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Research on Construction Period Estimation Method for Hydropower Projects During Rainy Season Based on Monte Carlo Model

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ABSTRACT

Aiming at the problem that traditional methods tend to have serious risks of underestimation or overestimation in the construction period prediction of hydropower projects during the rainy season, this paper intends to realize the scientific prediction of the construction period through the Monte Carlo model. Traditional methods rely on single-point estimation, making it difficult to handle random factors such as rainfall intensity and equipment failure, as well as the impact of risk superposition, which leads to deviations in construction period judgment. The research first sorts out key risk factors such as natural environment and construction resources, and assigns probability distributions to them based on historical data and expert judgment; then constructs a construction period calculation model that includes process dependencies and connection logic; conducts tens of thousands of random simulations using Python to generate a probability histogram and cumulative distribution curve of the construction period, which intuitively present the occurrence frequency and compliance probability of different construction periods. The results show that this method can effectively quantify uncertainties, accurately capture the impact of risk superposition, and provide construction period references for projects under multiple probability scenarios. Its application promotes the transformation of construction period management for hydropower projects during the rainy season from experience-based judgment to data-driven decision-making, improving the project's risk resistance and management scientificity.

KEYWORDS

Monte carlo model; Hydropower construction during rainy season; Construction period prediction; Risk quantification; Data-driven

1 Introduction

Under the national strategic background of the "dual carbon goals" (carbon peaking and carbon neutrality) and the construction of a new power system, hydropower, as a renewable energy source with mature technology, cleanliness, low carbon emissions, and strong regulatory capabilities, is one of the core pillars for ensuring energy security and optimizing the energy structure [1]. According to the 14th Five-Year Plan for the Modern Energy System, China needs to further promote the construction of large-scale hydropower bases. The installed capacity of hydropower is expected to reach 470 million kilowatts by 2025 and exceed 500 million kilowatts by 2030. The development scale and commissioning efficiency of hydropower projects are directly related to the implementation effect of the national energy strategy. However, hydropower projects are characterized by large investment scales, long construction cycles, and complex construction environments: on the one hand, most projects are located in deep mountain valleys and river basins, which are strongly restricted by natural and geographical conditions; on the other hand, the construction processes include dozens of key links such as diversion works, dam filling, underground powerhouse excavation, and generator set installation. The logical relationships between various processes are close and highly coupled. Delays in any link may trigger a series of chain reactions, leading to project cost overruns, delayed grid connection and power generation, and even affecting the stability of regional energy supply [2-4]. Therefore, accurate prediction of the construction period has become a core requirement for hydropower project management.

Currently, the construction period estimation of hydropower projects mainly adopts deterministic methods and traditional risk analysis methods. The Critical Path Method (CPM) uses a single time estimation approach, which has high requirements for time estimation and is difficult to adapt to complex and changeable project environments, and it also fails to consider resource constraints [5]. The Program Evaluation and Review Technique (PERT) takes the average longest path as the duration of key estimation tasks, ignoring the actual impact of other paths on the total construction period [6].

Therefore, focusing on the characteristics of hydropower projects during the rainy season, such as long construction periods, complex processes, and numerous uncertain factors, this study proposes to use Monte Carlo simulation for construction period estimation, breaking the limitations of previous methods by quantifying complex uncertainties.

2 Monte carlo simulation

Monte Carlo simulation, also known as the statistical simulation method or random sampling technique, is a numerical calculation method that solves complex uncertainty problems by "randomly generating input variables and observing the distribution of output results". Its core idea is to use randomness to simulate uncertainties in the real environment, and convert complex probability problems into computable statistical results through a large number of repeated experiments to help decision-makers quantify risks and predict result ranges.

3 Preparation for monte carlo simulation

3.1 Analysis of main risk factors of hydropower project construction during rainy season

The rainy season refers to the season with relatively concentrated precipitation in a year, usually accompanied by increased rainfall, enhanced precipitation intensity, and extended duration. For hydropower project construction, the impacts of the rainy season are mainly reflected in the following aspects:

Precipitation intensity and duration: Heavy precipitation affects the safety and efficiency of open-air operations, such as key processes like earth excavation and concrete pouring; at the same time, high-intensity rainfall may also lead to site waterlogging and excessive soil moisture content, affecting the operation of construction machinery; continuous rainfall may cause cumulative delays in the construction period.

Changes in river hydrological conditions: During the rainy season, river water levels rise and flow velocities accelerate, increasing the difficulty and risk of diversion, river closure, and cofferdam construction. In extreme cases, floods may occur, which may wash away temporary facilities, submerge construction sites, and even damage completed parts.

Deterioration of geological conditions: Precipitation may trigger geological disasters such as landslides, which interrupt the construction progress. Especially, hydropower projects in mountainous and valley areas are at a particularly high risk of such disasters.

Restricted construction conditions: During the rainy season, roads become muddy and transportation is inconvenient, which greatly affects material transportation and equipment transfer; high air humidity may also cause equipment failures and material deterioration; reduced visibility affects high-altitude operations and the operation of large-scale equipment.

3.2 Mechanism of rainy season risks on construction period

Different risk factors have different mechanisms of impact on the construction period of hydropower projects, which can be mainly manifested in the following four ways:

Direct delay: Some risk factors directly prevent construction activities from being carried out or reduce their efficiency.

Chain reaction: The occurrence of one risk factor triggers a series of subsequent problems.

Resource conflict: Rainy season construction leads to concentrated demand for resources such as drainage equipment and rainproof materials, which may cause shortages of such resources and result in delays in some tasks.

Safety hazards: To ensure construction safety, construction speed may be reduced or additional safety measures may be added during the rainy season, thereby extending the construction period.

4 Construction and simulation of monte carlo model

4.1 Decomposition of hydropower project construction system and construction of process network

The first step of Monte Carlo simulation is to decompose the hydropower project construction system and construct a process network model. This process mainly includes the establishment of a Work Breakdown Structure (WBS), the determination of logical relationships between construction processes, the formulation of a baseline schedule, and the verification of the process network model. The specific decomposition is shown in Table 1.

4.2 Probability distribution model and correlation analysis of rainy season risk factors

Establishing a reasonable probability distribution model for various risk factors affecting the construction period is a key step in estimating the construction period of hydropower projects during the rainy season. Through risk factor identification and classification, as well as historical data collection and analysis, appropriate probability distribution types are selected for the risk factors. For the key risk factors in hydropower projects during the rainy season, the probability distributions selected in this study are shown in Table 2.

At the same time, there are often complex correlations between various risk factors. For example, there is a positive correlation between rainfall and flood occurrence probability, and the number of consecutive rainy days is also correlated with geological hazard risk. Accurately describing these correlations is crucial for improving the accuracy of construction period estimation. The correlation analysis results for the key risk factors in hydropower projects during the rainy season are shown in Table 3.

Table 1 Decomposition table of main work packages and key processes of hydropower station main project

tool bag	Main construction procedures	Lead-in process	Base period (days)	Impact of rainy season
diversion works	Cofferdam filling	-	60	tall
	Excavation of diversion tunnel	-	120	centre
foundation treatment	excavation of foundation pit	The cofferdam was completed	45	tall
	Basic seepage protection	The foundation pit was excavated	30	centre
concrete work	Dam concrete pouring	The basic seepage prevention was completed	365	centre
	Plant concrete pouring	Base processing completed	240	centre
metal structure installation	Gate installation	Relevant concrete structures completed	60	low
Electrical and mechanical installation	Hydroelectric generator installation	Plant concrete completed	120	low

Table 2 Probability distributions of key risk factors for hydropower projects during rainy season

risk factor	Recommended distribution type	Parameter determination method	Example parameters
daily rainfall	log-normal distribution	Based on historical rainfall data fitting	μ=3.5, σ=1.2
Number of consecutive rainy days	Geometric distribution or negative binomial distribution	Statistical analysis of historical data	p=0.3
Extreme Rainfall Event	General Extreme Value distribution (GEV)	Extreme value theory estimates	μ=50, σ=10, ξ=0.1
Frequency of floods	Poisson distribution	Historical flood records statistics	λ=0.5 times/year
Geological hazard risk	Beta binomial distribution	Expert evaluation combined with historical data	α=2, β=8
Construction efficiency reduced	triangular distribution	expert judgement	a=0.6, m=0.8, b=1.0

Table 3 Correlation analysis of key risk factors for hydropower projects during rainy season

Risk factors for	Type of correlation coefficient	Correlation coefficient values	Relevance explanations
Daily rainfall and number of consecutive rainfall days	Spearman rank correlation	0.65	Strong positive correlation
Rainfall and flood probability	Pearson correlation	0.72	Strong positive correlation
Number of consecutive rainy days and risk of geological hazards	Spearman rank correlation	0.58	Moderate positive correlation
Floods and geological hazards	Kendall Tau coefficient	0.43	Moderate positive correlation
Construction efficiency and rainfall	Pearson correlation	-0.68	Strongly negatively correlated

When there are nonlinear or non-normal correlations between risk factors, traditional correlation coefficients are insufficient to describe their dependence structure. We will use the Copula function to establish a multivariate joint distribution.

$$F(x_1,x_2,\cdots,x_n)=C(F_1(x_1),F_2(x_2),\cdots,F_n(x_n)) \tag{1}$$

Where, F is the joint distribution function, F_1, F_2, ..., F_n are the marginal distribution functions of each variable, and represents the Copula function.

For the risk factors in hydropower projects during the rainy season, a two-step method is adopted: first, estimate the parameters of each marginal distribution, and then use maximum likelihood estimation or non-parametric methods to estimate the Copula function. In this way, an appropriate function is selected from the commonly used Copula functions [7]. Through the above process, a joint distribution model of multiple risk factors can be constructed, which can more accurately describe the complex correlations between risk factors and provide more reliable input for subsequent Monte Carlo simulations.

4.3 Quantification of process construction period uncertainty

In Monte Carlo simulation, it is also necessary to convert the uncertainty of risk factors into the uncertainty of the construction period of construction processes. This study will use the three-point estimation method to achieve this goal.

$$\text{Expected value: } t_e=(a+4m+b)/6 \tag{2}$$

$$\text{Variance: } \sigma^2=[(b-a)/6]^2 \tag{3}$$

Where, a is the most optimistic construction period, m is the most likely construction period, and b is the most pessimistic construction period [8].

4.4 Construction of construction period estimation model based on monte carlo simulation

Based on the aforementioned steps, the Monte Carlo model for estimating the construction period of hydropower projects during the rainy season can be constructed. The composition of the core part of the specific model is shown in Figure 1. The specific implementation process of the simulation is shown in Figure 2.

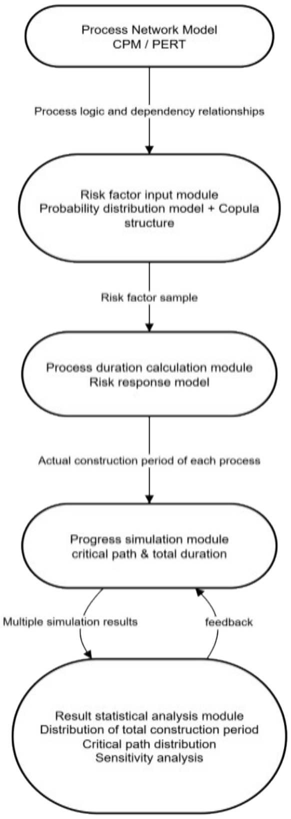

Figure 1 Composition of the core part of the model

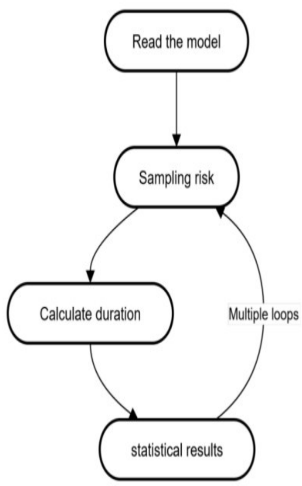

Figure 2 Specific implementation process

4.4.1 Determination of simulation times

According to the project scale and accuracy requirements, the appropriate number of simulations is determined. The minimum required number of simulations can be determined by calculating the relationship between estimation error and the number of simulations:

$$\varepsilon = Z \times \sigma / \sqrt{N} \tag{4}$$

(Where, ε is the estimation error, Z is the Z-value corresponding to the confidence level, σ is the population standard deviation, and N is the number of simulations)

For hydropower projects, at least 5,000 simulations are required to ensure the stability and reliability of the results.

4.4.2 Random number generation and setting of risk factor correlation parameters

To ensure the reproducibility of simulation results, the initial seed value should be recorded. Pseudorandom number generation algorithms such as Mersenne Twister can be used in computer software. At the same time, based on the previous analysis results, the correlation coefficients and Copula parameters of each risk factor are set to ensure that the generated risk factor samples have a reasonable correlation structure.

4.4.3 Implementation of monte carlo simulation

Monte Carlo simulation can be implemented using libraries such as NumPy and SciPy in Python. Through n independent simulations, samples of the total project construction period are generated.

The calculation formula for the total construction period is:

$$T_i^{actual} = \sum_{j \in \text{rainy season}} \frac{\Delta t}{\alpha_j} + T_i^{non-rain} \quad (5)$$

Where, Δt is the daily planned workload, $T_i^{non-rain}$ is the construction period in the non-rainy season. If a flood occurs, $\triangle t_{flood}$ (additional days due to flood) is added.

Finally, through statistical analysis of a large number of simulation results, the probability distribution of the total project construction period and other useful information are obtained, as shown in Figure 3.

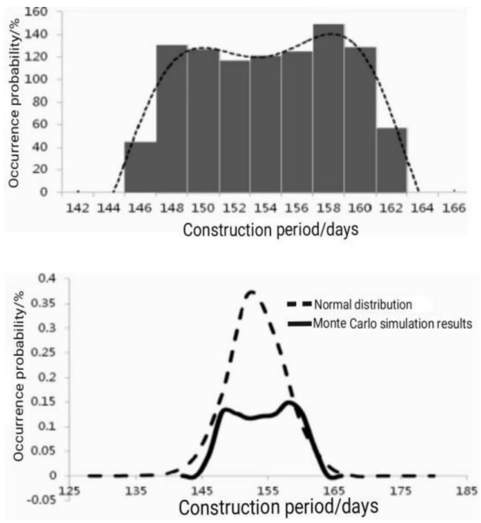

Figure 3 Construction period estimation diagram obtained from monte carlo simulation output

5 Conclusion

This study concludes that Monte Carlo simulation is an effective method for estimating the construction period of hydropower projects during the rainy season. By identifying and quantifying uncertain risk factors, the accuracy of construction period estimation is improved. At the same time, Monte Carlo simulation not only provides a single construction period estimation value but also gives the probability distribution of the construction period, providing more comprehensive information for project decision-making.

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