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# Multi-objective optimization of diversion tunnel under the water conservancy project

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**Abstract.** Tunnel diversion is a method of diverting upstream water through a diversion tunnel where the river valley is narrow and not conducive to the placement of an open channel, and where the geological conditions of the riverbank hills are favourable for the excavation of a tunnel. The construction of a tunnel diversion is limited by topographical conditions, construction budget, and construction scale. Therefore, the choice of a reasonable solution for the construction of a tunnel diversion has a certain influence on the cost, efficiency, and risk of construction A comprehensive consideration of how to construct a tunnel diversion can achieve a multi-objective optimization to reduce costs and increase efficiency. This paper incorporates risk as a constraint, with the radius of the upper part of the tunnel half arch and the lower tunnel elevation as optimizable variables for optimization. Based on the analysis of actual hydropower project data, Matlab is used to derive the most optimizable solution considering different possible scenarios of water flow, and the obtained results, show that the comprehensive objectives of shorter construction time and lower cost can be effectively achieved by analyzing the variables under different scenarios where the risk is a constraint.

**Keywords:** diversion tunnels, tunnel diversion, hydraulic engineering, multi-objective optimization, overflow.

## 1. Introduction

Construction diversion is an important part of hydraulic engineering, where the downward flow of water is diverted through a constructed channel in order to allow the construction of hydraulic structures to proceed on dry land. Construction diversion is a unique and very important engineering measure in the construction of gates and dams. Precise calculations are required prior to construction. Since the 1980s, China's water conservancy projects have gradually moved to the west, especially in Xinjiang, where tunnel diversions are mostly used.

The study of tunnel diversion encompasses many aspects, but most of the previous studies considered minimizing the cost and duration to the exclusion of consideration of the impact of risk on construction [1]. This paper constructs a multi-objective optimization system for inflow tunnels by studying the radius of the upper part of the arch of the inflow tunnel and the elevation of the lower end of the tunnel based on the cost of the inflow tunnel and the duration of the construction of the inflow tunnel.

Most engineering problems are multi-objective optimization problems where there are multiple conflicting objectives, and how to select the optimization objectives and obtain the optimal solution for these objectives becomes the key to the study [2]. In this paper, the research content takes the tunnel flood flow situation under different conditions as the constraint, establishes a multi-objective optimization model under different risks [3], and uses Matlab to solve it. Finally, based on examples of hydropower projects, further optimization and solutions are carried out in real situations. The maximization of benefits for the environment and the construction side as well as for the inhabitants living along the river is achieved and it is indicative and informative for the establishment of hydroelectric power stations in reality.

## 2. Research methods

*2.1. Multi-objective optimization method*

The multi-objective optimization algorithm is an algorithm to solve the optimal solution of multiple objective functions, which can be used to measure the relationship between multiple objective functions and has the advantages of being simple, fast, and efficient. Its basic mathematical model is shown as follows [4]:

$$min/maxy(x) = f(x) = [f1(x), f2(x), ..., fn(x)]n = 1,2, ..., N \tag{1}$$

$$s.t.\ g_i(x) \le 0i = 1,2, ..., m \tag{2}$$

$$h_j(x) = 0, j = 1,2, . . . q \tag{3}$$

$f_i(x)$is the objective function of the optimization, x is the optimization design variable, $g_i(x)$,$h_j(x)$ is the equation with inequality constraints. Moreover, there are two multi-objective optimization methods of the evaluation function, namely the linear weighting method, which is the most commonly used method for converting multiple objectives into a single objective, and the main objective method, where a sub-objective is selected as the main solution objective and the rest are regarded as secondary objectives [5], and the secondary objectives are treated as constraints.

*2.2. Optimization objectives and algorithm selection for inflow tunnels*

Based on the scientific nature of the research problem, the broad applicability of the optimization objectives, and the availability of data in the target calculation and optimization process, the factors influencing the optimization of the tunnel diversion are analyzed in terms of the cost and construction duration of the tunnel diversion project, so as to select a suitable optimization target. The cross-sectional form of the tunnel depends on the geological conditions, the working conditions of the tunnel, the construction conditions of the tunnel, etc. The common forms are round, horseshoe, and square [6].

*2.2.1. Analysis of the radius R of the arch in the upper part of the tunnel and the target $h_d$under the influence of the elevation arrangement in the lower part of the tunnel.* $C_s$ refers to the cost analysis of the upper part of the arch radius and the lower part of the tunnel elevation [7]. The cost of the tunnel includes two aspects, namely the cost of lining and masonry $c_c$ and the cost of excavation $c_w$. The excavation cost is the product of the volume of the excavation $v_w$ and the unit price of the construction $p_w$, which is the volume of the upper half of the arch and the volume of the lower half of the rectangular tunnel. The filling cost of the tunnel is the product of the lining construction volume $v_c$ and the unit price of the lining construction $p_c$, which is the volume of concrete used to build the lining with a thickness of s around the outer ring of the tunnel. where the thickness of the lining (s) is a fixed value.

$$v_w = [\frac{\pi}{2} \times (R + S)^2 + (H - h_d - R - s) \times (B_d + 2s) \times ]L_d \tag{4}$$

$$V_c = [\frac{\pi}{2} \times [(R + S)^2 - R^2] \times L_d + 2 \times (H - h_d - R) \times S \times ]L_d \tag{5}$$

In the formula above, R is the radius of the upper arch structure, S is the thickness of the lining, and H is the top elevation of the tunnel. The unit price of the tunnel masonry lining is $P_c$ and the unit price of the tunnel excavation volume is $P_w$. Then the cost of the tunnel is:

$$c_s = c_c + c_w = v_c p_c + v_w p_w \tag{6}$$

*2.2.2. Analysis of the effect of the radius of the upper part of the tunnel arch and the lower part of the tunnel elevation on the construction period.* The tunnel excavation and masonry lining cannot be carried out simultaneously and there is no lap construction, so the construction period $T_s$ is divided into two aspects, i. e. the period required for excavation and the period required for masonry lining. The duration required for excavation is expressed as a ratio of the total excavation volume to the unit excavation speed, and the time required for masonry lining is a ratio of the total masonry volume to the unit masonry speed. The total duration of construction is the sum of the time required for excavation and the time required for masonry lining.

Let the speed of excavation be $g_w$, the speed of masonry lining be $g_c$, the time required per unit of excavation be $T_w$, and the time required per unit of masonry be $T_c$. Therefore the construction duration function for the tunnel can be established as:

$$T_s = T_w + T_c = v_w/g_w + v_c/g_c \tag{7}$$

*2.3. Construction of a multi-objective model for the inflow tunnel*

Based on the analysis of the optimization objectives in Part 2, a multi-objective optimization model of the diversion tunnel building can be established to obtain the lowest engineering cost and the shortest construction period. Establishment of the multi-objective optimization model is shown below:

$$f = min[C_s(h_d, R), T_s(h_d, R)] \tag{8}$$

*2.4. Constraints*

*2.4.1. Constraint on the flow rate of the inflow tunnel (p).* In the determination of the criteria of the diversion tunnel, the risk of the tunnel diversion is the main risk [8], and the risk of the tunnel diversion mainly depends on the flow rate in the tunnel and the water flow in the tunnel. The more flow in the tunnel and the greater the flow rate is, the stronger the threat is to the flushing resistance of the tunnel, and the main influence on the flushing resistance of the tunnel is the cross-sectional size of the tunnel, therefore the larger the cross-sectional size of the tunnel, the greater the drainage capacity, the lower the water level in the tunnel, the larger the cross section, the greater the discharge capacity, the lower the water level in the tunnel, and the lower the risk.

The design flow rate of the diversion tunnel is constrained by the size of the cross-section, which constrains the design flow rate of the diversion tunnel. The flow regime in a diversion tunnel can be divided into pressurized, semi-pressurized, and unpressurized flow, which is determined by the ratio of the tunnel roof elevation to the tunnel height [9].

In this paper, the specific research problem is an unpressurised flow tunnel. The overflow is calculated according to Manning's formula:

$$q = a\frac{1}{n} \times r^{\frac{1}{6}} \times \sqrt{r_i} \tag{9}$$

Where q is the overwater flow $m^3/s$, a is the overwater cross-sectional area $m^2$, and n is the design roughness (this paper calculates according to c20 concrete with roughness n=0.014, r is the hydraulic radius, and i is the slope drop).

*2.4.2. Constraints on the building height to width ratio of the diversion tunnel.* According to the requirements for the construction method of the diversion tunnel and the safe diversion, a section height-to-width ratio of around 1.2m to 1.5m is required.

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*2.4.3. Constraint on the size of the tunnel building.* The construction method of the diversion tunnel is generally the drill and blast method, which requires that the cross-sectional area of the diversion tunnel should not exceed 200m$^2$.

*2.5. Model calculation*

For multi-objective optimization problems, the indirect method is generally applied to calculate, according to the complexity of water conservancy engineering and the characteristics of non-linearity, this paper adopts the method of converting multi-objective into a single objective for calculation, that is, through the weighting method multi-objective problems into the form of a single objective [5], so the optimization objective can be expressed as:

$$miny = min(a_1 c_s + a_2 ts) \tag{10}$$

$a_1$ and $a_2$ are the cost weights and the duration weights, respectively. If the delay in the construction inflow schedule has no or less impact on the total project schedule, the weights can be chosen to range from (1:1), (1:2)...(1:n) [10].

The genetic algorithm (ga) and the particle swarm algorithm (pso) are both commonly used in solving multi-objective optimization problems. In this paper, the particle swarm algorithm [4] is used to solve the single-objective optimization model established above.

The particle swarm method, also known as the bird swarm algorithm, is based on a model of a flock of birds constantly flying in order to forage for food. The particle swarm algorithm is one of the evolutionary algorithms with the concept of population [8].

## 3. Engineering example analysis

*3.1. Project overview*

There is a large hydropower project, where the top plate elevation is 2216 m, the cross-section of the diversion tunnel is a square circle, and the upper arch corresponds to the angle of the centre of the circle for the tunnel length of 1500 m. The riverbed topography is relatively gentle, and the tunnel slope drop i=1/25000, n=0.014. As a special case, the proposed cross-section top arch is a half-circle, and the water section is made rectangular, then the top arch to the centre angle is a and the water surface to the centre angle is also a. Besides, a is π. The unit lining cost of the diversion tunnel is 180 Yuan/m$^3$, the unit excavation cost of the diversion tunnel is 60 Yuan/m$^3$, the unit lining speed of the diversion tunnel is 8m/d, the unit excavation speed of the diversion tunnel is 10m/d, the lining thickness is 800mm, the peak flood flow during the 10-year dry period is 1200m$^3$/s, and the peak flood flow during the flood period is 2500m$^3$/s.

*3.2. Target modelling and calculation*

*3.2.1. Establishment of the target model.* Construction cost functions are shown below:

$$v_w = \frac{\pi}{2} \times (R + 0.8)^2 + (2212 - h_d - R - 0.8) \times (2R + 1.6) \times 1500 \tag{11}$$

$$V_c = \frac{\pi}{2} \times [(R + 0.8)^2 - 0.8^2] \times 1500 + 2 \times (H - h_d - 0.8) \times 0.8 \times 1500 \tag{12}$$

$$Min\ C_s = C_w + C_C = v_w p_w + v_c p_c \tag{13}$$

$$Min\ T_s = T_w + T_c = v_w/g_w + v_c/g_c \tag{14}$$

*3.2.2. Model constraints.* First, 1.500-2500 is divided by taking every 200m$^3$/s as a stage so that the risk constraint ranges from 0 to 1 interval.

p<0.1, that is, the range of the overflow Q is less than 500m$^3$/s.

p=0.1, that is, the range of the overflow Q is 500 to 700m$^3$/s.

p=0.5, that is, the range of the overflow Q id 1300 to 1500$m^3/s$.

p>1, that is, the range of the overflow Q is greater than 2500$m^3/s$.

Choose p=0.1, 0.3, 0.5, and >1 to establish the constraint case respectively for programme comparison selection. In this case, the formula for calculating the excess water flow Q is referred to the following formula for the unpressurised flow case.

$$m = \frac{1}{4K}(a - sina) - \frac{\pi}{4} \tag{15}$$

$$h_0 = \left[ \frac{(\frac{1}{m}(\pi+2+2m-a))^{\frac{2}{3}}Q}{(\frac{1}{2m^2}(1-K)(4m+\pi))^{\frac{5}{3}}i^{\frac{-1}{2}}} \right]^{\frac{3}{8}} \tag{16}$$

In this case, K=0.25 and a=2.6245.

Second, constrain the cross-sectional area of the diversion tunnel according to the actual terrain conditions and the analysis of the flooding survey.

$$\frac{\pi R^2}{2} + (H - h_d - R) \times 2R \leq 200 \tag{17}$$

Third, according to the construction requirements of the diversion tunnel, the height-to-width ratio of the diversion tunnel is between 1.2 and 1.5.

$$1.2 \leq \frac{H-h_d}{2s+2R} \leq 1.5 \tag{18}$$

*3.2.3. Results and Analysis.* The Matlab calculation results are shown in Table 1. From the table, it can be seen that when p<0.1, that is, the range of the overflow Q is less than 500 $m^3/s$, Min $h_d$ =2215.0m and Min R=1.0222m; when p=0.1, that is, the range of the overflow Q is 500 to 700$m^3/s$, Min $h_d$=2213.7m and Min R=1.1255m; when p=0.5, that is, the range of the overflow Q is 1300 to 1500$m^3/s$, Min $h_d$=2213.1m and Min R=1.6104m. When the risk is out of control, that is, Q>1500$m^3/s$, a new programme should be developed as appropriate.

**Table 1.** The Matlab calculation results.

| Probability (P) | Flow (Q) | Min $h_d$ | Min R |
|---|---|---|---|
| P<0.1 | Q=0-500$m^3/s$ | 2215.0m | 1.0222m |
| P=0.1 | Q=500-700$m^3/s$ | 2213.7m | 1.1255m |
| P=0.5 | Q=1300-1500$m^3/s$ | 2213.1m | 1.6104m |

## 4. Conclusion

This paper investigates the analysis of diversion tunnels under different scenarios using overland flow as a constraint, and uses a multi-objective optimization approach to select the most optimal solution in terms of duration and cost, so as to shorten the duration and reduce the cost of the project based, to some extent, on a thorough hydrological investigation. However, there are many uncertainties in hydraulic engineering, and this paper does not analyse all the risks thoroughly. It is idealistic about the geographical and hydrological conditions and the form of the tunnel masonry in the project example, making the algorithm simplistic and lacking in realism and field references.

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