severity levels and specificity of risk accident cases (from a single bolt loosening to a plant flooding accident), and it is greatly influenced by human factors.

For example, health assessments in other relatively mature industries, often comparable, mainly involve rotating machinery and long-term operation equipment. High-frequency vibration spectrum analysis can obtain rich information, and long-term operation accumulates a large amount of data. Simultaneously, there are sufficient failure samples generated by wear and tear. These characteristics are not present in hydraulic steel structure scenarios. Relatively speaking, hydraulic steel structure equipment operates at low speeds and for short durations. Failures due to the degradation of the equipment's own performance are rare. Hydraulic steel structure equipment includes not only individual devices such as motors and reducers but also a mechanical load-bearing and energy transmission chain, with the latter's reliability being equally important. As show in figure 3.

FIG. 3. Individual specificity of non-standard steel structures

Therefore, in terms of health assessment and fault diagnosis functions, authoritative standards and methods are lacking. In practice, reference can only be made to certain specifications from other industries or within the industry, such as the "Technical code of safety inspection for hydraulic steel gate and hoist machinery" DL/T 835-2003, "Safety Operation Regulations for Hydraulic Steel Gates and Hoists" SL/T 722-2020, "Technical Conditions for Online Monitoring System of Steel Structure Equipment Status in Hydropower Projects" NB/T 10859-2021, and " Technical code of safety inspection for hydraulic steel gate and hoist machinery" DL/T 835-2003. When referring to practices from other industries, significant differences exist due to different research objects, leading to practical differences.

The non-standard characteristics of steel structures require that monitoring and analysis must be tailored to each specific project. This necessitates long-term investment and experience accumulation.

Due to the lack of unified authoritative standards and specifications, this part of the functionality is the least mature and uniform, with different design institutes and manufacturers providing different answers. This also reflects the depth of understanding of the safe operation of hydraulic steel structures. To date, the evaluation algorithms generally combine multi-level weighted analysis (Analytic Hierarchy Process) with logical judgments[8], some are using machine learning algorithms[9], often in a black-box state with weak interpretability. Although mainstream solutions use classical algorithms, their index structure, hierarchical classification, and weight settings directly affect the quality of the evaluation, reflecting the "true skills" of the design party.

Also as part of the power station, the hydraulic machinery field already has expert systems for online monitoring and fault diagnosis[10]. However, due to its long development time, specialized functionality, and highly modular products, they have been integrated into the digital station's information systems. In contrast, hydraulic steel structure equipment is relatively scattered in the power station, with related information system products having broader functionality and a wider scope, still in the early stages of development and suitable for independent design and application. Although both are information projects, there is a certain degree of chimney design, but under the coordination of design institutes, the repetition of design and construction can be reduced.

In terms of software iteration and construction, unlike consumer-grade information products that are quickly iterated based on demand, information products in this industry are driven by policies, regulations, owners, design institutes, and the industry chain. Investors, designers, and end-users find it challenging to quickly and effectively communicate and clarify needs to enter a virtuous feedback loop. The construction of power stations takes a long time, generally requiring 5-10 years from feasibility planning to commissioning, making it impossible to iterate products quickly through project implementation. Additionally, the strategic importance of hydraulic steel structures in ensuring the safety and efficiency of power stations necessitates a more robust and thorough approach to system development and implementation.

Although hydraulic steel structures are highly important, the inherent perception of "iron lumps" is difficult to change in the short term. When comprehensive resources are limited, the emphasis on safety and investment in safety is often low. There is often a contradiction where units that need safety assurance the most and are most urgent have insufficient investment in safety and cannot afford the cost of building an information system, or outdated concepts treat safety information systems as decorations. The acceptance of owners needs improvement.

Additionally, the construction of online monitoring and sensing facilities is also a focus of information system construction. In the industry's early stages, attempting to establish accurate models and even digital twins by deploying as many monitoring points and types as possible is not suitable for large-scale promotion. The difference between scientific research projects and engineering applications should be well distinguished. Meanwhile, attention should be paid to the construction technology of sensing equipment, ensuring durability, reducing additional maintenance workload, and improving data quality from the source. Furthermore, ensuring the reliability and accuracy of data collection and analysis processes is critical in developing predictive maintenance capabilities and enhancing overall system performance.

5. Prospects and Summary

Despite the aforementioned problems and challenges in the industry, the year 2024 still presents a rare development opportunity for hydraulic steel structure safety information management systems.

First, the industry is gradually recognizing the needs for the digitalization of hydraulic steel structures, reflected in feasibility study estimates and various technological upgrading projects at major power plants. This is the prerequisite for all development.

Second, as previously mentioned, application and iteration through engineering projects are very important. With the rapid development of pumped storage, the design uniformity of various power stations over the past decade is strong, at least within the same power generation group. Excellent digital product designs can be replicated in batches. With sufficient data accumulation and feedback from users at all levels, the product can enter a virtuous cycle of optimized design.

Currently, it is more suitable for the hydraulic steel structure profession in design institutes to take the lead in such systems. Design institutes possess comprehensive design data for the entire power station and can coordinate and integrate owner needs for product design, driving the joint development of upstream and downstream industries such as monitoring equipment manufacturers and software development companies during implementation. Taking the PowerChina Huadong Engineering Corporation Limited as an example, its advantages in surveying and design, and engineering digitalization, as well as the data foundation from the Large Dam Safety Supervision Center, National Energy Administration, are irreplaceable. By integrating software and hardware equipment and providing comprehensive services, it offers a cross-platform collaborative digital solution. This will enhance the stability and safety of national energy infrastructure, support the digital transformation and upgrading of the energy industry, and contribute to the implementation of national energy strategies. Looking ahead, with continuous technological advancements and clearer industry demands, the design and application of this system will become more refined and intelligent, bringing revolutionary improvements to the management and maintenance of hydraulic steel structure equipment and ensuring the achievement of sustainable energy production and environmental protection goals.

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