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To cite this article: Yue Zhang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **592** 012102

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# Optimization design research on the impervious curtain structure based on improved PSO algorithm

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**Abstract:** In this study, the impervious curtain structure of riverbed part of the concrete face rockfill dam (CFRD) is optimized. This method is based on the particle swarm optimization (PSO) algorithm and combines with finite element method to calculate the seepage discharge of dam foundation in riverbed part at different depth and thickness. The result shows that the seepage discharge decreases with the increase of curtain depth, and the effect of curtain thickness on seepage discharge is not obvious. This is an effective and practical method to solve engineering problems that meeting the requirement on structural stability and satisfy the economic.

## 1. Introduction

Grouting technology is characterized by convenient construction, safety and environmental protection, and high economic efficiency. Thus, it is widely used in the water conservancy projects, oil, coal, and other industries [1-2]. When cement slurry is injected into bedrock, it penetrates, diffuses and fills the surrounding fissures and pores to prevent groundwater flow, so as to reduce the bedrock permeability and osmotic pressure [3]. For bedrock seepage problems occurred in the running projects, according to the actual situation, the appropriate remedial measures, secondary grouting, generally, are taken to reduce the bedrock leakage [4-5].

Considering the lack of researches on the impervious curtain structure design that affects the safety and economy of the structure, therefore, it is worth studying to choose the best curtain structure. The semi-empirical formula is generally used in the design of traditional curtain grouting, the result of which is only a good design but not the optimal one. It is worth studying how to save the grouting material amount and give full play to grouting in construction. Chai [6] analyzed the influence of various parameters of curtain grouting on the seepage pressure of the base surface based on a simplified 1D seepage model, and proposed a theory of curtain optimal thickness.

## 2. Particle swarm optimization (PSO) algorithm

### 2.1. Standard PSO

The velocity of each particle is based on its own and group flight experiences to adjust its size and direction dynamically and thus become close to the optimal solution [7]. PSO algorithm will update the velocity and position of the particle by equations (1) and (2).



$$V(t+1) = V(t) + c_1 \text{rand}() (P(t) - X(t)) + c_2 \text{rand}() (G(t) - X(t)) \quad (1)$$

$$X(t+1) = X(t) + V(t+1) \quad (2)$$

where,  $V$  is the particle velocity;  $X$  is the particle position;  $P$  is the optimal historical position of the individual;  $G$  is the optimal historical position of the group;  $t$  is the number of iterations;  $c_1$  and  $c_2$  are learning factors;  $\text{rand}()$  is a random number of 0~1.

## 2.2. Improved PSO

The inertia weight,  $\omega$ , plays a role in balancing the global and the local search ability. When  $\omega$  is large, it is beneficial to the global search. When  $\omega$  is small, be helpful for local search. The improved PSO algorithm is a random adjustment of inertia weight. Several scholars believe that a set of random values should be set. For example, Eberhart [7] proposed a dynamic inertia weight method that can be used to solve the problem of optimizing the target change. The method can be expressed as:

$$\omega_x = \frac{0.5 + c_1 \text{rand}()}{2}, \omega_z = \frac{0.5 + c_2 \text{rand}()}{2} \quad (3)$$

The particles fall on the boundary maybe result in a local optimum. Therefore, in this paper, the following mutation operations are performed particles on the boundary and in the fly out of the boundary:

$$\begin{aligned} \text{if } x > x_{\max}, x &= x_{\max} - \text{rand}() \times (x_{\max} - x_{\min}) & \text{if } x < x_{\min}, x &= x_{\min} + \text{rand}() \times (x_{\max} - x_{\min}) \\ \text{if } z > z_{\max}, z &= z_{\max} - \text{rand}() \times (z_{\max} - z_{\min}) & \text{if } z < z_{\min}, z &= z_{\min} + \text{rand}() \times (z_{\max} - z_{\min}) \\ \text{if } v > v_{\max}, v &= v_{\max} - \text{rand}() \times (v_{\max} - v_{\min}) & \text{if } v < v_{\min}, v &= v_{\min} + \text{rand}() \times (v_{\max} - v_{\min}) \end{aligned}$$

where,  $x$  is the abscissa of the particle,  $x_{\max}$  and  $x_{\min}$  are the upper and lower limit of the abscissa of the particle respectively;  $z$  is the ordinate of the particle,  $z_{\max}$  and  $z_{\min}$  are the upper and lower limit of the ordinate of the particle respectively;  $v$  is flying speed of the particle,  $v_{\max}$  and  $v_{\min}$  are the upper and lower limit of speed respectively.

Based on the improved PSO algorithm mentioned above, this study combines the Miaojiaba project as a case to analysis concretely. In this paper, the improved PSO algorithm is applied to the curtain structure optimization, as shown in the flow chart of Figure 1.

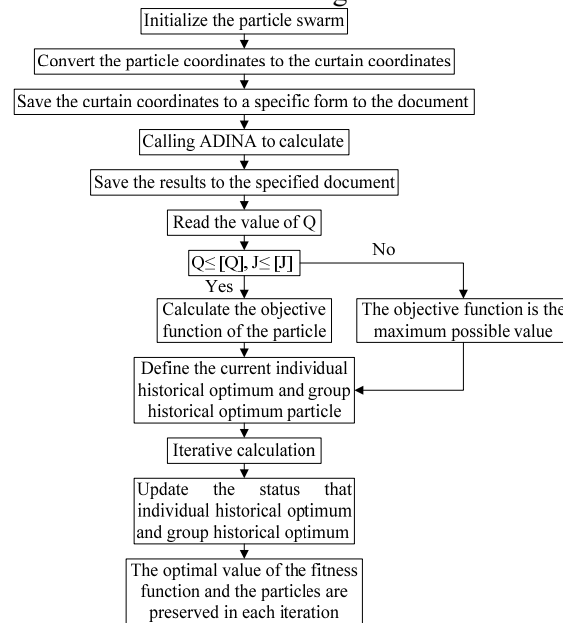


Figure 1. The flowchart of optimization calculation

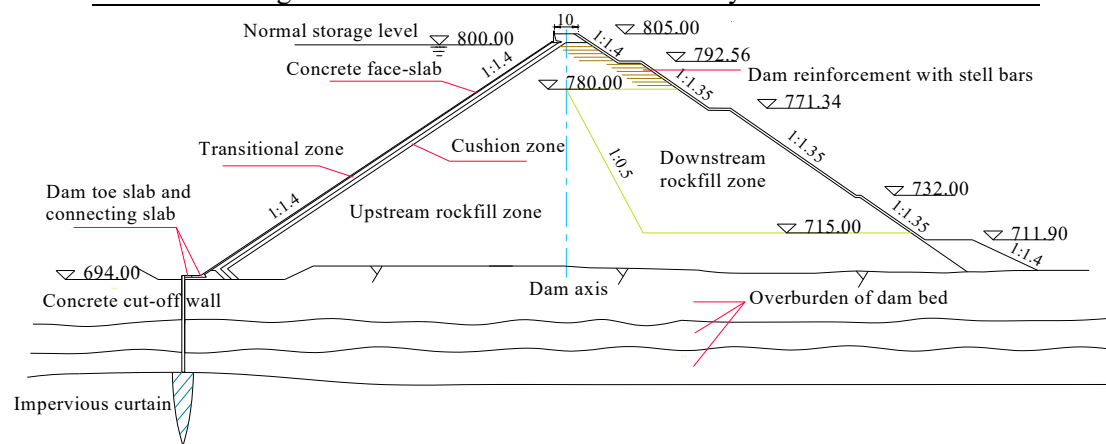
## 3. Modeling calculation and programming

### 3.1. Project overview of Miaojiaba CFRD

The dam site of Miaojiaba Hydropower Station is located in the lower reaches of Bailongjiang, Gansu Province and is located 31.5 km away from the downstream of Bikou Hydropower Station. The overburden of the river bed is 44~48 m. The seepage control system of river bed foundation is concrete cut-off wall with thick of 1.2 m and a maximum depth of 48 m. In addition, the main engineering information is provided in Table 1. Figure 2 is the typical cross-section of the Miaojiaba CFRD.

**Table 1.** Engineering information

Crest elevation	805 m	surface reservoir	2-4 m
Normal water level	800 m	upper layer	6-20 m
Dead water level	795 m	middle layer	12-15 m
Dam height	111 m	lower layer	5-10 m

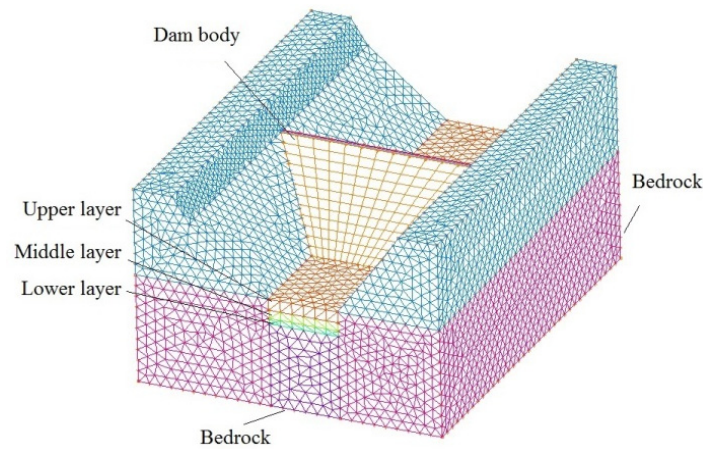


**Figure 2.** A typical cross-section of the Miaojiaba CFRD

### 3.2. Finite element model

According to the topographic map of Miaojiaba water conservancy project, the coordinates and elevation around the dam are extracted, and the three-dimensional model is established.

Coordinate system selection: In the use of the 3D Cartesian coordinate system, the coordinates of the origin is (0, 0, 0). The positive axis of X is perpendicular to dam axis and along the river direction. The positive axis of Y is parallel to dam axis and points to the left bank. The positive axis of Z is perpendicular to the dam axis and vertical up. Calculation area: the upstream boundary is taken to the 170 m upwards, and the downstream boundary is taken to the 170 m downward. The bottom boundary is 148m below the dam foundation (the elevation of 546 m). The left bank boundary is 100 m outward, and the right bank boundary is 100 m outward. The three-dimensional finite element model is shown in Figure 3. The mesh size of the model is 30m and type of element is linear. For the model of the bottom boundary, the left and right sides of the boundary is impermeable. The upstream load is 800 m, and the downstream load is 715 m. The calculation area has 12 different materials, which are expressed in different colors in the model. The material parameters are listed in Table 2.



**Figure 3.** The three-dimensional finite element model

**Table 2.** The parameters of seepage calculation

Zone names	Permeability coefficients (m/s)
Bedrock	$1.0 \times 10^{-6}$
Massif	$2.0 \times 10^{-7}$
Lower layer	$1.7 \times 10^{-4}$
Middle layer	$1.7 \times 10^{-4}$
Upper layer	$1.4 \times 10^{-4}$
Concrete cut-off wall	$1.0 \times 10^{-8}$
Impervious curtain	$1.0 \times 10^{-9}$
Concrete face-slab	$1.0 \times 10^{-8}$
Cushion zone	$1.5 \times 10^{-4}$
Transitional zone	$1.0 \times 10^{-5}$
Upstream rockfill zone	$3.2 \times 10^{-3}$
Downstream rockfill zone	$3.2 \times 10^{-3}$

### 3.3. Improved PSO algorithm based on MATLAB

In this study, the PSO algorithm was developed based on MATLAB platform. The batch file can be used to call ADINA for the calculation.

Objective function:

$$C = c \times V \quad (4)$$

$$V = T \times H \times L \quad (5)$$

where,  $C$  is the total engineering cost,  $c$  is the cost for a cubic meter of material;  $V$  is the curtain volume;  $T$  is the curtain thickness;  $H$  is the curtain depth;  $L$  is the curtain length and it is constant value.

Constraint condition 1:  $Q \leq [Q]$

Constraint condition 2:  $J \leq [J]$

where,  $Q$  is the seepage discharge of dam foundation,  $[Q]$  is the allowable seepage discharge of dam foundation,  $[Q] = 3.5 \times 10^{-3} \text{ m}^3/\text{s}$ ;  $J$  is the hydraulic gradient,  $[J]$  is the allowable hydraulic gradient.

The method of dealing with hydraulic gradient that one of the constraints is to control it within a feasible domain in this paper. The hydraulic gradient of curtain is expressed as follows:

$$J = \frac{h_f}{L} \quad (6)$$

It can be obtained  $h_f=72$  m from equipotential lines. The permeability coefficient of the curtain is  $k = 1.0 \times 10^{-9}$  m/s. Therefore, according to the specification, the allowable hydraulic gradient of the curtain is  $[J] = 20$ .

Design variables:  $T = 2 \sim 6$  m

$$H = (0.3 \sim 0.7) \times h = 31.8 \sim 74.2 \text{ m.}$$

where,  $h$  is the barrage head (water depth in front of dam).

According to the specification, the curtain depth is 31.8~74.2 m. The range of the curtain thickness is 2~6 m using the following formula:

$$T = (\delta / I) \times h \quad (7)$$

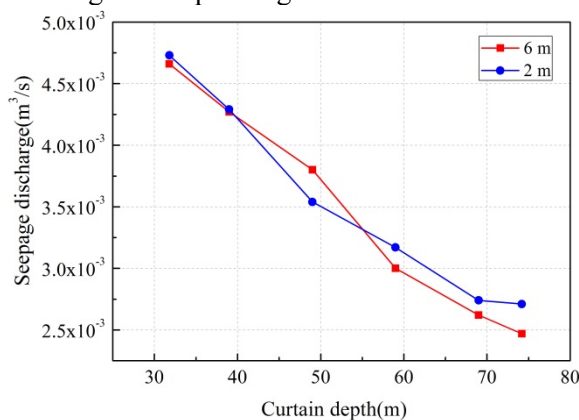
where,  $\delta$  is the head attenuation coefficient through the curtain, and  $I$  is the allowable hydraulic gradient of curtain.

Base on MATLAB program, the seepage discharge is calculated by calling the ADIAN. Call ADINA by calling a batch file. The batch file is as follows:

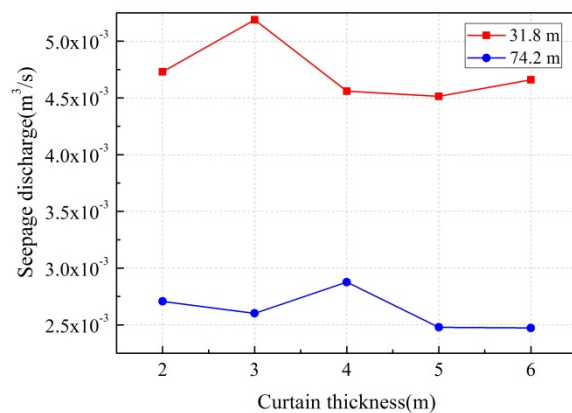
```
@echo off
CD: E:\adina\bin\
aui.exe -b -m 500m *.in
adinat.exe -b -s -m 300m -M 800m -t 8 *.dat
aui -b -m 500m *.plo
```

#### 4. Calculation results

When the curtain thickness are 2m and 6m, the seepage discharge corresponding to the different curtain depth is drawn in Figure 5. When the curtain depth are 31.8 m and 74.2 m, the seepage discharge corresponding to the different curtain thickness is drawn in Figure 6.

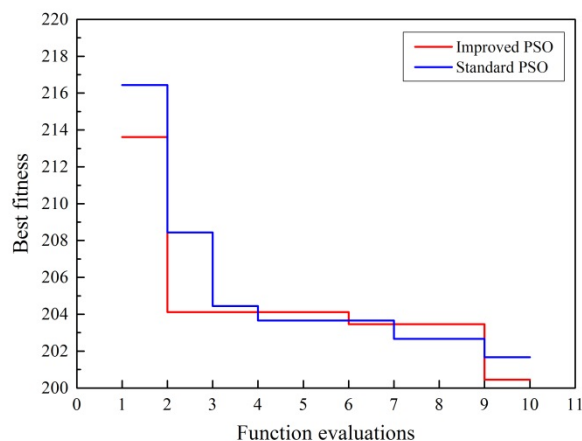


**Figure 4.** Relationship between the seepage discharge of dam foundation and curtain depth

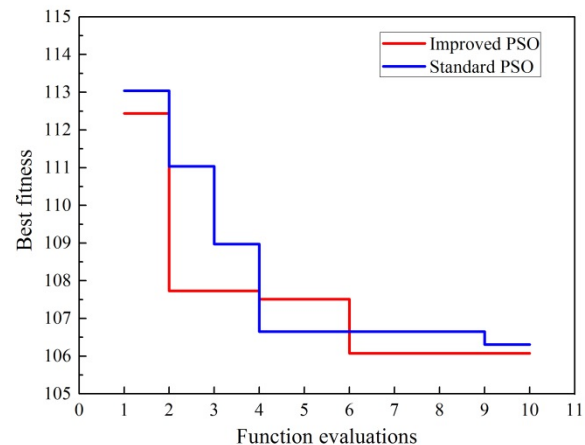


**Figure 5.** Relationship between seepage discharge of dam foundation and curtain thickness

In Figure 4, the maximum and minimum seepage discharge of dam foundation is  $4.73 \times 10^{-3} \text{ m}^3/\text{s}$  and  $2.71 \times 10^{-3} \text{ m}^3/\text{s}$  respectively when the curtain thickness is 2m. The maximum and minimum seepage discharge of the dam foundation is  $4.66 \times 10^{-3} \text{ m}^3/\text{s}$  and  $2.47 \times 10^{-3} \text{ m}^3/\text{s}$  respectively when the curtain thickness is 6m. In Figure 5, the seepage discharge at the depth of 74.2 m is less than 31.8 m, when the curtain thickness is 5 m, the seepage discharge is minimum. The maximum and the minimum seepage discharge of dam foundation are  $4.73 \times 10^{-3} \text{ m}^3/\text{s}$  and  $4.51 \times 10^{-3} \text{ m}^3/\text{s}$  respectively when the curtain depth is 31.8 m. The maximum and the minimum seepage discharge are  $2.88 \times 10^{-3} \text{ m}^3/\text{s}$  and  $2.47 \times 10^{-3} \text{ m}^3/\text{s}$  respectively when the curtain thickness is 6 m. From Figure 4 and Figure 5, we can see that at the same thickness, seepage discharge decreases with the increase of curtain depth, and the influence of curtain thickness on seepage discharge has no obvious regularity.



**Figure 6.** The relation between the objective function and iterations



**Figure 7.** The relation between the objective function and iterations

In Figure 6, when only constraint 1 is considered, the fitness value used improved PSO algorithm is 200.46, and the standard PSO algorithm is 201.99. When considering constraint condition 1 and 2 simultaneously, as is shown in Figure 7, the fitness value used improved PSO algorithm is 106.07, and the standard PSO algorithm is 106.30. The objective function is minimum when the number of iterations reaches the given value, and it can be considered that the curtain structure not only satisfies the constraint conditions and relatively has a low project cost.

## 5. Conclusions

When the curtain thickness is constant, the seepage discharge decreases with the increase of curtain depth. When the curtain depth is constant, the influence of curtain thickness on seepage discharge has no obvious regularity. The reason may be that the groundwater flows along the bottom of the curtain when the curtain reaches a certain thickness.

In this study, firstly, the seepage discharge is considered as the constraint condition to calculate. Secondly, add another constraint condition, that is the hydraulic gradient of curtain, then the optimal parameters of the curtain (curtain thickness and depth) are calculated respectively by the standard PSO and improved PSO. The finite element software makes the whole process automatic, which reduced the workload. It is necessary to choose the optimal curtain structure because the seepage discharge, engineering cost and schedule have been influenced by the structural design of impervious curtain. Therefore, it is useful to utilize the method to provide guidance for similar engineering.

## Acknowledgements

This study was financially supported by National Natural Science Foundation of China (Nos.51722907, 51679197 and 51579207).

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