Hindawi
Geofluids
Volume 2023, Article ID 6447565, 12 pages
https://doi.org/10.1155/2023/6447565

Research Article

Multiobjective Optimization Method for the Diversion Scheme of Lean Concrete Overtopped Cofferdam under Multiconstraint Conditions

Zhengyu Dong and Kebin Shi

College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, China

Correspondence should be addressed to Kebin Shi; xndsg@sina.com

Received 22 June 2022; Revised 5 August 2022; Accepted 16 August 2022; Published 7 February 2023

Academic Editor: Hao Wu

In this paper, a multiobjective optimization method considering both time limit and cost of lean cemented overtopped cofferdam diversion scheme as objectives is proposed. In the multiobjective optimization method, the main constraint condition is the reliability of the construction period, which also considers the design specification, dam site rainfall, construction capacity, and other constraint conditions. Pareto solutions with the diameter of the diversion tunnel and the height of cofferdam as parameters are obtained using perturbation weight method. Finally, the optimal scheme was obtained according to the importance of the critical node project period and its free time difference. The case study showed that the cost is low, the construction period is reasonable, and the results are consistent with the expert decision system in this model. The Monte Carlo method was used to simulate the construction of lean cemented cofferdam. The study shows that the construction speed of lean cemented cofferdam is slow under frequent rainfall condition. The lower limit of construction speed of key projects greatly affects the scheme. Increasing construction equipment redundancy is an important way to increase construction speed. The free float time difference of cofferdam construction is the key point of scheme decision.

1. Introduction

Water diversion is one of the most important parts of designing and constructing a water conservancy project. Local condition is an important factor that must be considered in formulating diversion schemes. Various diversion schemes that adapt to local conditions often generate better economic outcome. According to whether the foundation ditch is flooded, the diversion schemes are classified into submerged foundation ditch diversion and nonsubmerged foundation ditch diversion. In rivers with relatively high floods and drought rate, when constructing water conservancy projects, the submerged foundation ditch diversion scheme can often bring significant benefits to the projects without prolonging the construction period [1].

Due to its overtopped characteristic, the construction period risk of the key schedule control plan of the submerged foundation ditch diversion process needs to be strictly monitored. Generally, the risk assessment of diversion scheme is to estimate the risk, construction period, and cost separately. Hu et al. [2] used the Monte Carlo method to simulate the flood and discharge process during construction and determined the dynamic risk of the cofferdam operation through statistical analysis model; Nasir et al. [3] studied and analyzed the construction schedule and proposed a construction schedule risk calculation model; Fan et al. [4] used the Monte Carlo method to establish a comprehensive risk analysis model, which considered the hydrology and hydraulic uncertainty and the uncertainty of construction progress and which was then used to analyze the risk of construction diversion system on the embankment under the condition that the construction progress is determined. Luo [5] studied the multidimensional joint risk of construction diversion systems and established an evaluation model that can reasonably reflect the diversion risk, construction schedule risk, cost risk, and interactive influence among the three. Marengo et al. and Marengo [6, 7] conducted risk analysis on practical diversion cases and found that reducing the roughness of the diversion tunnel can greatly improve the reliability of the diversion system. Therefore, for submerged foundation pit diversion, in addition to cost and construction period, construction period risk is an important objective function for diversion system.

The submerged foundation ditch diversion process mostly relies on the temporary overtopped cofferdam, which are further classified into earth-rock overtopped cofferdams and non-earth-rock overtopped cofferdams. Non-earth-rock overtopped cofferdams are considered to have high reliability and small footprint. Lean cemented cofferdam is a kind of non-earth-rock cofferdam.

In 1970, Professor J.M. Raphael proposed the optimal gravity dam theory. The basic section of the optimal gravity dam is symmetric trapezoid, and the temperature control requirement is reduced by reducing the cementing material. The optimal gravity dam has the advantages of shorter construction period, lower cost, and lower foundation requirements than earth-rock dam and has better reliability than earth-rock dam. Lean cemented dam is also called cemented sand and gravel dam. Cemented sand and gravel dam construction technology is recognized by engineers all over the world and known as the safest dam [8]. In recent years, with the development of embankment materials such as lean cemented dregs and gravel (cemented granular material), the research into its performance [9], economics [10], environmental protection [11, 12], and application [13, 14] has gradually increasing. In China, lean cemented dam construction technology is often used to build overtopped cofferdams. Currently, a number of lean cemented dregs and gravel roller compacted concrete cofferdams have been built in China, such as the main upstream cofferdam of the Hongkou Hydropower Station in Ningde, Fujian, the downstream cofferdam of the Youxijie Hydropower Station in Fujian, and the upstream cofferdam of the Gongguoqiao Hydropower Station in Dali, Yunnan [15–18]. Furthermore, specifications such as “Guidelines for the Construction of RCC in Lean Cemented Dregs and Gravel” (DL/T 5264-2011) and “Technical Guidelines for Cemented Granular Material dams” (SL 678-2014) have also been published successively. The application of lean cemented dregs and gravel (cemented granular material) has gradually entered into the field of water conservancy engineering [19, 20]. The research direction of gelled sand and gravel dam construction technology mainly focuses on material properties [21], structural characteristics [22], and section design. Cemented sand and gravel dam construction technology has the advantages like short construction period, low cost, better reliability, and lower foundation requirements.

The research on lean cemented cofferdam and diversion tunnel as diversion system is relatively less. Based on the Monte Carlo method and the Lagrange interpolation method, this paper establishes a multiobjective model of the diversion scheme considering the construction period, construction cost, and construction period risk as objectives. Based on the deterministic logical relationship among construction period, construction speed, effective construction time, and rainfall probability, the Monte Carlo method was used to simulate the reliability of various diversion schemes, that is, the combination of different diversion tunnel diameters and cofferdam heights and their possibility to be completed on time. By constructing a multiobjective optimization model, considering the specification, construction environment, and the ability of the construction party, an optimization study was carried out on the diversion scheme constructed using the lean cemented dregs and gravel concrete overtopped cofferdam tunnel in the construction of a certain high roller compacted concrete dam. Through this study, it is helpful for the researcher to understand the duration risk of diversion scheme and offer a reference in diversion scheme design.

2. Multiobjective Optimization Model

2.1. Method. The height of the cofferdam and the diameter of diversion tunnel in designing the diversion scheme are considered to be two of the most important technical parameters. In order to construct a model which can best reflect the relationship between the two and the construction period risk, this study adopts a multiobjective optimization model under construction period risk as a constraint condition. According to the functional relationship between the height of the cofferdam and the diameter of the diversion tunnel, a multiobjective mathematical model is established, taking into account the design specifications, dam site rainfall, construction capacity, project cost, and other constraints simultaneously under restrictive conditions. Eventually, according to the functional relationship between the height of the cofferdam and the diameter of the diversion tunnel, the Pareto solutions between the height of the cofferdam and the diameter of the diversion tunnel are obtained.

2.2. Construction of the Model. In order to optimize the diversion scheme, two optimization objectives are selected, namely, the cost objective and the duration objective, and their objective functions are established, respectively.

The diversion tunnel is a circular tunnel (Figure 1), the tunnel diameter is D (m), the tunnel lining thickness is δ (m), the tunnel excavation section area is S_{dw} (m^2), and the tunnel concrete lining section area is S_{dc} (m^2).

$$S_{dw} = \pi \left(\frac{D}{2} + \delta \right)^2, \quad (1)$$

$$S_{dc} = \pi \left(\delta^2 + D\delta \right). \quad (2)$$

The overtopped cofferdam is based on the main upstream cofferdam of Hongkou Hydropower Station (Figure 2), the height of the typical section of the cofferdam is h (m), and the width of the typical section of the cofferdam is b (m). The width of the weir crest is (m), the upstream slope of the cofferdam is $1 : m_1$, the downstream slope of the cofferdam is $1 : m_2$, the slope of the right bank is α_1 (degrees), the slope of the left bank slope is α_2 (degrees), the riverbed width is t (m), the volume of cofferdam is V_y (m^3), the average thickness of soil excavation in the cofferdam foundation

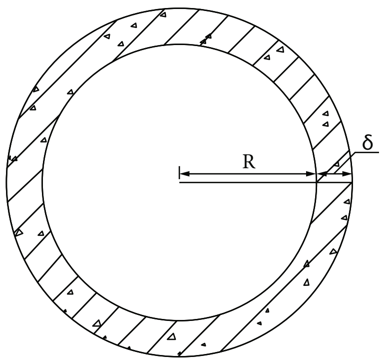

Figure 1: Schematic diagram of the cross section of the diversion tunnel.

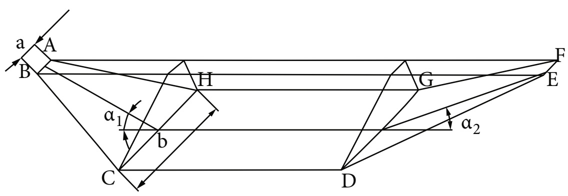

Figure 2: Three-dimensional view of the lean cemented cofferdam.

is h_{yw} (m), and the volume of soil excavation in the cofferdam foundation is V_{yw} (m^3); the cofferdam volume calculation diagram is shown in Figure 2.

$$b = a + h(m_1 + m_2), \tag{3}$$

$$\begin{aligned} V_y = {} & \frac{h}{2}(a+b)\left(t + h\frac{\tan\alpha_1 + \tan\alpha_2}{\tan\alpha_1 \tan\alpha_2}\right) \\ & - bh^2\frac{\tan\alpha_1 + \tan\alpha_2}{2\tan\alpha_1\tan\alpha_2} + \frac{1}{3}h^3\frac{m_2}{\tan\alpha_1} + \frac{1}{3}h^3\frac{m_1}{\tan\alpha_1} \\ & + \frac{1}{3}h^3\frac{m_2}{\tan\alpha_2} + \frac{1}{3}h^3\frac{m_1}{\tan\alpha_2}, \end{aligned} \tag{4}$$

$$V_{yw} = h_{yw}t(a + h(m_1 + m_2)). \tag{5}$$

The soil excavation cost of the lean cemented cofferdam foundation is C_{yw} (¥), and the unit price is c_{yw} (¥/m^3); the cofferdam construction cost is C_y (¥), and the unit price is c_y (¥/m^3); the tunnel excavation cost is C_{dw} (¥), and the unit price is c_{dw} (¥/m^3); the cost of tunnel lining is C_{dc} (¥), and the unit price is c_{dc} (¥/m^3); the length of the tunnel is L (m). The corresponding lining thickness of the tunnel is also different; then,

$$C_{yw} = V_{yw} \cdot c_{yw}, \tag{6}$$

$$C_y = V_y \cdot c_y, \tag{7}$$

$$C_{dw} = c_{dw} \times \sum_{i=1}^{n} \pi\left(\frac{D}{2} + \delta_i\right)^2 \times L_i, \tag{8}$$

$$C_{dc} = c_{dc} \times \sum_{i=1}^{n} \pi\left(\delta_i^2 + D\delta_i\right) \times L_i, \tag{9}$$

$$G_{yw} = \frac{V_{yw}}{g_{yw}}, \tag{10}$$

$$G_y = \frac{V_y}{g_y}, \tag{11}$$

$$G_{dw} = \frac{\sum_{i=1}^{n} L_i}{g_{idw}}, \tag{12}$$

$$G_{dc} = \frac{\sum_{i=1}^{n} L_i}{g_{idc}}, \tag{13}$$

$$C = C_{yw} + C_y + C_{dw} + C_{dc}, \tag{14}$$

$$G = G_{yw} + G_y + G_{dw} + G_{dc}. \tag{15}$$

3. Restrictive Conditions

3.1. Stress Limit Condition of the Lean Cemented Cofferdam. Due to the needed requirements of water passing, the amount of cementation material needed in lean cemented cofferdam is large. Hongkou cofferdam is the lean cemented cofferdam with the smallest amount of cementation material in China. Its cementing material content is 70 kg/m^3. When the cementing material content is within 70 kg/m^3, the design theory of lean cemented cofferdam mainly follows that of gravity dams [23]. According to the “Design specification for concrete gravity dams” (NB/T35026-2014) and references drawn from similar projects using lean cemented concrete, restriction was made that the vertical normal stress on the upstream and downstream surfaces is allowed to be no more than 0.75 MPa, and there is no negative value of the vertical normal stress in both the upstream and the downstream of cofferdam [24]. Assuming that the most dangerous section is the typical section of the cofferdam, that is, the main riverbed section, the upstream metamorphic concrete has a good antiseepage effect, there is no uplift pressure on the section, and the cofferdam has a short service life without sediment accumulation and sediment pressure. The quadrilateral centroid calculation formula was used to calculate the coordinates of the centroid point of the cofferdam section; then,

$$y_c = \frac{bh + 2ah}{3(b+a)}, \tag{16}$$

$$x_c = \frac{2ab + 2b^2 - a^2 - 2ahm_1 - bhm_1}{3(b+a)}, \tag{17}$$

$$\sum W = \frac{1}{2}h^2 m_1 \gamma_w + \frac{1}{2}h(a+b)\gamma_c, \tag{18}$$

$$\sum M = \frac{1}{2}h^2\gamma_w\left(y_c - \frac{1}{3}h\right) + \frac{1}{2}h^2 m_1\gamma_w\left(b - \frac{1}{3}m_1 h - x_c\right), \tag{19}$$

$$\sigma_y^u = \frac{\sum W}{T} + \frac{6\sum M}{T^2} < 0.75\,\text{Mpa}, \quad (20)$$

$$\sigma_y^d = \frac{\sum W}{T} - \frac{6\sum M}{T^2} < 0.75\,\text{Mpa}, \quad (21)$$

where a is the width of weir crest of the upstream cofferdam (m); b is the width of weir base of the upstream cofferdam (m); m_1 is the slope of the upstream face of the cofferdam $1:m_1$; m_2 is the slope of the backwater surface of the upstream cofferdam $1:m_2$; y_c is the y-axis coordinate of the centroid of the section for the cofferdam (m); x_c is the x-axis coordinate of the centroid of the section for the cofferdam (m); $\sum W$ is the sum of all vertical forces on the section, with downward as positive (kN); $\sum M$ is the sum of the moment of inertia created by the vertical and the horizontal force on the calculated section centroid; the counterclockwise direction is positive (kN·m); γ_w is the bulk density of water, generally using 9.8 kN/m^3; T is the length of the calculated section along the upstream and downstream (m); σ_y^u is the vertical normal stress on the upstream surface (MPa); and σ_y^d is the vertical normal stress on the downstream surface (MPa).

3.2. Restrictions on the Relationship between Tunnel Radius and Cofferdam Height. Under the same flood control standard and water retention time condition, it is assumed that the bottom elevation of the inlet of the diversion tunnel is the bottom elevation of the riverbed H_1. The corresponding cofferdam crest elevation Z_y (m) is calculated using flood regulation calculation. Select four tunnel diameters D and the weir crest elevation of corresponding cofferdam Zy into the Lagrange interpolation formula to obtain the $f(D)$ function. Adjust the bottom elevation of diversion tunnel entrance H_1 (m) according to the river topography and sedimentary at dam site, and H_d (m) is the elevation of the bottom of the diversion tunnel inlet. After considering H_d, the cofferdam weir crest elevation function $Z_y(D, H_d)$ was obtained and is shown in formula (22). The difference between the crest elevation and the bottom elevation of the riverbed is the cofferdam height h (m), and the close correlation restriction among the cofferdam height h, the diversion tunnel diameter D, and the elevation at the inlet bottom of the diversion tunnel H_d is shown in formula (23).

$$Z_y(D, H_d) = f(D) + H_d = \sum_{j=0}^{4} \left(\prod_{\substack{i=0 \\ i \neq j}}^{4} \frac{(D - D_i)}{(D_j - D_i)} \right) \cdot Zy_j + H_d, \quad (22)$$

$$h = Z_y(D, H_d) - Z_d = f(D) + H_d - Z_d. \quad (23)$$

3.3. Stress Limit Condition of the Lean Cemented Cofferdam. The diversion tunnel is generally constructed using drilling and blasting method. Due to the limitations in construction technology, the diameter of the circular tunnel section should not be less than 2 meters [24]. On the other hand, the number and diameter range of diversion tunnels need to be set according to the surrounding rock grade and the flood flow during the construction period. The elevation of the inlet floor of the diversion tunnel needs to be determined according to the river sedimentary content, river topography, and geology.

4. Model Calculation

There are two types of calculation methods for multiobjective models: direct method and indirect method. For multiobjective multivariable problems, indirect methods are generally used. The indirect method can be further classified as the following three types: the first one converts multiobjective problems into single-objective problems for calculation; the second is to convert multiobjective problems into multiple single-objective problems; the for the last one, each target value of the multiobjective has already been determined, and it is required to approach the target value under restrictive conditions.

Due to the complexity of water conservancy projects, this paper adopts the first method, which is using weighting method to transform multiobjective into single-objective problem.

$$\min F = \min \{\omega_1 C + \omega_2 G\}. \quad (24)$$

The perturbation weight values ω_1 and ω_2 vary within a certain range. The practical application should be according to the project condition, the importance of the two objectives is compared, and the variation range is estimated. According to the characteristics of the overtopped cofferdam of the water conservancy project, if the delay of the construction diversion schedule has no or little impact on the overall progress of the project, the selected weight range is (1 : 1), (1 : 2), (1 : 3)…(1 : n); if the construction diversion progress is on the key route of the entire project progress, the selected weight range is (1 : 1), (2 : 1), (3 : 1)…(n : 1). After selecting the weight variation range, convert the ratio into the standard ratio, which meets the conditions, namely, (0.25 : 0.75), (0.33 : 0.67), (0.5 : 0.5), (0.67 : 0.33), and (0.75 : 0.25), by constantly changing the weights, to find the noninferior solution set.

5. Reliability of the Cofferdam Completed on Schedule

Whether the overtopped cofferdam can be completed on schedule plays a key role in its immediate predecessor—construction of the permanent structure and water passing of the foundation ditch. The construction time of the overtopped cofferdam is usually limited to a draught season, when the cofferdam filled to a certain height will ensure the construction conditions and construction period of the permanent building. Therefore, the paving of the overtopped cofferdam structure is determined as a critical objective.

The construction period of the cofferdam structure is strictly limited, and the cofferdam paving must be completed within the construction window period.

If the construction time of the cofferdam is longer than the effective construction time, the cofferdam is deemed to be completed on time. The construction period of the cofferdam is mainly determined by the work load and construction speed, where the effective construction time is determined by the construction window period and the external environment conditions. In order to integrate the reliability of the cofferdam on schedule into the multiobjective optimization model, the reliability is used as the restrictive condition in the multiobjective model, and the free float difference is arranged as the final decision condition.

5.1. The Distribution Probability of Cofferdam Construction Speed. The construction of the lean cemented cofferdam is mainly divided into two steps: the soil excavation of the cofferdam foundation and the laying of the lean concrete.

Cofferdam foundation excavation has dry ground construction conditions, mainly affected by the number of machinery. Since the aggregate of the lean concrete is mainly from the sand and gravel excavated from the riverbed, the appropriate stacking location is of great significance to reduce the unit cost of the lean concrete.

The preparation process of lean concrete is quite different from that of normal concrete. Lean concrete does not need to use complete set of fixed equipment such as sand and gravel processing systems, mixing units, and mixing plants; moreover, its unit price does not increase significantly with the production speed. The mixing of normal concrete completely relies on fixed equipment such as mixing units and mixing plants, such as HL360 mixing plants, whose available peak pouring strengths is up to $300m^3/h$, $4000m^3/d$, $90000m^3$/month, and $810000m^3/a$, and HL240 mixing plants, whose available peak pouring strength is $200m^3/h$, $3000m^3/d$, $75000m^3$/month, and $675000m^3/a$, and increasing the peak pouring strength of normal concrete can only be achieved by expanding the scale of fixed equipment and supporting facilities. The lean concrete is made of riverbed sand, gravel, and waste slag with small amount of cementitious material added. After mixing by the backhoe excavator, the lean concrete is put into the warehouse and rolled to complete the paving.

Because the lean cemented overtopped cofferdam is not only used to retain water but also allows certain overtopped capacity, the height of the overtopped cofferdam constructed using lean concrete with low strength is generally lower than 50 m. When constructing low cofferdam, the quickest and most reasonable way to fill the site is to directly use a dump truck.

After solving the problems of the transportation distance and the synchronous rise of the upper dam road with the dam body, the dump truck directly enters the warehouse to reduce the intermediate links and reduce the possibility of concrete loss or concrete heating. Due to the low elevation of the cofferdam, the concrete transportation speed can reach $100\,m^3/h$ even without setting up the circulating lane, and the concrete transportation capacity of the circulating lane will be greatly improved if it was a circulating lane. In conclusion, the concrete transportation speed of the lean cemented cofferdam is basically unrestricted.

In the case of unrestricted concrete transportation capacity, the configuration of paving machinery is one of the main factors limiting the pouring strength. The paving machinery is usually designed to work two shifts, maintaining 14 hours a day, and then verified with three shifts over 21 hours a day. Equipped with enough and complete sets of leveling and rolling machines, a continuous thin-layer rolling and paving operation cycle can be established.

The paving speed of lean concrete is affected by factors such as the lift of lean roller compacted concrete, the lift interval time, and the mechanical failure rate. The soil excavation of the cofferdam foundation is affected by factors such as mechanical failure rate, geology, transportation distance, etc. The paving speed of lean concrete and the excavation speed of cofferdam foundation are assumed to be random variables obeying the triangular probability distribution TRLA (a, m, b) [25] (where a is the most optimistic value, m is the most probable value, and b is the most pessimistic value).

5.2. Restrictions on the Reliability of the Lean Cemented Cofferdam Completion. The construction of lean cemented cofferdam is known to have characteristics like needing a large concrete surface, heavy workload, and tight construction schedule. Among the external influencing factors, rainfall is particularly disturbing to the construction of lean concrete. At present, there is no clear design specification for the layer and joint surface treatment of the lean cemented cofferdam. It is relatively safe to carry out the construction design according to the roller compacted concrete. According to the roller compacted concrete construction specification, when the rainfall is greater than 5 mm/h, that is, light rain, the roller compacted concrete construction should be suspended. In order to understand the impact of rainfall events on roller compacted concrete construction, it is necessary to analyze the roller compacted concrete construction process. The roller compacted concrete construction process is shown in Figure 3. When a rainfall event with a precipitation greater than 5 mm/h occurs during the roller compacted concrete construction, it is necessary to take rainproof and drainage measures before the rainfall. Once the initial setting time of the concrete is exceeded, it needs to be paved or treated as construction joints. Generally, the initial setting time of concrete is 12 to 24 hours, and the minimum time unit of visible rainfall events is 24 hours.

Rainfall events usually include characteristic attributes such as rainfall intensity, total rainfall, and rainfall duration. However, in practical applications, people only establish monthly average rainfall, monthly average rainfall days, monthly rainfall duration, and other indicators due to lack of rainfall data and convenience. During roller compacted concrete construction, engineers would want to know the actual hours that can be used for roller compacted concrete

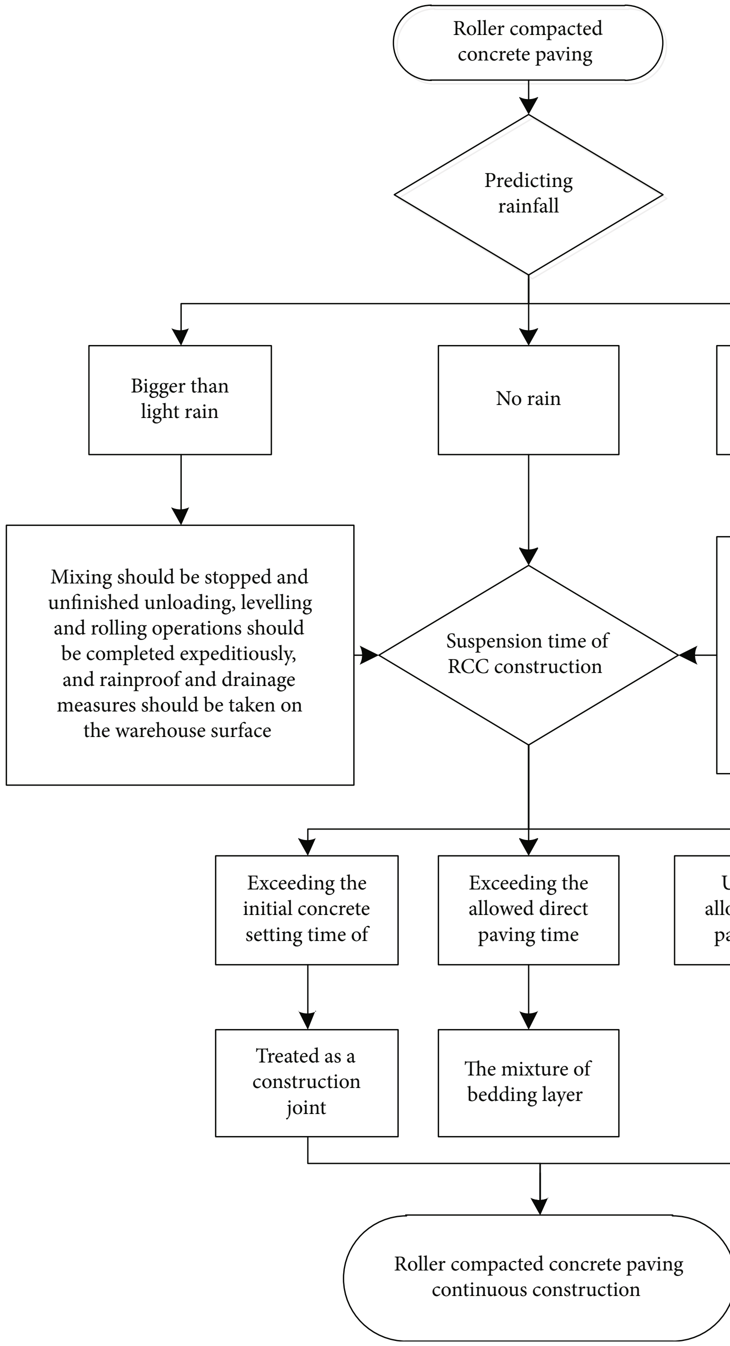

Figure 3: Flow chart of roller compacted concrete laying.

construction during the construction period, which is difficult to describe with only above indicators. In the uncertainty analysis of lean concrete construction period, expressing rainfall events by probability distribution can better reflect the uncertainty of the external environment of lean concrete construction.

The difference between the construction window period $[G]$ (d) minus the time when rainfall occurs G_y (d) can be considered as the effective construction time G' (d), as shown in formula (25). If the effective construction time G' (d) is greater than the actual construction time G, the lean cemented cofferdam can be completed as planned; otherwise, it cannot be completed as planned.

$$G' = [G] - G_y. \tag{25}$$

The complementary cumulative probability distribution function of the effective construction time $F(G')$ can be

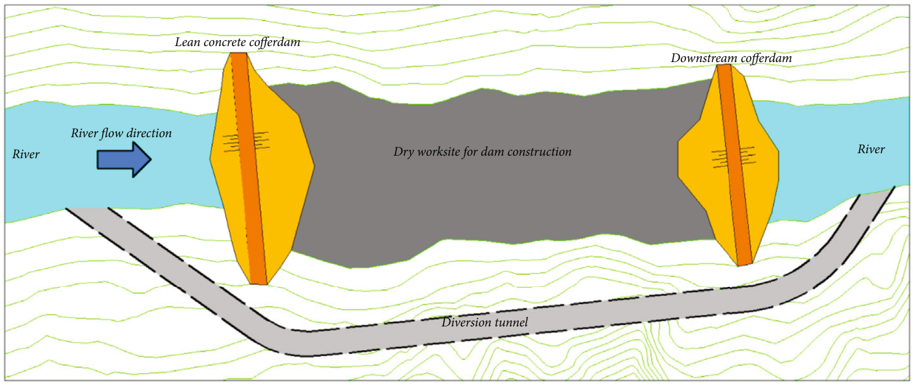

Figure 4: The plane layout of the dam construction diversion.

calculated according to the probability distribution function of the rainfall event $F_y(G_y)$, as shown in

$$F_y\left(G_y\right) = P_y\left\{X \le G_y\right\} = \int_0^{G_y} f_X(t)dt, \quad (26)$$

$$F\left(G'\right) = P\left\{X > G'\right\} = 1 - F_y\left(G_y\right). \quad (27)$$

Comparing the effective construction time with the actual construction time, the reliability of the on-time completion of the lean cemented cofferdam can be obtained, as shown in formula (28). The project completion reliability should meet the design requirements, as shown in formula (29).

$$R = p_f = p\left[G' > G\right] = 1 - \int_0^{G_y} f_X(t)dt, \quad (28)$$

$$R \ge [R]. \quad (29)$$

6. Case Study and Discussion

6.1. Project Overview. Azad Pattan Hydropower Station is an unstarted project in Pakistan. The diversion layout of preliminary design is shown in Figure 4. The AP water conservancy project is designed to be built in a "U"-shaped canyon. The dam site is a hilly area terrain, where the terrain of the riverbed is relatively gentle, with a width of 50~80 m and a slope that less than 0.5%. The slopes on the right bank of the riverbed are relatively steep, the gradient of the slope is between 70° and 80°, with an elevation between 460 and 800 m, therefore making it difficult for the layout of the construction site. The slope of the left bank of the riverbed is relatively gentle; the gradient is between 30° and 40°. The slopes are mostly covered with thick layers of loose material, with an elevation between 460 and 600 m.

There is a big fluctuation in flood peak flow between the dry season and the flood season at the dam site. The peak flow in the dry season, which occurs once in ten years, is 1616 m^3/s, and the peak flow in the flood season is 6650 m^3/s, and the flood-to-drain ratio reaches 4.12; therefore, the construction diversion scheme is an overtopped cofferdam. The main project barrage adopts the curved roller compacted concrete gravity dam, the maximum dam height is 108 m, and it is a level 2 building. According to the diversion standard in "Specifications for construction planning of water resource and hydropower projects" (SL 303-2017), the level of the cofferdam is 4. The lean cemented overtopped cofferdam scheme is adopted, the width of the weir crest is 5 m, the upstream slope is 1 : 0.3, and the downstream slope is 1 : 1.0 [26].

Table 1: Construction capacity parameter.

Item	Excavation speed of lean cemented cofferdam foundation (m^3/d)	Pouring speed of lean cemented cofferdam (m^3/d)
Maximum	2500	1100
Average	2000	1400
Minimum	1500	1700

According to the feasibility study report of the project and the construction experience of similar projects, it is concluded that the excavation cost c_{yw} of the foundation of the lean cemented cofferdam is 13.44 (¥/m^3) and the unit cost c_y of the lean cemented cofferdam is 66.33 (¥/m^3), the unit excavation cost c_{dw} of the diversion tunnel is 183.26 (¥/m^3), and the unit lining cost of the diversion tunnel is 2482.42 (¥/m^3), where g_{pw} is the excavation rate of earth for lean cement concrete cofferdam foundation and g_p is the pouring speed of lean rubber concrete cofferdam. As shown in Table 1, the most probable value is taken as the average velocity, and the surrounding rock of the diversion tunnel determines the average footage speed g_{dw} of the tunnel. Two diversion tunnels are designed and to be constructed in this project, and the lines of the two diversion tunnels are arranged in parallel. The total length of the two diversion tunnels is 1276 m. The proportion of surrounding rock of the diversion tunnels is type III rocks about 30%, type IV rocks about 40%, and type V rocks about 30%.

The tunnel adopts two-way excavation. The specified range of the cyclic footage of the flat tunnel according to "construction specifications on underground excavating engineering of hydraulic buildings" (SL378-2007) considers

Table 2: Design rainfall data.

Time	Average monthly rainfall days over the years	Position parameter (minimum)	Shape parameter α	Scale parameter β
October-January	6	0	4.19	1.61

the actual parameters of this project; it is concluded that the cyclic footage of the surrounding class III rock is 7 m/d, class IV rock is 5 m/d, and class V rock is 3 m/d [21]. Due to the different types of surrounding rock of the tunnel, the thickness of the full-section concrete lining of the type III rock is 0.6 m, the thickness of the type IV rock is 0.8 m, and the type V rock is 1 m. The full-section concrete lining speed g_{dc} of the tunnel is 8 m/d.

6.2. Establishment of Cost and Duration Objective Functions. A variety of theoretical probability distribution functions were used to simulate rainfall sequences, such as the Weibull, lognormal, gamma, and mixed exponential distributions. Among the above theoretical probability distribution functions, the gamma distribution has advantages like variable nonnegativity, positive tail bias, and simulation flexibility [27]. The above characteristics of the gamma distribution are considered suitable for simulating the distribution characteristics of rainfall sequences and are favored by many scholars. In summary, the gamma distribution is selected to fit the 30-year rainfall data of the hydrological station at the dam site, and the design rainfall data table is generated as shown in Table 2.

$$f(x|\alpha,\beta) = \frac{x^{\alpha-1}\beta^{\alpha}e^{-\beta x}}{\Gamma(\alpha)}. \tag{30}$$

The parameters required in equations (1)–(13) to be found in engineering materials are as follows: the average slope of the right bank is 75°, the average slope of the left bank is 35°, the average width of the riverbed is 65 m, the upstream slope m_1 is 0.3, and the downstream slope m_2 is 1.0. Substitute into equations (1) to (13), and finally, equations (14) and (15) were obtain.

6.3. Establishment of Constraints. The constructed diversion structure adopts both tunnel diversion and overtopped cofferdams which retain water in dry season and passing water in flood season. The bottom elevation of the fixed tunnel entrance is 454 m, and the diversion tunnel is calculated according to the circular section of the tunnel diameter corresponding to the design flood elevation. The overtopped cofferdam does not need safety superelevated, and the sum of the design flood elevation and the wave climb in dry season is weir crest elevation. After calculation, under the premise of a certain flood control conditions, the technical parameters of the cofferdam corresponding to the circular tunnel section of each diameter are shown in Table 3.

As shown in Table 3, the weir crest elevation decreases steadily with the increase of the diversion tunnel diameter. It is suitable to use the Lagrange interpolation formula to express the relationship between the tunnel diameter and the weir crest elevation. According to the selected diversion tunnel diameters of 8.5 m, 9.5 m, 10 m, and 11 m, the weir crest elevation values are substituted into equations (22) to (23) and simplified to obtain the following equation:

Table 3: Scheme table of cofferdam height of each diversion tunnel section.

Project	Diversion hole diameter (m)	Design flood elevation (m)	Cofferdam height (m)
Scheme 1	8.5	486.80	42.55
Scheme 2	9.0	481.10	36.85
Scheme 3	9.5	477.12	32.87
Scheme 4	10.0	474.25	30.00
Scheme 5	10.5	472.20	27.95
Scheme 6	11.0	470.69	26.44

$$\begin{aligned} Z(D, H_d) = {} & 502.40D^3 - 14064.57D^2 + 130943.84D \\ & - 404906.10 - H_d. \end{aligned} \tag{31}$$

The Lagrange interpolation equation is used to compare and analyze the results obtained from the flood regulation calculation. The results are shown in Table 4. The weir crest elevation calculated by the interpolation formula is higher than the flood regulation calculation results, and the differences are within 0.1 m. The calculation result of flood adjustment is too large, which does not affect the objective of the scheme.

According to the stress limit conditions of the cemented cofferdam, the relevant parameters are substituted into equations (16) and (17), and then, equations (16) and (17) are substituted into equations (18) and (19), and finally, equations (18) and (19) are substituted into equations (20) and (21) to obtain the equations of the upstream vertical normal stress σ_y^u and the downstream vertical normal stress σ_y^d. As mentioned earlier in this paper, the vertical normal stress of the lean concrete material on the upstream and downstream surfaces is not to exceed 0.75 MPa, and the vertical normal stress of the upstream and downstream does not appear to be negative in equations (32)–(35).

Since the project is an overtopped cofferdam, the cofferdam needs to be completed before the flood season. The project is the schedule to start paving the upstream soil-rock cofferdam and the downstream cofferdam in early October and will complete the air closure in mid-October and start the construction of the upstream lean cemented cofferdam. The upstream lean cemented cofferdam will be completed at the end of January. The construction period of the weir, that is, the construction window period, is 75 days [28].

$$V_y/g_y \leq 75\text{d}. \tag{32}$$

Table 4: Lagrange interpolation method calculation error analysis.

Diversion hole diameter (m)	Cofferdam height (m)		Difference (m)
	Lagrange interpolation method	Flood calculus	
9.0	36.93	36.85	+0.08
10.5	27.97	27.95	+0.02

Rain events usually include characteristic attributes such as rainfall intensity, total rainfall, and rainfall duration. By statistic of the total rainfall and rainfall duration at the dam site, the number of rainfall days from the beginning of October to the end of January of the following year was obtained. After fitting, the gamma distribution was obtained, as shown in Table 2.

$$f(x, \beta, \alpha) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}, \quad x > 0. \tag{33}$$

The bottom elevation of the river channel in this project is 452 m, so the lower limit of the elevation H_d of the bottom plate at the inlet of the diversion tunnel is set to be 452 m; that is, the elevation of the inlet bottom plate is the same as the riverbed. The diversion tunnel is circular, and the diameter of the tunnel should not be less than 2 m. Due to the limitations of geology and construction technology, the maximum diameter of the hole is limited to 14 m.

$$H_d \geq 452\,\text{m}, \tag{34}$$

$$D \geq 2\,\text{m}, \tag{35}$$

$$D \leq 14\,\text{m}. \tag{36}$$

7. Results and Analysis

7.1. Calculation and Analysis of Noninferior Solution Set. According to the distribution probability of different schemes in Figure 5, the following can be concluded: (1) for the diversion tunnels with diameters of 9.6 m and above, the probability of the completion of the lean cemented cofferdam on time is 100%. (2) It can be seen in Figure 5 that a large slope curve in the range of 8.7~9.1 m in diameter of the diversion tunnels indicates that the probability of timely completion of lean cemented cofferdam is very sensitive to the changes in diversion tunnel diameter.

Under the constraint conditions which the reliability of the lean cofferdam construction completed on time is 80%, 90%, and 99.9%, the noninferior solution $\omega_1 : \omega_2$ can be obtained by the perturbation weight calculation, as shown in Table 5. The higher the reliability of the noninferior solution set, the higher the minimum limit of the diversion tunnel diameter. By reducing the weight of the cost and increasing the weight of the construction period, the scheme with high diversion tunnel diameter and low cofferdam height can be obtained [29–32].

The network analysis shows that the pouring of lean cemented cofferdam is a key node project on the key route. Failure to complete the lean cofferdam project on time will

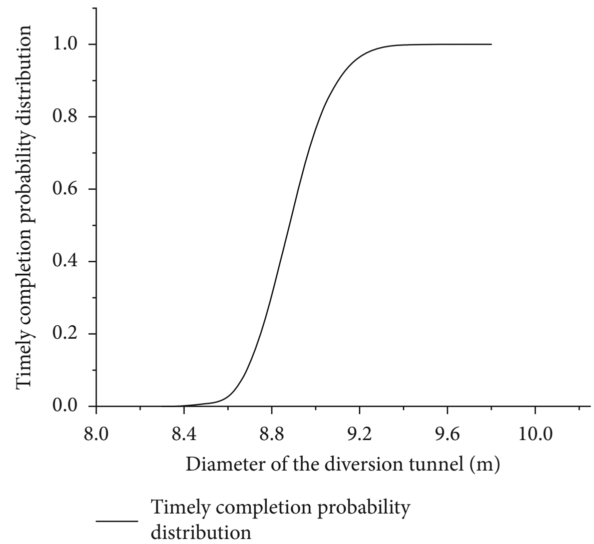

Figure 5: Distribution probability diagram of timely completion for different schemes.

not only affect the progress of the whole water conservancy project but also inflict damages to the already completed project and ultimately cause irreparable damages to the whole project. So to sum up, the lean cemented cofferdam with completion on time is the primary goal, and then, the cost effectiveness is the second goal. As shown in Table 6, it is clear that under the 99.9% reliability of the construction period, the scheme which the diameter of the diversion tunnels is 9.6 m ~10.5 m can better balance the advantages of both cost effectiveness and construction period. The technical characteristics of these schemes are shown in Table 6.

7.2. Decision-Making. The diversion schemes in which the diameter of the diversion tunnels is 9.6 m ~10.5 m can take into account both the economy and construction period. It is difficult to determine a satisfactory scheme from these diversion schemes. In network analysis model, there is a required free float time concept in the key route in which the maneuver time can be used in the current work without affecting the earliest starting time of its subsequent work. Due to the uncertainty of construction speed and construction environment, the required free float time adopted in this paper is defined as the flexible time for cofferdam paving under the condition that the reliability of cofferdam completing on time is 99.9%. The required free float time can reserve more redundant time for emergencies and can start the subsequent work in advance, providing more guarantees for the safety of the water conservancy projects in flood season.

Table 5: Noninferior solution set table under different reliability.

Weight	Construction reliability								
	80%			90%			99.9%		
$\omega_1 : \omega_2$	H (m)	D (m)	Average construction time (d)	H (m)	D (m)	Average construction time (d)	H (m)	D (m)	Average construction time (d)
0.90 : 0.10	38.3	9.0	114	36.3	9.1	103	32.2	9.6	83
0.75 : 0.25	38.3	9.0	114	36.3	9.1	103	32.2	9.6	83
0.67 : 0.33	38.3	9.0	114	36.3	9.1	103	32.2	9.6	83
0.50 : 0.50	36.3	9.1	103	36.3	9.1	103	32.2	9.6	83
0.33 : 0.67	33.7	9.4	90	33.7	9.4	90	32.2	9.6	83
0.25 : 0.75	32.2	9.6	83	32.2	9.6	83	32.2	9.6	83
0.10 : 0.90	28.0	10.5	65	28.0	10.5	65	28.0	10.5	65

Table 6: Characteristics of noninferior solution diversion schemes.

Diversion scheme	Diameter of the diversion tunnel (m)	Weir height of the cofferdam (m)	Required free float time (d)	Construction cost (10^4¥)	Construction time of cofferdam (d)
1	9.6	32.2	3	11649.37	60
2	9.7	31.6	7	11727.52	57
3	9.8	31.0	10	11809.88	55
4	9.9	30.5	13	11896.09	53
5	10.0	30.0	16	11985.76	51
6	10.1	29.5	19	12078.59	49
7	10.2	29.1	21	12174.26	48
8	10.3	28.7	23	12272.50	46
9	10.4	28.3	25	12373.05	45
10	10.5	28.0	27	12475.67	44

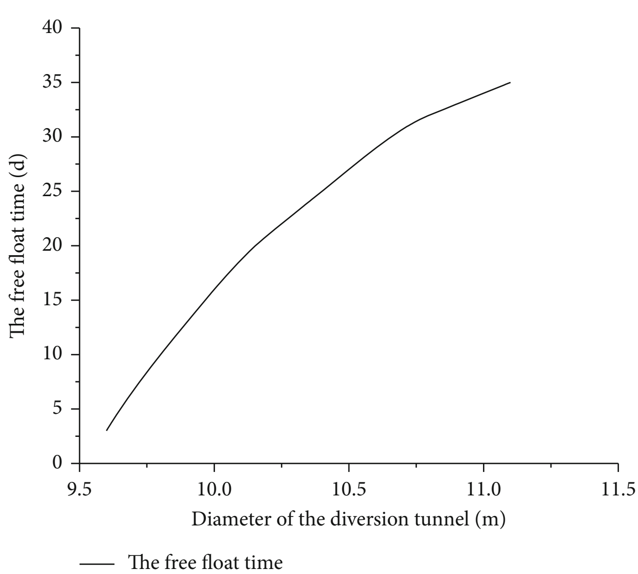

Figure 6: Required free float time chart for different schemes.

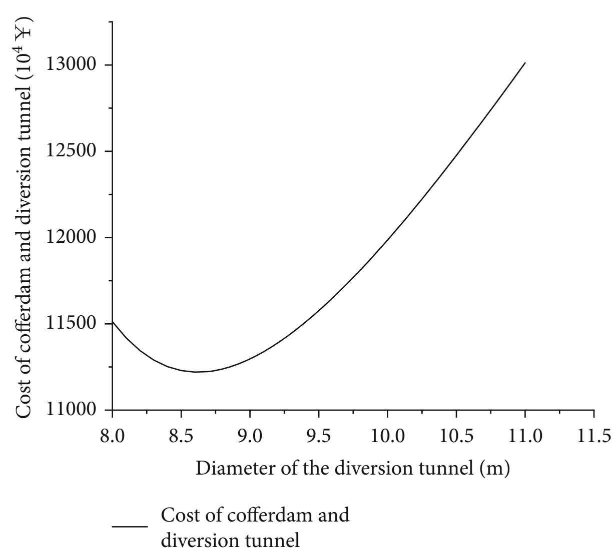

Figure 7: Cost projections for diversion structures in different schemes.

As shown in Figure 6, the larger the diameter of the diversion tunnels, the larger the required free float time of the diversion schemes, and the growth rate of the required free float time decreases with the increase of diversion tunnel diameter. In summary, the determination of the required free float time is crucial for decision-makers, and the final diversion scheme is also determined by the determination of required free float time. The work subsequent to lean cemented cofferdam construction in AP water control project is the water passing of the dam foundation ditch, to which the required free float time has little effect. Therefore after careful consideration, the diversion scheme 1 is selected.

The relationship between the diameter of the diversion tunnels and the cost of the diversion structure is shown in Figure 7. The lowest cost of the diversion structure is when the diameter of the diversion tunnel is 8.6 m. Since the required free float time could not bring more benefits to the whole project, it is reasonable to select diversion scheme 1 which considered both the economy and construction period.

8. Conclusion

Diversion is an important part of hydraulic engineering. Optimal diversion scheme can save cost and time for the project.

This paper presents a multiobjective optimization method for the diversion scheme of overtopped cofferdam with lean cemented concrete. In this model, the relation between cofferdam height and diversion tunnel diameter is obtained using Lagrange interpolation formula, and the decision variables of multiobjective optimization model are reduced. The multiobjective optimization model uses Monte Carlo method to simulate the rainfall at the dam site and the construction speed of the cofferdam to obtain the reliability of the cofferdam completed on schedule. The multiobjective optimization model mainly includes time limit reliability, design specification, construction speed, and other constraint conditions. Finally, the nonsplitting of the multiobjective optimization model is calculated, and the optimal diversion scheme decision is made according to the free float time difference.

The case study of AP hydraulic engineering found the following conclusions:

(1) The time limit and cost of the model are reasonable, and the results are not different from the preliminary design

(2) The free float time difference of different projects varies greatly due to the needs of subsequent work. The difference of free float time difference has great influence on deciding the diversion scheme

(3) The rainfall at the dam site has a great influence on the construction period of lean cemented cofferdam. Lean cemented cofferdam should be carefully used in projects with frequent rainfall

(4) Due to the positive bias appeared in gamma distribution, the reliability of the actual period is higher than that of the simulation

(5) It is better to equip mechanical equipment with smaller capacity and leave equipment redundancy to increase the lower limit of construction speed to

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Q. Luo, S. Guo, and W. Tang, "Summary of over-topped earth-rock dam," *Water Science, Technology and Economy*, vol. 16, no. 9, pp. 1023–1025, 2010.

[2] Z. Hu, Q. Liu, C. He et al., "Risk analysis of water prevention and diversion of earth-rock cofferdam based on Monte-Carlo method," *Advances in Water Science*, vol. 5, pp. 518–527, 2002.

[3] D. Nasir, B. Mccabe, and L. Hartono, "Evaluating risk in construction–schedule model (ERIC–S): construction schedule risk model," *Journal of Construction Engineering & Management*, vol. 129, no. 5, pp. 518–527, 2003.

[4] X. Fan, Z. Hu, and P. Jing, "Comprehensive risk analysis of construction diversion system based on Monte-Carlo method," *Advances in Water Science*, vol. 4, pp. 604–608, 2007.

[5] L. Luo, "Multidimensional assessment of diversion risk throughout the construction process of high dam," *Journal of Central South University-Science and Technology*, vol. 45, no. 3, pp. 840–846, 2004.

[6] H. Marengo, F. I. Arreguin, A. A. Aldama, and V. Morales, "Case study: risk analysis by overtopping of diversion works during dam construction: the *La Yesca* hydroelectric project, Mexico," *Structural Safety*, vol. 42, pp. 26–34, 2013.

[7] H. Marengo, "Case study: dam safety during construction, lessons of the overtopping diversion works at Aguamilpa dam," *Journal of Hydraulic Engineering*, vol. 132, no. 11, pp. 1121–1127, 2006.

[8] M. A. Stevens and J. Linard, "The safest dam," *Journal of Hydraulic Engineering*, vol. 128, no. 2, pp. 139–142, 2002.

[9] Q. Shen and Y. Fen, "Experimental study on RCC material with CSG lean gravel," *Value Engineering*, vol. 35, no. 4, pp. 114–116, 2016.

[10] S. Jia, "Economical study on dam constructed using lean cemented with gravel," *Water Conservancy Supervision*, vol. 25, no. 6, pp. 111–113, 2017.

[11] J. Jia, M. Lino, F. Jin, and C. Zheng, "The cemented material dam: a new, environmentally friendly type of dam," *Engineering*, vol. 2, no. 4, pp. 490–497, 2016.

[12] Z. Liu, J. Jia, W. Feng, F. Ma, and C. Zheng, "Shear strength of cemented sand gravel and rock materials," *Sains Malaysiana*, vol. 46, no. 11, pp. 2101–2108, 2017.

[13] J. Jia, F. Ma, X. Li, and Z. Chen, "Research progress and engineering application of lean cemented particle dams," *Journal of Hydraulic Engineering*, vol. 47, no. 3, pp. 315–323, 2016.

[14] W. Chen, "Application of lean cemented gravel material in cofferdam engineering," *Dam and Safety*, vol. 2, pp. 35–41, 2011.

[15] Y. Mao, "Construction technology of CSG cofferdam in upper reaches of Fujian Hongkou hydropower station," *New Technology and Products in China*, vol. 17, pp. 80-81, 2012.

[16] F. L. Lai, "Design of lean cemented dregs and gravels cofferdam for Hongkou hydropower station," *Hydrology Technology*, vol. 4, pp. 48–51, 2011.

[17] Z. M. Liu, "Study on basic profile of lead cemented dregs and gravel dams," *Water Conservancy Planning and Design*, vol. 11, pp. 1-2, 2016.

[18] Y. Z. Zhang and Y. S. Gong, "Integrated management of lean cemented gravel over-topped cofferdam of Dahuaqiao hydropower station," *Hydroelectric Power*, vol. 6, pp. 10–12, 2019.

[19] "Guidelines for the construction of RCC in lean cemented dregs and gravel," *Hydraulic Industry Standard CN-SL 2011-China*.

[20] "Technical guidelines for cemented granular material dams," *Electrical Engineering Industry Standard-CN-SL 2014-China*.

[21] L. Guo, S. Li, L. Zhong et al., "A study on the effects of the fractal characteristics of aggregates on the mechanical behavior of cemented sand and gravel," *Materiales de Construcción*, vol. 71, no. 342, article e250, 2021.

[22] M. E. Omran and Z. Tokmechi, "Sensitivity analysis of symmetrical hard fill dams," *Middle East Journal of Scientific Research*, vol. 6, no. 3, pp. 251–256, 2010.

[23] L. Guo, J. Zhang, L. Guo, J. Wang, and W. Shen, "Research on profile design criteria of 100 m CSG dams," *Construction Materials*, vol. 16, article e01137, 2022.

[24] "Design guide of cofferdam for hydropower and water conservancy projects," *Industry Standard Electrical Engineering CN-NB 1999-China*.

[25] R. Liu, J. Zhang, and X. Han, "Project risk identification based on triangular fuzzy number," *Journal of Harbin Institute of Technology*, vol. 10, pp. 1617–1620, 2008.

[26] "Construction specifications on underground excavating engineering of hydraulic structure," *Industry Standard Hyrology CN-SL 2007-China*.

[27] G. J. Husak, J. Michaelsen, and C. Funk, "Use of the gamma distribution to represent monthly rainfall in Africa for drought monitoring applications," *International Journal of Climatology*, vol. 27, no. 7, pp. 935–944, 2007.

[28] N. T. Nguyen, Q. A. Bui, H. H. N. Nguyen et al., "Curcuminoid co-loading platinum heparin-poloxamer P403 nanogel increasing effectiveness in antitumor activity," *Gels*, vol. 8, no. 1, p. 59, 2022.

[29] S. Ahmed, B. Qiu, F. Ahmad, C.-W. Kong, and H. Xin, "A state-of-the-art analysis of obstacle avoidance methods from the perspective of an agricultural sprayer UAV's operation scenario," *Agronomy*, vol. 11, no. 6, p. 1069, 2021.

[30] D. Pan, K. Hong, H. Fu, J. Zhou, N. Zhang, and G. Lu, "Influence characteristics and mechanism of fragmental size of broken coal mass on the injection regularity of silica sol grouting," *Construction and Building Materials*, vol. 269, article 121251, 2021.

[31] M. He, Z. Zzhiqiang, Z. Jiwei, and L. Ning, "Correlation between the constant mi of Hoek-Brown criterion and porosity of intact rock," *Rock Mechanics and Rock Engineering*, vol. 55, 2022.

[32] M. He, Z. Q. Zhang, J. W. Zhu, N. Li, G. Li, and Y. S. Chen, "Correlation between the rockburst proneness and friction characteristics of rock materials and a new method for rockburst proneness prediction: field demonstration," *Journal of Petroleum Science and Engineering*, vol. 205, article 108997, 2021.