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Optimization of Clay Core Dimensions in Earth Fill Dams Using Particle Swarm Algorithm

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ORIGINAL ARTICLE

ABSTRACT: The flow rate from earth fill dam body mainly depends on the dimensions and characteristics of the clay core. Thus, finding the optimized dimensions for clay core in non-homogeneous earth fill dam is essential. In order to decrease water loss, the clay core should be expanded this leads to dramatic increment in construction volume and costs. The novelty of this issue could be expressed as an optimization material in which the total cost of lost water and earthwork should be minimized. The method serves us a simpler and an accurate solution for an earth fill dam to be in optimised dimensions. The objective function is consisting of two parts. The first part is to calculate the water seepage volume through the dam core with a combination of finite element method and artificial neural network (ANN) and the second part encounters the costs regarding to the volume of earth works. Finally the best answer from the economical view will be chosen according to the amount of seepage and core volume. Since calculating water seepage through soil using finite element method is time consuming, first a combination of 600 different potential shapes of the core has been modelled by finite element and then the result have been used to train an artificial neural network. Comparing this model with linear and logarithmic regression models proved that ANN evaluates water flow rate with more precession. Output data, including flow rate, entered to the particle swarm optimization (PSO) algorithm and the optimized dimensions were achieved. The proposed model for optimizing the clay core dimension can be applied for non-homogeneous earth fill dams with impervious foundation. Allavian earth fill dam was chosen to show the benefit of using the proposed optimization method in a real world case study. The results indicated that the construction cost could be dramatically less than what has been already spent on the case study.

Key words: Optimization, Clay core, Artificial neural network, Particle swarm optimization.

INTRODUCTION

Earth fill dams are one of the ordinary ways to store water in large amounts. Small amount of seepage is inevitable in these types of dams. On the other hand water cost is growing day after day and it put more stress on designing dams with more impermeable cores which costs more. Therefore, studying the related seepage flow rate and the controlling devices is very important to decrease the overall costs. Finding an optimized dimension for the clay core of an earth fill dam has been the subject of several researches recently. Economical considerations are the main factors in the selecting of geometrical dimensions of clay core. As Creager et al (1963) mentioned, the cheapest dimension which can cause stable situation would be the best. To find a good design of dimensions for a clay core multi objective function should be applied and proper constraints lead to reasonable answers, Creager et al (1963). Classic optimization methods for such problems cannot be applied, because the numbers of variables are too many, the relation between them and the objective function is nonlinear and implicit. In these cases, scientists suggest to use new techniques of optimization like heuristic algorithms. In heuristic algorithms many variables can be optimized at the same time. In recent years, PSO algorithm has been used in many structural and hydraulic problems. The first study to optimize clay core dimensions in non-homogeneous earth fill dams was done by Rasskazov et al (1992). Abdul Hossein et al (2007) used multi objective functions with weighting method. In their research, objective function includes: dam section, wetted area, and flow rate and drainage section. Kazim et al (2003) studied the effects of permeability on the flow pattern in an earth fill dam. They used SEEP/W software to understand the water flow pattern in homogenous and non-homogenous earth fill dams. By concentrating on the variables it was shown that the upstream part of a dam mostly controls the flow rate which is catching the downstream part.

This paper proposes a model to evaluate and find the optimized dimensions for a clay core by using particle swarm optimization algorithm (PSO). The clay core has variable slopes and the best slope for minimizing the total cost has been determined.

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MATERIALS AND METHODS

Particle Swarm Optimization Algorithm

Particle swarm optimization algorithm was firstly designed by Eberhart and Kennedy (1995) and was based on social behaviour of birds or fishes. This algorithm is very similar to genetic algorithm (GA) in its main process. In comparison PSO is simpler than GA in understanding and also has less parameter. Swarm can be defined as a group which corporate together in an organization. Particles move in the search space. The results of this social behaviour lead the particles to move towards the answers in every moment. Arora (1989) declared that, each particle adjusts its position and velocity in order to reach its best position or the global best of the search space. If the search space is D-dimensional, each dimension of the space shows one of the variables of the clay core. The optimization problem has six dimensions which can be defined in equation (1).

$$D_i = \{D_1, D_2, D_3, D_4, D_5, D_6\} \tag{1}$$

The position of a particle can be shown like equation (2).

$$X_i = \left\{ Z_{i1}, Z_{i2}, Z_{i3}, Z_{i4}, \frac{B_{1i}}{H_i}, \frac{K_i}{K_{i1}} \right\} \tag{2}$$

The best position of a particle can be determined with equation (3).

$$P_{ibest} = \left\{ Z_{m1}, Z_{m2}, Z_{m3}, Z_{m4}, \frac{B_{mi}}{H_m}, \frac{K_m}{K_{m1}} \right\} \tag{3}$$

Particle's velocity is shown by equation (4).

$$V_i = \left\{ V_{Z_{i1}}, V_{Z_{i2}}, V_{Z_{i3}}, V_{Z_{i4}}, \frac{V_{B_{i1}}}{V_{H_i}}, \frac{V_{K_i}}{V_{K_{i1}}} \right\} \tag{4}$$

In these equations Z_1 and Z_2 are up slope and down slope of upstream section of clay core, respectively, Z_3 and Z_4 are up slope and down slope of upstream section. B_1/H is the non-dimensional parameter of clay core width in the top respect to height of water in the reservoir, and K/K_1 is the ratio of hydraulic conductivity of core and shell materials. All parameters are shown in figure 1.

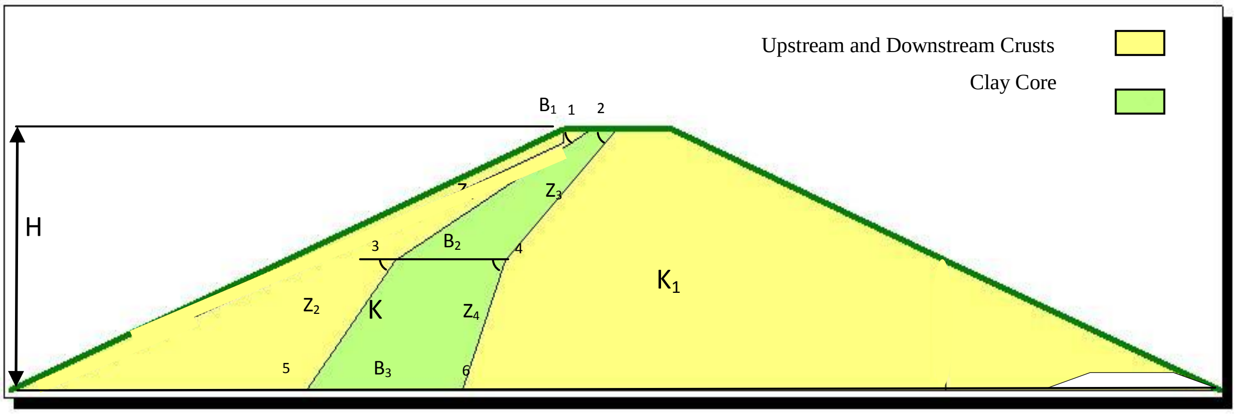

Figure 1. Variable parameters for clay core

Dependent parameters of the PSO algorithm are defined as: perceptual learning rate, $C_1 = 2$. Global learning rate, $C_2 = 2$. Weighting parameter, $w = 0.65$. W is limited to 0.4-0.9 and can be defined by equation (5).

$$w = w_{\max} - \frac{(w_{\max} - w_{\min}) \times n}{iTer_{\max}} \tag{5}$$

In which, W is weighted inertia, w_{max} initial value of weighted inertia, w_{min} final value of weighted inertia, n is the current iteration number and $iTer_{max}$ is the maximum number of iteration. The velocity and the position of a particle have been shown in equations (6) and (7). The PSO diagram is illustrated in figure (2).

$$\begin{aligned} V_{i,d}(t+1) &= T.V_{i,d}(t) + \mathrm{C}_1.rand(\ ) \\ &\times \left[Pbest_{i,d}(\mathrm{t}) - x_{i,d}(t) \right] + \mathrm{C}_2.rand(\ ) \\ &\times \left[gbest_{i,d}(t) - x_{i,d}(t) \right] \end{aligned} \tag{6}$$

$$X_{i,d}(t+1) = x_{i,d}(t) + V_{i,d}(t+1) \tag{7}$$

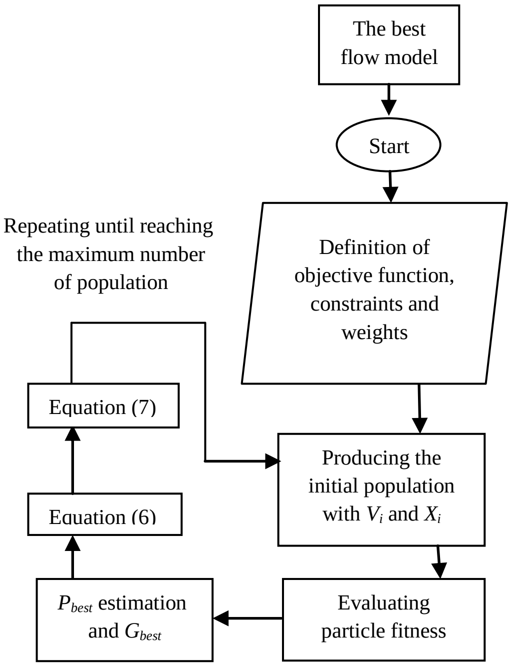

Figure 2. PSO algorithm

Flow model

To find the best model, three models were proposed: linear regression model, logarithmic regression model and an artificial neural network. The procedure is shown in figure (3).

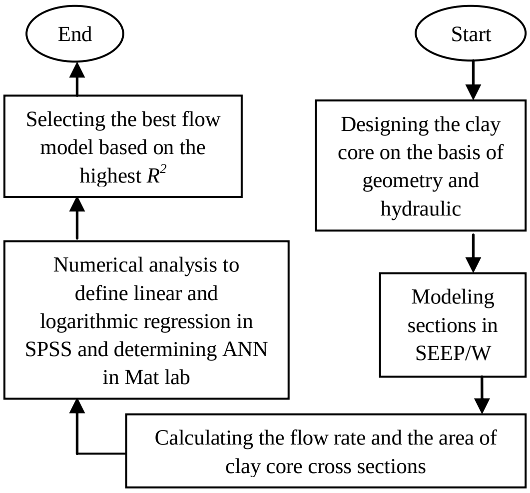

Figure 3. Determining the flow model

Input and output model parameters

Input data include those parameters which affect flow rate directly. These parameters are Z_1, Z_2, Z_3, Z_4 as the slopes of clay core, B_1/H shows the clay core width and the K/K_1 defines the hydraulic conductivity. Output data is only the non-dimensional parameter for flow rate which can be shown as q/KH. For each flow model output and input data were defined and the value of R^2 related to each one was evaluated. For linear and logarithmic model, SPSS software has been used. In figure (4) the artificial neural network flow model is shown. Non-dimensional input and output data are defined in equation (8).

$$y = f\left(\frac{q}{KH}, \frac{\mathrm{K}}{\mathrm{K}_1}, \frac{B_1}{H}, Z_1, Z_2, Z_3, Z_4\right) \qquad (8)$$

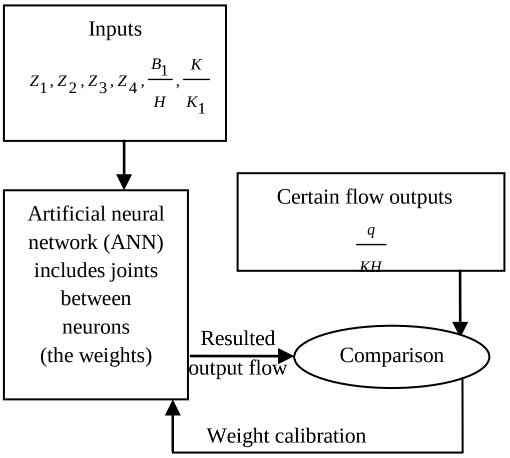

Figure 4. ANN procedure for finding the best flow rate network

Optimization of clay core dimensions

Objective function: Objective function could be defined as in equation 9. The goal is to minimize the total cost (equation (9)).

$$\begin{aligned} F &= F_1 + F_2 \\ F_1 &= LeakageCost \\ F_2 &= CapitalCost \end{aligned} \qquad (9)$$

In which, F_1, the waste water cost, is calculated for a period of fifty years as the useful lifetime of the dam. F_2 is the construction cost.

Constraints: According to previous researches, to minimize the objective function on the basis of designing vector, constraints were used as equation (10).

$$G = f(G_1, G_2, G_3, G_4, G_5, G_6) \qquad (10)$$

Hydraulic conductivity with clay core material considerations was determined as table (1).

Table 1. Hydraulic conductivity of different materials. Bear (1972).

Material	K(cm/s)
Pervious	10^{-1}-10^{2}
Semi-pervious	10^{-2}-10^{-5}
Impervious	10^{-6}-10^{-9}

Brassington (1988) considered the hydraulic conductivity for grading between 0.0005-0.002 mm 10^{-5}-10^{-2} m/day or 10^{-11}-10^{-5} cm/s. As a result for hydraulic conductivity constraints the 10^{-10}-10^{-5} was used. For dam main body material which is pervious the hydraulic conductivity assumed to be 10^{-2} cm/s as a constant parameter (equation 11).

$$G_1 \rightarrow 10^{-8} \leq \frac{K}{K_1} \leq 10^{-3} \qquad (11)$$

With practical considerations, in order to have better transportation of materials and proper movement of vehicles during the clay core compaction phase, the minimum clay core width is considered as 3m and the maximum is equal to 6-12m, ICOLD, 1986. Therefore in this research the limitation for the width of clay core in the top is defined between 4.5-9m (equation 12).

$$G_2 \rightarrow 0.112 \leq \frac{B_1}{H} \leq 0.225 \qquad (12)$$

Based on ICOLD (1986), in most earth fill dams, the average of upstream slope of the dam main body is 1V: 2.5H and for the downstream it would be approximately 1V: 2H. So, in this research for each of the core slopes, a boundary was considered in order not to exceed from downstream and upstream slopes in the main body and also not to be so close to them. These four slopes were somehow arranged that they won't cross over each other and a certain distance is always kept between them. As the result of above explanation we have (13) relations.

$$\begin{aligned} G_3 &\rightarrow 26 \leq Z_1 \leq 140 \\ G_4 &\rightarrow 15 \leq Z_1 \leq 164 \\ G_5 &\rightarrow 40 \leq Z_1 \leq 153 \\ G_6 &\rightarrow 16 \leq Z_1 \leq 165 \end{aligned} \qquad (13)$$

The cost of lost water: For each year of fifty years period for the project life span, the cost of wasted water was calculated by applying inflation and interest rates which has been in equation (14).

$$V = \left(C_1 \times Q\left({}^{m^3}\!\!\diagup_{year} \right) \right) \times (1+t)^n \qquad (14)$$

In which, V is the cost of agriculture water per m^3 in the nth year. C_1 is the cost of agriculture water per m^3 in the present year. T is the inflation rate and n is the number of the year. Present value of the costs in fifty years can be calculated with equation (15).

$$PV = \frac{V}{(1+i)^n} \qquad (15)$$

i is the interest rate. The cost of waste water for fifty years in every project would be the total amount of present values (equation 16).

$$LeakageCost = \sum_{i=0}^{n} PV_i \qquad (16)$$

Construction cost: The cost of construction operations per m^3 of clay core can be determined by the price list in every region. Some factors such as preparing the human power and machinery and tools, gathering materials and equipments can strongly affect the cost of constructions.

Case study: With the aim of studying the effects of optimized dimensions on the costs, the present optimization model put into application for Allavian earth fill dam. It has a vertical clay core, locating on the distance of 3.5 km from Maraghe city in the state of Azarbaijan Sharghi and is constructed on the Sofichay River. The purpose of this dam is to collect and control the surface run off from Sofichay River and also to compensate lack of irrigation water. In 1990, studied and designed steps by Mahab Gods consultant engineering. Geometry properties of Allavian dam has been illustrated in table (2). The hydraulic conductivity of clay core materials is 2.75×10^{-6} cm/s and 10^{-2} cm/s for the body.

Table 2. Geometry properties of Allavian dam

Top width	22.8m
Dam height	58m
Core top width	16.8m
Core bed width	40m
Upstream slope of the body	1 : 2.5
Downstream slope of the body	1 : 2
Core slopes	5 : 1
Water height	52m

In SEEP/W software 160 different sections were used to estimate the flow rate. Linear and logarithmic and also artificial neural network models were trained. The best flow model was put into the optimization model and the optimized dimensions were resulted.

DISSCUSION AND RESULTS

For a sample dam the input and output flow data from 900 different cross sections were extracted. The linear regression flow model has been shown in equation (17) with $R^2 = 0.659$.

$$\begin{aligned} \frac{q}{KH} &= 3.356\times10^{-5} Z_1 + 1.757\times10^{-5} Z_2 \\ &- 1.293\times10^{-4} Z_3 - 1.342\times10^{-4} Z_4 \qquad (17) \\ &- 7.033\times10^{-8}\left(\frac{B_1}{H}\right) + 39.782\left(\frac{K}{K_1}\right) \end{aligned}$$

Logarithmic regression model with R^2 = 0.935 is shown in equation (18).

$$\begin{aligned} ln\left(\frac{q}{KH}\right) &= 0.177\,ln(Z_1) + 0.122ln(Z_2) \\ &- 1.196\,ln(Z_3) - 0.884\,ln(Z_4) \qquad (18) \\ &- 0.052\,ln\left(\frac{B_1}{H}\right) + 0.565ln\left(\frac{K}{K_1}\right) \end{aligned}$$

Various networks for the artificial neural network model have been shown in table (3).

Table 3. Different networks for ANN

No.	No. of hidden layers	R^2	RMSE
1	5	0.837	0.247
2	6	0.884	0.542
3	7	0921	0.491
4	8	0.908	0.629
5	9	0.912	0.495
6	10	0.957	0.736
7	11	0.974	0.433
8	12	0.983	0.402
9	13	0.962	0.693
10	14	0.910	0.741

As it shown in table 3 Artificial Neural Network (ANN) produces the best results thus the ANN model was chosen as the best model to be utilized in the PSO algorithm. The flow rate of 581 clay core sections which has been extracted from ANN compared with the value of flow rate from the SEEP/W software. The linear regression between the flow rate in SEEP/W and ANN was computed and the correlation coefficient $R^2 = 0.975$ resulted. Studies showed the high accuracy between them and finally the ANN model was selected to estimate seepage (figure (5)).

Sensitivity Analysis

The population size in each generation made a significant change in the value of objective function which the curve of it is illustrated in figure 6.

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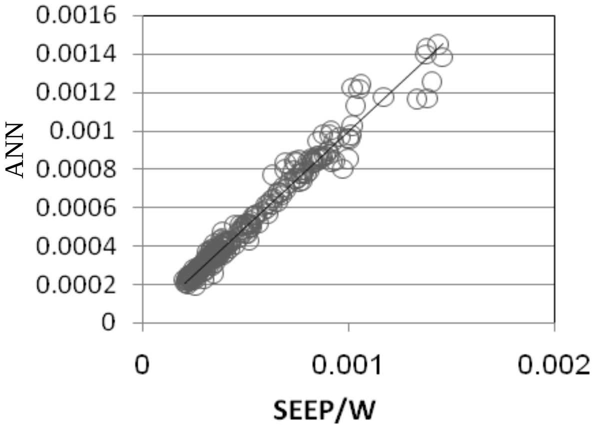

Figure 5. Comparison of flow rate in SEEP/W and ANN

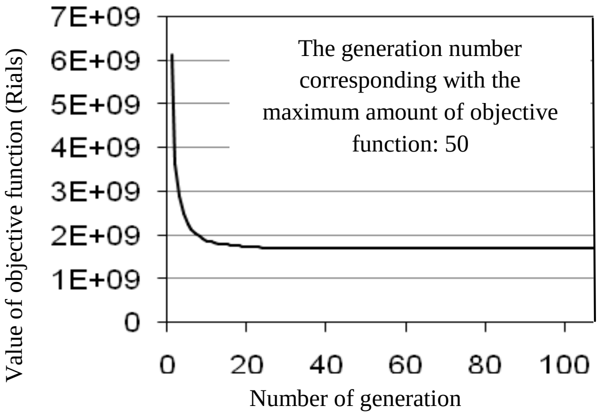

Figure 6. Changes in the value of objective function in consecutive generations with the interest rate of 12 %

This curve shows that the optimization function with the 50 number of generation has received the best answer.

To study the effects of each optimization variables on the value of objective function, the sensitivity analysis was done while other variables were supposed to be constant. In figure (7) to (12) the results of sensitivity analysis has been demonstrated.

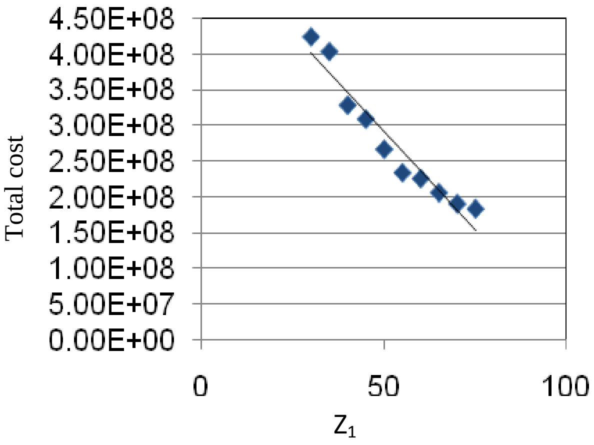

Figure 7. Changes in objective function with Z_1

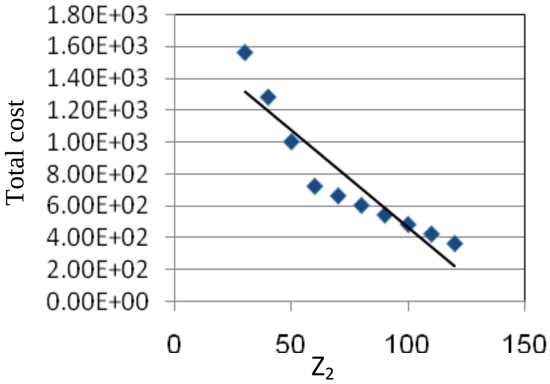

Figure 8. Changes in objective function with Z_2

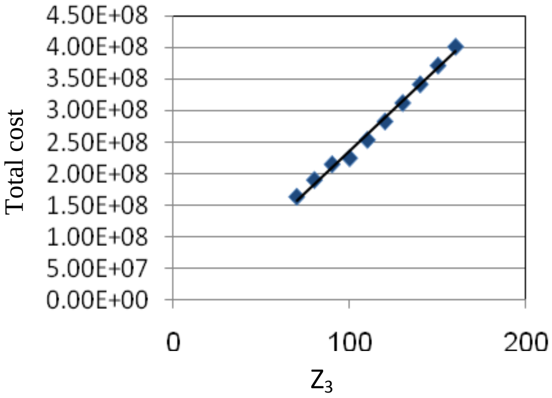

Figure 9. Changes in objective function with Z_3

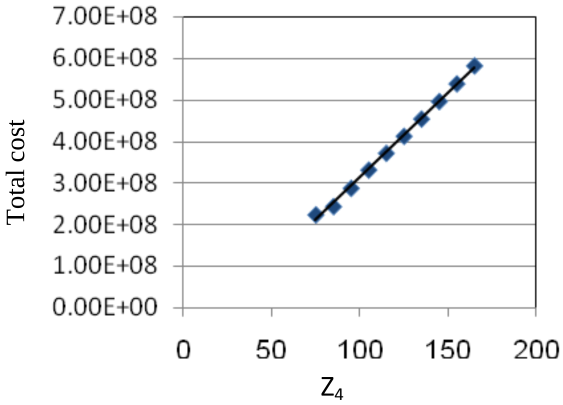

Figure 10. Changes in objective function with Z_4

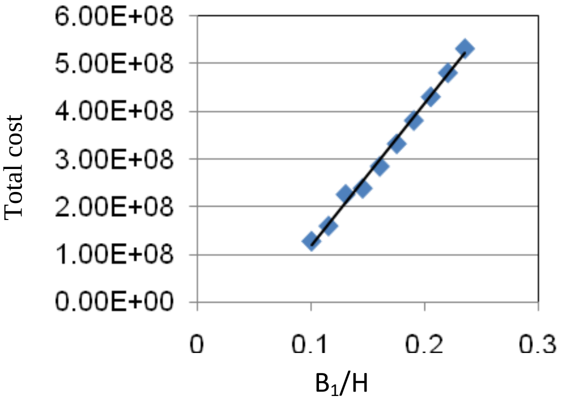

Figure 11. Changes in objective function with B_1/H

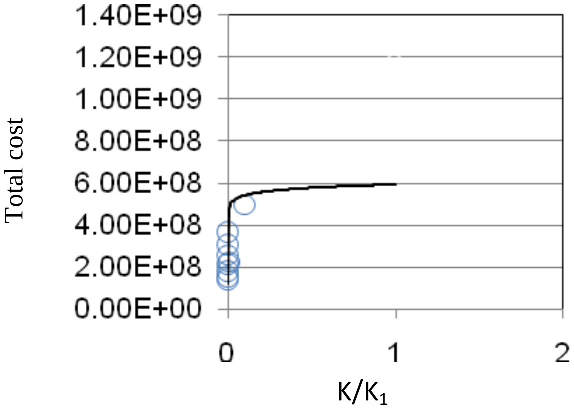

Figure 12. Changes in objective function with K/K_1

When the Z_1 angel increased, the width of clay core and the constructive cost decreased, but the amount of seepage increased. The objective function was also decreasing. The changes of Z_2 were the same as Z_1. For angles Z_3 and Z_4, when they increase, the seepage decreased but the objective function was increasing.

The top width of the clay core increases reduced the amount of seepage but the objective function was adverse. When the hydraulic conductivity increased, the total waste water was bigger and the objective function was also increasing.

Sample Test Results

Applying the present program, the optimized dimensions for the sample earth fill dam has been computed. Dam height is 40m with top width 19m, upstream water height 37m, length of horizontal filter 30m, hydraulic conductivity of the body 10^{-2} cm/s and the interest rate was 12 %. The results are proposed in table 4.

Table 4. Sample earth fill dam optimized variables

Interest rate	12 %
Z_1	73.13
Z_2	76.92
Z_3	90
Z_4	69.06
B_1/H	0.149
K/K_1	9.335×10^{-4}
q/KH	6.334×10^{-4}
Total Cost (Rial)	1706374290.994

Case Study Results

The optimization model estimates the total cost of optimized clay core of Allavian dam and the comparison between the optimized costs with current costs is accessible then. Table (5) shows the current costs and table (6) is the optimized results.

Table 5. Current costs for Allavian dam

Constructive costs (Rial)	42662480
Waste water cost (Rial)	3769384878.08
Total cost (Rial)	3812047358.08

Table 6. Results of optimization for Allavian dam

Z_1	Z_2	Z_3	Z_4	B_1/H	B_1	q/KH	Q
96.4	159	152	153.5	0.259	15.03	1.325	2.113×10^{-4}

As it can be seen in table (7), the cross section area of the optimized dimensions is bigger than the real cross section, therefore the construction costs is higher. The total waste water is reduced so that the cost of it is smaller and as the result the total cost has been reduced.

Table 7. Optimized costs for Allavian dam

Constructive costs (Rial)	56825092.1
Waste water cost (Rial)	3630885415.47
Total cost (Rial)	3687710507.57

Comparing the results of optimized costs with current costs of Allavian earth fill dam clay core, it can be seen easily that the optimized cost has a reduction of 124336851 Rials, which is about 4 percent of reduction. So, the proposed model seemed to be very useful to reduce the costs and can be suggested to utilize in earth fill clay core design with impervious bed.

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