Design and Optimization of Water Conservancy and Hydropower Engineering Structures

Yinfeng Liu

Xihua University, Chengdu, Sichuan, 610039, China

Abstract: *This article is based on the practical needs of modern water conservancy and hydropower engineering construction, and deeply explores the core principles and optimization strategies of engineering structure design. This article systematically analyzes the selection logic of key structures such as anti-seepage, compression resistance, and energy dissipation in response to the technical bottlenecks faced by current water conservancy buildings in complex geological environments and high load requirements. By introducing multi-objective optimization algorithms and refined modeling techniques, this paper proposes a full cycle optimization path that covers the entire design phase from scheme comparison to dynamic adjustment during the construction phase. The research focuses on how to minimize material loss and improve engineering operational efficiency while ensuring structural safety and durability. The research results aim to provide theoretical reference and practical guidance for improving the standardization and scientific level of hydraulic structure design in China, so as to achieve sustainable and coordinated development of water conservancy engineering benefits and ecological environment.*

Keywords: *water conservancy and hydropower engineering; Structural design; Multi objective optimization; durability*

1. Introduction

As the core carrier of energy regulation and resource utilization, the safety and stability of the structure of water conservancy and hydropower projects are directly related to the long-term development of the national economy. As the construction environment extends towards high altitudes, strong earthquake zones, and complex geological conditions, traditional design models are no longer able to meet the stringent requirements of modern engineering for full life cycle reliability. This article aims to explore the optimization path of hydraulic structures in material modification, mechanical simulation, and intelligent monitoring through multidimensional technological innovation. The research focuses on the micro mechanism of concrete crack resistance control, and combines it with the reinforcement and strengthening design of dangerous engineering to construct a closed-loop optimization system from theoretical simulation to dynamic feedback, in order to provide scientific theoretical basis and practical guidance for improving the disaster resilience and operational efficiency of China's water conservancy infrastructure.

2. Core principles and current situation analysis of structural design in water conservancy and hydropower engineering

Within the construction framework of modern water conservancy and hydropower projects, structural design is not only the material basis for ensuring the overall stability of the project, but also a key link in determining the operational efficiency of the project. Currently, the structural design of hydraulic engineering is facing multiple challenges such as increasingly complex geological conditions and constantly increasing ecological protection requirements. In order to enhance the scientificity of design, it is necessary to adhere to the principle of balancing safety, applicability, and economy. The safety requirement is that the structure should be able to maintain overall stability and prevent destructive collapse even in extreme conditions such as floods or earthquakes that exceed the standard; Applicability emphasizes that the structure can meet various functional requirements for water diversion, power generation, or irrigation during long-term operation, and has good durability[1]. At the same time, the principle of economy requires designers to minimize construction investment through in-depth exploration of material properties while ensuring quality. At present, traditional empirical design methods are gradually shifting towards probabilistic design methods based on reliability theory, which makes structural design more in line with engineering practice and provides theoretical support for subsequent refined optimization[2].

3. Optimization strategies for structural selection and layout of water conservancy and hydropower projects

Structural selection is of paramount importance in the early stages of hydraulic engineering design, as its quality directly affects the cost of the project and the difficulty of later operation and maintenance. When optimizing, full consideration should be given to the terrain and geological conditions, hydrodynamic characteristics, and material supply situation, and multiple technical and economic comparisons should be implemented. For example, in the design of a water gate, in response to the characteristics of soft soil foundation, the stress distribution of the foundation should be improved by optimizing the layout of the bottom plate and the structural ratio of the gate pier, effectively avoiding the risk of structural cracks caused by uneven settlement[3]. For dam structures such as concrete face rockfill dams, the optimization focus is on rationalizing the zoning of the dam body and improving the crack resistance performance of the concrete face. Through scientific proportioning and fine modeling, the overall coordinated deformation ability of the dam body can be significantly enhanced. In addition, the structural layout should also pay attention to the integration with the surrounding environment, dynamically adjust the design parameters through information management methods, and ensure that hydraulic structures achieve harmonious coexistence with the natural ecological environment while exerting functional benefits.

4. Deep optimization of durability and crack resistance control logic in hydraulic concrete structure design

In the long-term operation system of water conservancy and hydropower projects, the durability of concrete structures is the fundamental variable that determines the overall safety factor and economic life of the project. Given that hydraulic structures have long been subjected to the interweaving effects of high-pressure seepage, water flow pulsation erosion, and complex geological stresses, the evolution of structural microcracks is often a trigger for major engineering accidents. Therefore, optimization design must shift from traditional empirical matching to precise design based on service environment spectrum. Firstly, in the application of materials science, the optimization path should focus on the comprehensive construction of low heat, high density, and self-healing characteristics. By introducing highly active mineral admixtures such as finely ground coal ash and silica fume, the transition zone of the slurry aggregate interface inside concrete can be significantly improved, reducing capillary porosity and cutting off the path for moisture and harmful ions to penetrate into the structure at the microscopic level[4]. At the same time, in response to the contradiction between "external constraints and internal temperature rise" commonly faced by large volume concrete, design optimization should forcibly introduce full time temperature control simulation evaluation. By establishing a three-dimensional nonlinear temperature stress field model, the construction dynamic simulation of key parts such as the dam body and the bottom plate of the sluice chamber is carried out layer by layer and day by day, accurately calculating the contribution rate of the incoming temperature, peak hydration heat, and environmental temperature fluctuations to the structural stress. Optimization measures should not only include the conventional layout of cooling water pipes, but also extend to pre cooling of aggregates, adding high-performance water reducing agents to reduce cement consumption, and developing and applying expansion agents with compensating shrinkage function. This multidimensional crack control optimization aims to establish a stable self stress defense mechanism in the early stages of hardening, significantly improving the toughness and fatigue strength of the structure.

In terms of mechanical performance optimization, the design system must go beyond traditional linear elastic analysis and instead construct a dynamic constitutive model based on structural damage mechanics. By studying the evolution process of plastic damage in concrete under complex loads, optimization design can more accurately identify the deformation law of structures under the combined action of static pressure of reservoir water and dynamic pressure of overflow water. The focus of this optimization process is to use topology optimization theory to reconstruct the internal stress transmission path of concrete, by adjusting the cross-sectional shape and curvature radius of the components, and eliminating sudden changes in stress distribution. This structural optimization based on topology and damage mechanics not only achieves an excellent match between the self weight and stress performance of the structure, but also provides reliable data support for safety reserves under extreme load conditions in the future.

At the same time, design optimization must be deeply embedded in real-time monitoring and feedback mechanisms during the construction period, achieving a transition from "static preset" to "dynamic adaptive" mode. By embedding high-sensitivity fiber optic sensors and intelligent strain gauges inside the structure, designers can obtain real-time real-time stress trace and deformation field data during the concrete hardening process, and integrate them into the digital twin management system. When the measured stress value approaches the design warning threshold, the optimization algorithm can quickly generate targeted construction parameter correction suggestions, such as adjusting the water cooling intensity or delaying the demoulding time. This closed-loop optimization path based on monitoring data feedback effectively eliminates the uncertain risks caused by environmental random disturbances and construction process deviations, providing dual guarantees for crack control of hydraulic structures in high-intensity areas or complex flow field environments, ensuring that the safety indicators in the design blueprint can be accurately transformed into quality assurance for physical engineering[5].

In addition, the deep optimization of durability design also needs to be based on precise control of the micro air entraining structure and long-term permeability degradation mechanism of concrete. In the optimization process, by quantitatively introducing high-performance air entraining agents and combining them with micro nano level crystal nucleus strengthening agents, a large number of uniformly distributed and disconnected micro bubbles can be formed in the concrete matrix, effectively alleviating the frequent freeze-thaw compression stress in high-altitude areas. The reshaping of this microstructure, by establishing a correlation model between the fractal characteristics of pore structure and macroscopic permeability, enables designers to scientifically predict the neutralization rate and chloride ion migration depth of the structure over several decades of service life. In response to the dual effects of physical abrasion and chemical erosion on hydraulic structures in variable water level zones, the optimized design significantly improves the bonding strength between the matrix and aggregates by adjusting the mineral composition of the interface transition zone, thereby enhancing the anti abrasion toughness of the surface layer of the structure[6]. This full-scale optimization thinking from micro component modification to macro degradation evolution not only compensates for the shortcomings of traditional design in long-term durability evaluation, but also significantly reduces the maintenance frequency and technical risks of the project throughout its entire life cycle through the construction of active defense mechanisms.

Exploring the evolution of fatigue damage under the coupling of multiple physical fields is a necessary step towards achieving a significant increase in structural toughness. In the design optimization path, it is necessary to focus on the high-frequency microseismic loads generated by high-speed pulsating water flow on energy dissipation structures, gate bottom plates, and other parts. By introducing an elastic-plastic fracture mechanics model, the initiation and propagation mechanism of microcracks under alternating stress can be quantitatively analyzed. The optimization plan should focus on regulating the dynamic characteristics of the structure, using damping energy dissipation materials or changing the stiffness distribution of components to avoid resonance frequency bands, thereby maintaining the mechanical integrity of the structure in complex dynamic environments. By deeply simulating the energy dissipation mechanism, designers can implement precise prestressing compensation strategies at key stress nodes, ensuring that the structure maintains a benign compressive stress state under dynamic loads. This kind of resilience design optimization based on dynamic response enables hydraulic structures to have stronger resistance to continuous damage and rapid recovery ability after failure when facing super standard flood impacts or sudden vibration loads, further strengthening the safety defense line of water conservancy hubs.

Furthermore, the refined optimization of structural design should also extend to complex structural connections and redundant protection under special operating conditions. Deformation joints, construction joints, and waterproofing systems in hydraulic engineering are often weak links in durability design, and their failure can lead to serious leakage and corrosion. The optimization design should adopt the idea of "combining rigidity and flexibility, and graded defense". By developing a new type of composite waterstop with high elastic modulus and combining with the anti-seepage pressure grouting reservation scheme inside the structural joints, a multiple closed anti-seepage network should be constructed. In the reinforcement scheme under stress, the traditional principle of uniform distribution should be abandoned, and non-uniform and refined reinforcement based on stress cloud maps should be adopted instead. The tension zone and stress concentration zone should be strengthened in a graded manner, and the thickness of the steel reinforcement protective layer should be appropriately increased to cope with extreme erosion environments. In addition, optimization strategies also need to consider the impact of global climate fluctuations, such as the accelerating effect of extreme high or cold temperatures on material aging rates. Environmental impact factors should be introduced during the design reference period to dynamically adjust the reliability indicators of the structure. This optimization of concrete structures based on the perspective of the entire life cycle not only significantly reduces the cost investment of later operation and maintenance, but also fundamentally strengthens the comprehensive ability of water conservancy projects to resist natural disasters, achieving a deep coupling between technical performance and engineering benefits.

5. Reinforcement and enhancement design of key hydraulic structures and optimization of overall structural stability

One of the most challenging tasks in modern hydraulic engineering is to optimize the reinforcement and enhancement design for completed water conservancy and hydropower projects, especially those that have entered the aging stage or exhibit hazardous characteristics due to external environmental changes. Reinforcement design is not a simple reinforcement, but a systematic engineering that involves the assessment of residual bearing capacity of the original structure, reconstruction of the stress at the interface between new and old concrete, and dynamic coupling of foundation response. In the optimization of dam reinforcement, the core objective is to enhance the overall coordinated deformation capacity and anti sliding stability of the dam body[7]. By introducing prestressed anchor cable reinforcement technology, the strong prestress generated by the anchoring system can be used to apply active horizontal and vertical constraints to the dam body, effectively reshaping the stress distribution gradient inside the dam, transforming the potential danger zone of tensile stress into a compressive stress state, and significantly enhancing the structural toughness of the dam body under super standard floods or strong earthquakes. During the optimization process, it is necessary to use a high-performance computing platform to conduct sensitivity analysis on the tension value, anchoring angle, and spatial layout of the anchor cable, in order to seek the maximum safety margin under the premise of minimal engineering disturbance.

Thoroughly exploring the bonding mechanism and stress co evolution of the reinforcement interface is the key to ensuring the long-term effectiveness of the reinforcement scheme. In optimization design, it is necessary to focus on addressing the risk of shear failure at the interface between new and old concrete due to poor shrinkage and mismatched elastic modulus. By introducing the interface shear slip model, the contribution rate of different interface treatment processes to the overall collaborative force of the structure is quantitatively analyzed, in order to determine the optimal chiseling depth and reinforcement density. The optimization path should shift towards regulating the micro mechanical properties of the interface transition zone, using high-performance interface agents to improve the chemical bonding force and physical mechanical interlocking force of new and old materials, ensuring smooth load transmission under high-pressure stress conditions.

At the same time, the optimization of reinforcement engineering schemes should shift from single technical indicators to multi-objective decision-making optimization. In optimizing the model, it is necessary to comprehensively weigh the enhancement rate of reinforcement strength, the loss of storage capacity during the construction period, and the convenience of long-term maintenance. A multidimensional evaluation matrix is constructed by introducing the fuzzy analytic hierarchy process. For the reinforcement requirements under special working conditions, the optimization design should focus on evaluating the economic performance of different schemes throughout the entire life cycle. It is not only important to pay attention to the initial material and construction investment, but also to use a probability risk assessment model to calculate the potential disaster losses that the reinforced structure can avoid due to the improvement of flood control efficiency. This decision optimization based on life cycle cost (LCC) can guide designers to select the most resilient combination of solutions from multiple enhancement technology paths. For example, in the anti abrasion reinforcement of flood discharge facilities, by comparing the long-term wear rate of high-strength alloy steel lining and flexible anti abrasion coating, the optimal balance between protective performance and replacement cost can be achieved, thereby maximizing the safety and economic benefits of water conservancy hub operation under limited resources.

In addition, for old hydraulic structures located in high-intensity earthquake zones, the deep optimization of reinforcement design also needs to focus on improving the nonlinear dynamic response of the structure and reconstructing the energy dissipation mechanism. Introducing damping enhancement logic in the reinforcement scheme, by adding energy absorbing supports or wrapping key load-bearing components with high-performance damping materials, can significantly adjust the natural frequency of the structure, thereby avoiding the energy concentration frequency band of seismic waves. Optimization design should be based on elastic-plastic dynamic time history analysis, identifying weak areas that may enter plastic state first under the action of large earthquakes, implementing precise strength reserve optimization, and ensuring that the structure has sufficient ductility support to prevent brittle collapse. This optimization path based on seismic performance objectives establishes a balance equation between structural damage energy dissipation and earthquake input energy, enabling the reinforced water conservancy hub to absorb energy through controlled local deformation when encountering extreme geological disturbances, maintaining the overall stability of the main structure, and greatly improving the seismic resilience and rapid post disaster recovery ability of water resources infrastructure under extreme emergencies[8].

Further exploration of intelligent diagnosis and adaptive repair of structural damage in a multimedia coupled environment is an important milestone in the transformation of reinforcement design towards intelligence. In the process of design optimization, a refined numerical field of water structure foundation interaction should be established to quantitatively reveal the nonlinear evolution law of hidden defects under long-term service conditions. The optimization plan should integrate new reinforcement materials with "self sensing" function, such as microcapsule self-healing concrete or alloy materials with shape memory effect, to achieve active healing during the micro crack initiation stage. By introducing a damage recognition algorithm based on convolutional neural networks, designers can quickly compare the vibration signals returned by sensors with typical defect characteristic spectra, thereby achieving precise positioning of critical areas before macroscopic reinforcement construction.

In the enhancement and optimization of discharge structures such as water gates, pump stations, and culverts, the focus of design should extend from the main structure to the deep bedrock anti-seepage and bearing optimization. Due to insufficient consideration of the distribution of foundation stress in the design of many old projects, coupled with the evolution of seepage field caused by long-term operation, the structural foundation is prone to void or uneven settlement. For such problems, the reinforcement optimization design should introduce a composite treatment mode of "underground continuous anti-seepage wall+deep high-pressure rotary grouting". By constructing a deep anti-seepage curtain at the bottom of the gate foundation, not only can the seepage flow be effectively controlled, but more importantly, it can significantly reduce the uplift pressure of the bottom plate and improve the anti floating and anti overturning safety of the structure under empty storage or high water level conditions. In the upper part of the structure, optimization measures should focus on local reinforcement of load-bearing components such as gate piers and side walls, and achieve a stepped increase in bearing capacity through external bonding of carbon fiber cloth or the addition of external steel frames.

6. Conclusion

In summary, the design and optimization of water conservancy and hydropower engineering structures is a comprehensive system engineering that covers mechanical modeling, material science, and construction technology. In modern engineering construction, it is necessary to adhere to the principle of balancing safety and durability, and systematically enhance the ability of engineering to resist complex environmental risks through fine control of concrete performance, structural reinforcement of key buildings, and the introduction of information management methods. The research in this article shows that scientific structural optimization can not only significantly reduce material loss and construction costs, but also ensure the long-term stability and efficient operation of water resource allocation systems through performance enhancement throughout the entire lifecycle.

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