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Using Simulated Annealing (SA), Evolutionary Algorithm To Determine Optimal Dimensions of Clay Core in Earth Dams

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ABSTRACT

Earth dam is a structure as homogeneous or non-homogeneous forms for raising water level or water supply. Earth dam consist of different parts that one of the main parts is clay core. Choosing an optimal non permeable core which causes reduction of seepage through dam body and also being stable is necessary. The objective of this research is to optimize the geometry of earth dam clay core such that, beside of reduction of seepage through dam body, the volume of core material is minimized. For access of this objective a consolidated model consist of a simple model which obtained by linear regression and SA algorithm were used, to optimize the Birjand Hesar Sangi dam. Optimal parameters such as seepage through dam body, hydraulic gradient and safety factor of stability access from model compared by the values access from the direct run of the software modeling that show a good agreement. Also the result of access by modeling have been compared by actual dimensions of Birjand Hesar Sangi dam, that cause reduction of material volume for construction core dam and shell dam about 21 and 8 percent, respectively. Result show that the consolidated model has successful operations and a general optimal plan design of clay core dimensions in stable condition can be achieved.

Key words: Simulated Annealing Algorithm (SA), optimization, earth dam, seepage, clay core.

INTRODUCTION

A dam is an artificial barrier usually constructed across a stream channel to capture water. Dams must have spillway systems to convey normal stream and flood flows over, around, or through the dam. Spillways are commonly constructed of non erosive materials such as concrete. Dams should also have a drain or other water withdrawal facility for control the water level and to lower or drain the lake for normal maintenance and emergency purposes. Dams are constructed especially for water supply, flood control, irrigation, energy production, recreation, and fishing. Dams are mainly divided into four parts on the basis of their structure types. These are gravity dams, buttress dams, arch dams, and embankment dams. Embankment dams are more preferable due to being more economical. Embankment dams are two types- Earth fill dams and rock fill dams (Ersayin, 2006). In designing of an earth or rock fill dam, the foundation, abutments, and

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embankment should be considered as a unit. The entire assemblage must retain the reservoir safely without excessive leakage. Provisions for seepage control have two independent functions. The first is reduction of water losses loss water reduction to an amount compatible with the project purpose. Another independent function is that, eliminating the possibility of structure failure by piping. It may also be concerned with the stability of construction slopes and slopes around the reservoir after impoundment. One of the most important components in dam designing is the dam core. The dam core is significant factor in caulking and controlling dam body seepage. In unconsolidated terrain, when leakage velocities reach critical values, erosion takes place giving rise to sub fusion and subsidence leading to the dam collapse (Oglivy et al., 1969; James, 1968). Also, it establishes the importance of mapping the seepage paths and monitoring the changes in seepage as a function of time. In case of dam designing, the core should be made of fine materials due to its low permeability. Furthermore, dam core has relatively lower shear strength compared to the other parts. So considering the dam persistence, it is better to choose the core thinner on the other hand the thicker the core the more resistant the dam is. The seepage process will be reduced because the seepage and inner corrosion and the cracking risk. (Singh and Varshney, 1995). From the previous investigations, it is established that the economic considerations can be determined as one of the most significant factors in selection of the dam core geometry. Several studies of dam seepage were carried out with different conditions of field and laboratory. Occasionally, using of experimental and field investigations cause too much cost of equipment's to measure data sets, compared to the numerical and mathematical methods. Mathematic solutions take times and these methods can be produced inaccurate performances. Recently, various numerical methods have been used widely to identify different aspects of dam problems. Goldin and Raskaz (1985) initiated optimization studies for the clay core of the homogeneous dam using complete factor test and factor analysis. They utilized factor analysis method to optimize the design of the dam in charge of choosing various sources of bond and shell slopes. For optimum design of a 70 meters dam, four alternative options were presented for different sources of bond and side slopes of dam. They also applied the full operating method for a high dam (300 meters) to choose the effects of the stability factor. Results indicated that the shell sides embankment plasticity is more than the core itself. Also, and it imposes a thin and straight core. On the other hand, if the shell sides embankments are much less plastic than the clay dam core, an inclined core will be more justifiable (Goldin and Rasskazove, 1992). Pavlovsky (1956) developed an approximate method which allowed the piecing together of flow net fragments to develop a flow net for the total seepage problem. This method termed the "Method of Fragments" that, allows seepage problems with relatively higher complication to be resolved by breaking them into parts, analyzing flow patterns for each, and reassembling the parts to provide an overall solution. Harr (1962) explained the use of transformations and mapping to transfer the geometry of a seepage problem from one complex plane to another. Hadi (1978) studied the seepage through embankments into adjacent drains. In his investigation, the soil has been assumed to be homogeneous and isotropic. Also, the water flow was steady state condition. Flow nets for the different flow patterns were drawn using the circle method, for predicting the seepage discharges. Ishaq (1989) used a finite difference coordinate transformation to get pressure distribution under hydraulic structure and exit gradient with and without sheet pile in upstream or downstream only, resting on anisotropic porous media. Hillo (1993) used finite element method for seepage below hydraulic structures on anisotropic soil foundation. The structural appearance of the dam was examined by Hitashy (1996) using genetic algorithm. In their study, decision and construction supporting systems were developed to design the dam appearance. Aubertin et al. (1996) used commercial code/software to solve the unsaturated problems of multi-layer covers for an infinite aquifer pumping test. This software solves the underground water problems for stable, unstable, saturated and unsaturated conditions. Griffiths and Fenton (1997) combined random field generation and finite-element techniques to model steady seepage through a three-dimensional (3D) soil domain in which the permeability was randomly distributed in space Furthermore, Khsaf (1998) used finite element method to analyse seepage flow through pervious soil foundation underneath hydraulic structures that provided with flow control devices. it can be eliminated. Irzooki (1998) applied different technical study of seepage problems on the left side of Al-Qadisiya dam. Boger (1998) solved three-dimensional flux equations in transient condition by neglecting capillary forces. the capillary force in steady sate condition was considered as significant parameter through seepage problem. Akyuz and Merdun (2003) carried out experiments for predicting the seepage from an earth dam placed on an impervious base by using the Hele-Shaw viscous fluid. They validated their results with several traditional equations.. Benmebarek et al. (2005) used the finite difference method to numerical studies of seepage failure of sand soil within a cofferdam. Based on this study, the conditions for seepage failure are clearly identified by using the boiling. Abdul Hussein et.al (2007) used multi-objective functions by weighting method to optimize the designing of the homogeneous earth dam. Andrew and Anop (2009) applied genetic algorithm to determine the critical failure level in slope stability analysis. Furthermore, Nazari Giglou and Zeraatparvar (2012) presented the physical and geometric factors of earth dam such as permeability, upstream and downstream slope of the dam to solve seepage problem. The seepage rate through homogeneous earth includes saturated and unsaturated flow. The amount of water seeping through and under an earth dam, can be estimated by using the theory of flow through porous media. This theory is one of the most common analytical tools that is used widely by engineers. The computed amount of seepage is useful in estimating the loss of water from the reservoir. The estimated distribution of pressure in the pore water is used primarily in the analysis of stability against shear failure that is used widely by engineers study the hydraulic gradient at the point of seepage discharge which gives a rough idea of the piping potential (Sherard et al., 1963). Different aspects of seepage phenomena have been investigated because seepage through the dam body and under the foundation adversely affects dam stability. This study specifically investigated seepage in dam body. The seepage in the dam body follows a phreatic line. In order to understand the degree of seepage, it is necessary to measure it. In this study, a numerical model is developed to analyze the seepage problem. The core thickness depends on the seepage, the anticipated resistance to cracking and erosion of the available materials. In all but the more pervious core materials, a relatively thin core will suffice to keep the seepage to a negligible amount. A thin core will dissipate pore pressures more rapidly than a thick one . Also, it is safer during sudden drawdown. A thick core is more resistant to erosion, particularly if small cracks should develop from settlement. Also the core volume reduction as an impermeable part helps to economize plan. determination of the appropriate core size which has a minimum size is necessary in order to supply the demands and constraints. In this way, powerful optimized methods including the SA algorithm based multi-objective function and specified constraints are proposed to find out the size of the clay core dam.

METHODOLOGY

One of the key aims of this study is to develop the numerical model for measuring seepage through dam, stability factor and hydraulic gradient based on materials and geometry specification of earth dams. Figure1 shows the sample model of problem.

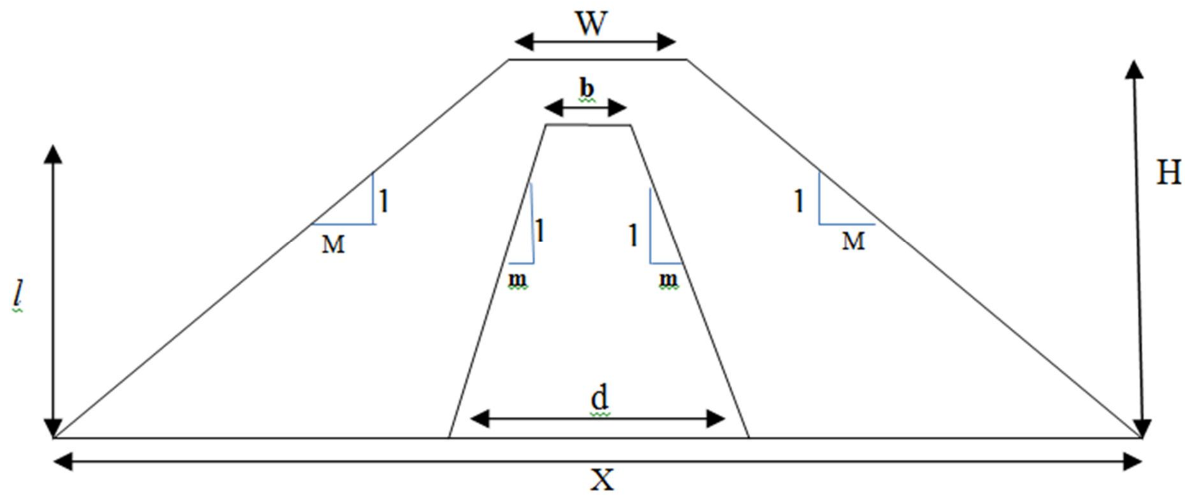

Figure1. Sample model of problem

Theoretical principles of Simulated Annealing Algorithm

In annealing, a material (i.e. metal) is heated until its molecules acquire sufficient mobility (a melted state). Then, by decreasing the temperature slowly, the molecules undergo various configuration changes, always seeking for a lower energy state. If the decrease is sufficiently slow, a perfect crystalline solid will form, and the system will be at its minimum energy state. If the temperature is decreased fast, as in quenching, the molecules will collapse into an amorphous solid and have poor physical properties (its energy state will be at a "local minimum"). Simulated annealing has several potential advantages over conventional algorithms. First, it can escape from local maxima. In thermodynamic terms, while conventional algorithms quench by simply heading up the current hill without regard to others, simulated annealing moves both uphill and downhill. Also, the function need not be approximately quadratic. In fact, it need not even be differentiable (Corana et al. (1987) successfully demonstrate simulated annealing on a parabolic function punctured with holes]. Another benefit is that the step length gives the researcher valuable information about the function. If an element of V is very large, the function is very flat in that parameter. Since it is determined by function evaluations at many points, it is a better overall measure of flatness than a gradient evaluation at a single point. Finally, simulated annealing can identify corner solutions because it can "snuggle" up to a corner for functions that don't exist in some region. The most important advantage of simulated annealing is that it can maximize functions that are difficult or impossible to otherwise optimize. This is demonstrated in the next section with the test problems.

Simulated annealing

Simulated annealing is a computational stochastic technique for obtaining near global optimum solutions to combinatorial and function optimization problems. The method is inspired from the thermodynamic process of cooling (annealing) of molten metals to attain the lowest free energy state Kirkpatrick et al. (1983) but this idea was first inspired by Metropolis et al., in 1953 who involved in publishing industry. When molten metal is cooled slowly enough it tends to solidify in a structure of minimum energy. This annealing process is mimicked by a search strategy. The key principle of the method is to allow occasional worsening moves so that these can eventually help locate the neighborhood to the true (global) minimum. The associated mechanism is given by the Boltzmann probability:

$$P = exp\left(-\frac{\Delta E}{TK_B}\right) \quad (1)$$

where $\Delta E$is the change in the energy value from one point to the next, K_B the Boltzmann's constant and T the temperature (control parameter). For the purpose of optimization the energy term .ΔE, refers to the value of the objective function and the temperature, T, is a control parameter that regulates the process of annealing. The consideration of such a probability distribution leads to the generation of a Markov chain of points in the problem domain. The acceptance criterion given by Eq. (1) is popularly referred to as the Metropolis criterion (Metropolis et al., 1953). Another variant of this acceptance criterion (for both improving and deteriorating moves) has been proposed by Galuber (1963) and can be written as:

$$P = \frac{exp\left(-\frac{\Delta E}{T}\right)}{1+ exp\left(-\frac{\Delta E}{T}\right)} \quad (2)$$

In simulated annealing search strategy: at the start any move is accepted. This allows us to explore solution space. Then, gradually the temperature is reduced which means that one becomes more and more selective in accepting new solution. By the end, only the improving moves are accepted in practice. The temperature is systematically lowered using a problem-dependent schedule characterized by a set of decreasing temperatures. Prilot (1996) discussed more about the parameters used in simulated annealing algorithms. Due to its simplicity and versatility, simulated annealing has the distinction of being one of the most widely used techniques for both function and combinatorial optimization problems. The basic structure of the simulated annealing method is illustrated in Figure 2.

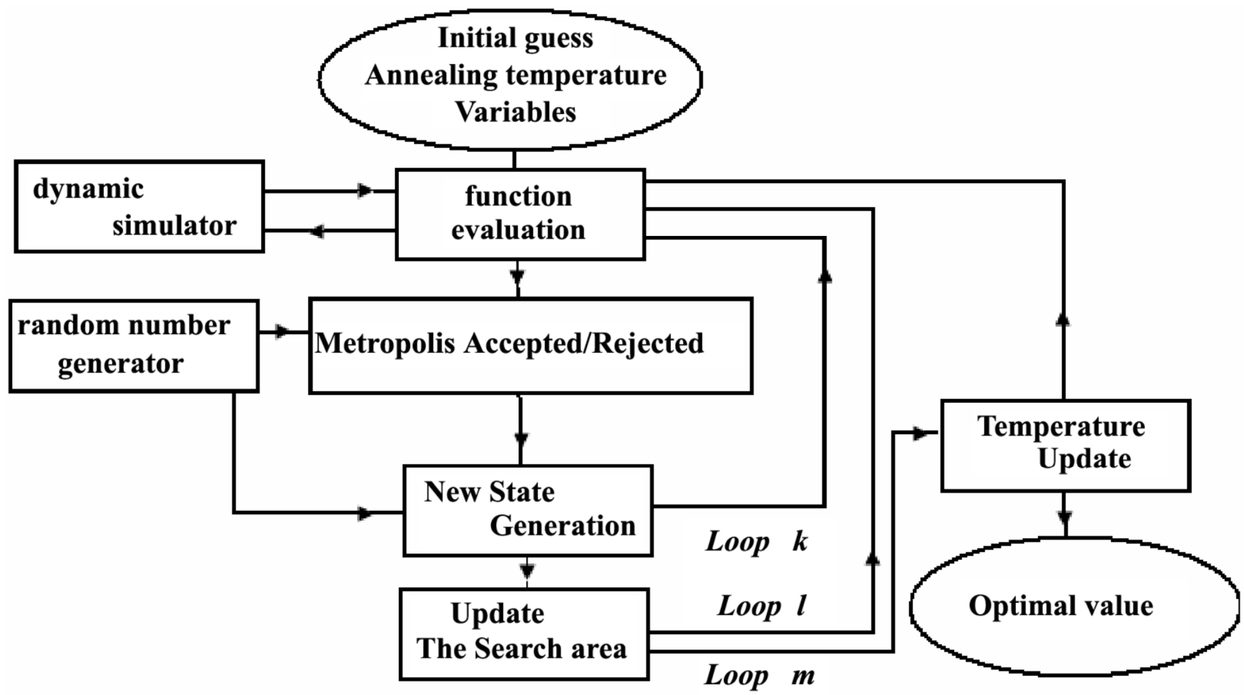

Figure 2. Basic flowchart of simulated annealing (Faber *et al*., 2005).

Modeling

In this study, a new model is proposed to predict seepage rate, slope stability, hydraulic gradient in non-homogeneous earth dams using Geo-Studio software. Thorough this model, seepage, slope stability, and hydraulic gradient are formulated by different factors which are related to material properties and geometric dimensions of dam. It should be noted that permeability in shell for the non-homogeneous earth dams is more than core. Hence, the seepage rate for shell can be ignored because existing remarkable difference between shell and core dam. Therefore, the core can be considered as a homogeneous dam (Goldin et al. 1992). In the research, 150 assumed sections with different materials and dimensions are designed. Ranges of effective parameters for optimization problem are given in Table 1. Performances of FEM-software for assumptive dam models were analyzed using non-linear regression model. Correlation coefficient (r^2) and standard error were considered in order to determine the model validity. For accessing the objective, a consolidated model consisted of a simple model obtained using linear regression and SA algorithms. In addition, evolutionary algorithm were coded using the MATLAB package.

Table 1. Up and down limit of effective parameters

Effective Parameter	Low Bound	Up Bound
Dam Height (meter)	15	40
Crest Width of core (m)	3	6
Up-stream Slope of Shell	1(Vertical):2(Horizontal)	1(V):5(H)
Down Stream Slope of Shell	1(V):2(H)	1(V):4(H)
Up Slope of Core	1(V):0.15(H)	1(V):0.53(H)
Down Slope of Core	1(V):0.15(H)	1(V):0.53(H)

Seepage Model

The model obtained in this research is based on modeling 150 assumed section with different materials and dimensions by SEEP/W. In this model, geometric parameters and materials characteristics are independent variables and seepage rate is dependent variable. Independent variables coefficient is recognized as a partial regression coefficient. It indicates increasing in dependent variables against adding a one unit to independent variables. The final results obtained by running SPSS model that show the best regression model, As it can be easily seen, the amounts of R and Std. Error are about 0.93 and 0.067 respectively. It is clear that there is a high accuracy and appropriate correlation in this model.

$$q = (2.167 - 0.958\frac{d}{h})\times k \times l \qquad (3)$$

Where q = Seepage in unit of dam length (m^3 / s /m); k = Permeability coefficient of core (m/ s); l = Water height in dam reservoir (m); h = Dam height (m); d = Core width on foundation (m).

Slope stability Model

The model obtained in this research is based on modeling 150 assumed section with different materials and dimensions by SLOPE/W. In this model, geometric parameters and materials characteristics are independent variables and seepage rate is dependent variable. The final results obtained by running SPSS model that show the best regression model, As it can be easily seen, the amounts of R and Std. Error are about 0.909 and 0.0098 respectively. It is clear that there is a high accuracy and appropriate correlation in this model.

$$SF=0.354+1.548\tan\varnothing+0.033\frac{d}{x}+2.194\frac{c'}{\gamma h} \qquad (4)$$

Where SF = Slope stability; x = Dam width on foundation (m); $\varnothing$ = Angel of internal friction; c' = Effective cohesion (kg/cm^2); γ = Specific weight (kg/m^3).

Hydraulic Gradient Model

The model obtained in this research is based on modeling 150 assumed section with different materials and dimensions by SEEP/W. In this model, With pay attention to this note in Non homogeneous earth dams that permeability in shell is more than core. When this difference become very much, shall is ignored to calculate the seepage rate and core is assumed as a homogeneous dam, Goldin et al (1992) and also assume that seepage line is as a direct line. The final results obtained by running SPSS model that show the best regression model, As it can be easily seen, the amounts of R and Std. Error are about 0.92 and 0.0098 respectively. It is clear that there is a high accuracy and appropriate correlation in this model.

$$i = 0.76 - 1.625\,\frac{l}{s} \qquad (5)$$

$$s = \left(l^2 + (d * l - 0.35(d - b).\,l)^2\right)^{0.5} \qquad (6)$$

Where i = hydraulic gradient; s = leak line length (m); b = crest width of core (m).

Optimization

In order to reduce the volume of the clay core dam to a minimum size and to prevent leaking from the dam’s body, considering mentioned constraints, its model is established in MATLAB (version 7.8) that uses SA algorithms to optimize. During performing this operation, problem constrains the stability safety factor and hydraulic gradient were investigated.

Variables design

Generally in dam’s crosses designing two types of variables are available. First environmental variables which are functions of the location of the plan such as bond sources and material properties which are defined as parametric variable in this study. And the others are geometrical variables which some of them are fixed such as the core axis angle and rest of them are parametric variables such as the height and width of the dam’s crest and the others are integrated as design variables in the objective function. Vector of design variables (decision variables, X: $\{X_1, X_2, X_3\}$) include X_1 (core crown width), X_2 (Core width on foundation), X_3 (Dam width on foundation). The parametric variables include h (total height of the dam), l (water level upstream of the dam), and w (width of the dam crest).

Objective Function

Water flow through the dam is one of the basic problems for geotechnical engineers. In this paper presents simple expressions to predict the total (saturated and unsaturated) seepage flow rate through a homogeneous embankment and discusses precautions to be taken. The physical and geometric factors of dam such as permeability, upstream and downstream slope of the dam slop (amplitude) are considered, and Cost estimation are developed based on the best available information at the time, the cost estimating based on mentioned information should be considered remarkably in terms of high accuracy and confidence. The purpose of this study is to reduce seepage through dam and volume of earth dam material. Hence the objective functions expressed as follow:

Volume of materials in unit of dam length

For minimizing the level of core materials and it’s stability in terms of dam geometry we can use below function. Since stability bind is a function of dam body parameters, in addition to optimization of core dimensions suitable slope obtained for dam.

$$F = \frac{1}{2}[(x_3 + w) \times h] - \frac{1}{2}[(x_2 + x_1) \times h] \quad (7)$$

Where F is the volume of the earth material (m^3 / m), h = Dam height (m); w= width of the dam crest (m).

Seepage through dam body

For minimizing of seepage through dam body equation (3) as objective function used in problem and determined as follow

$$q = \left(2.167 - 0.958\frac{x_2}{h}\right) \times k \times l \quad (8)$$

Constrains design

Here for reduction of objective function based on designing variables, constraints presented as follows:

For considering static stability of the dam in the steady seepage conditions, a factor is presented as Stability Safety Factor (SF) that should not be less than 1.5 (U.S Army, 2003). leakage from the dam body caused un stability of dam so, the methods for reduction of seepage through dam body are essential. Therefore, hydraulic gradient (*i*) is presented as constraint that must be less than the critical value (i_{cr}). Here, since the critical hydraulic gradient is calculated for the materials equal to 1. the constraint is defined in front of:

$$i=0.76-1.625\frac{1}{s} \quad (9)$$

Where *s* is the length of the phreatic line that is calculated using Eq. (6).

Case study

The Hesar Sangi dam is a earth dam with vertical clay core as a nutrition –storage in Birjand. It has with storage capacity of two million cubic meters of water that was constructed in 2003. Also, it is located 120 kilometers northern of Birjand and five kilometers up of the Hesar Sangi village (latitude $32^{0}53^{'}$, longitude $59^{0}13^{'}$), across the Dahaneh river. Figure 3. shows the location of this earth dam. Dam material properties and geometries are presented in Table 2 and 3, respectively.

Figure3. Location of Hesar Sangi Dam

Table 2. Dam material properties

Parameters	Shell	Core
$Ø$	40	30
$\gamma(\frac{kg}{m^3})$	2260	2080
$\gamma_w(\frac{kg}{m^3})$	10000	10000
$c'(kg/cm^2)$	0.05	0.3
K(m/year)	182.28	0.06

Table 3.geometries properties

Crest length(*m*)	250
Crest width(*m*)	6
Dam height (*m*)	15
core crest width (*m*)	4
Core width on foundation (*m*)	9.8
Slope of Shell	1:2.5
Slope of Core	1: 0.21
Dam width on foundation (*m*)	75

RESULTS AND DISCUSSION

In this modeling the material properties of Hesar Sangi earth dam and a series of known parameters such as the height and the width of the dam's crest is used. Table (4) presents a comparison of the results of the proposed model with optimum clay core dimensions and actual dimensions.

Table 4. Comparison of actual dimension by optimal dimension of clay core

	actual dimensions of clay core	optimal dimensions of clay core (SA)
Core crest width (*m*)	4	3.1
Core width on foundation (*m*)	9.8	7.8
Slope of Shell	1:2.5	1: 2
Slope of Core	1: 0.21	0.15
Dam width on foundation (*m*)	75	66.8
hydraulic gradient	-	0.46
Slope stability	-	1.69
Seepage	-	1.3

In this study, new regression models including seepage, hydraulic gradient and stability safety factor was developed to calculate the designing variables. After determining the designing variables, constraints and objective functions, models based on combining of SA and new linear regression models were presented to optimize the core of the Hesar Sangi dam. Optimal parameters of the dam's geometry and stability factor, the body seepage and hydraulic gradient were calculated. The results indicated the high performance of developed technique based on SA for optimization of clay core dimensions.

Model Evaluation

To consider the function of model in determination of primary optimized dimension of clay core rather than designing of core section based on engineering idea, the section dimension of homogenous earth dam for this three heights: 15, 20 and 25 calculated based on engineering idea and developed model. The result of calculation of both designs represented in figure (4) to (7).

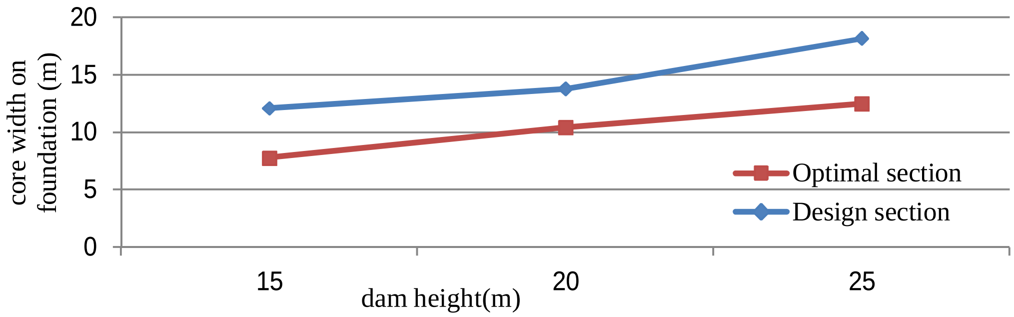

Figure 4. comparison of core width on foundation in optimized section rather than engineering design.

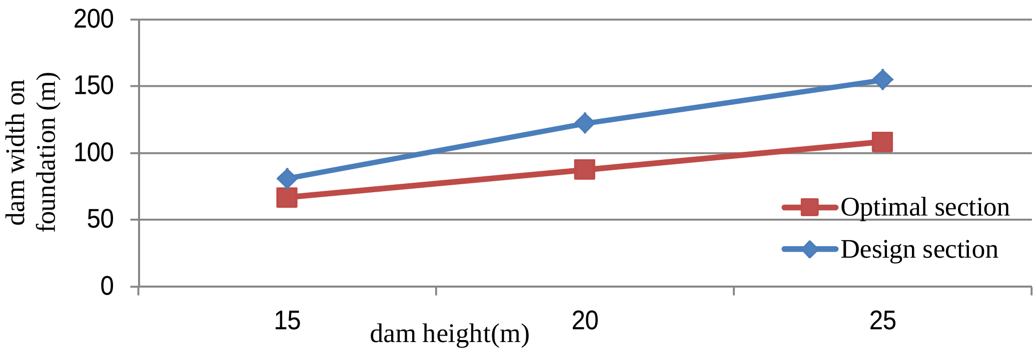

Figure 5. comparison of dam width on foundation in optimized section rather than engineering design.

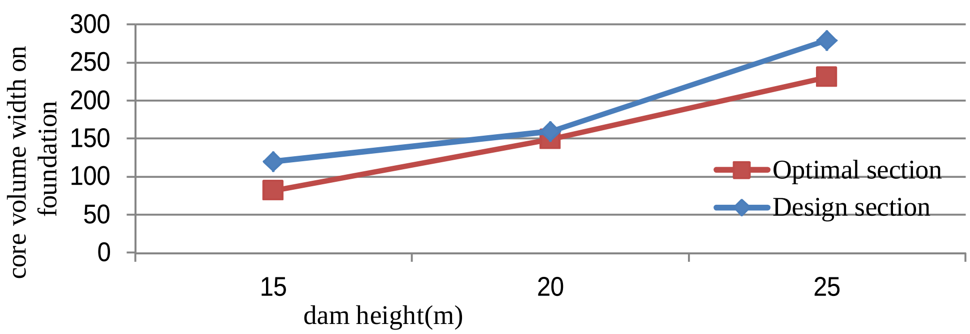

Figure 6. comparison of core volume width on foundation in optimized section rather than engineering design.

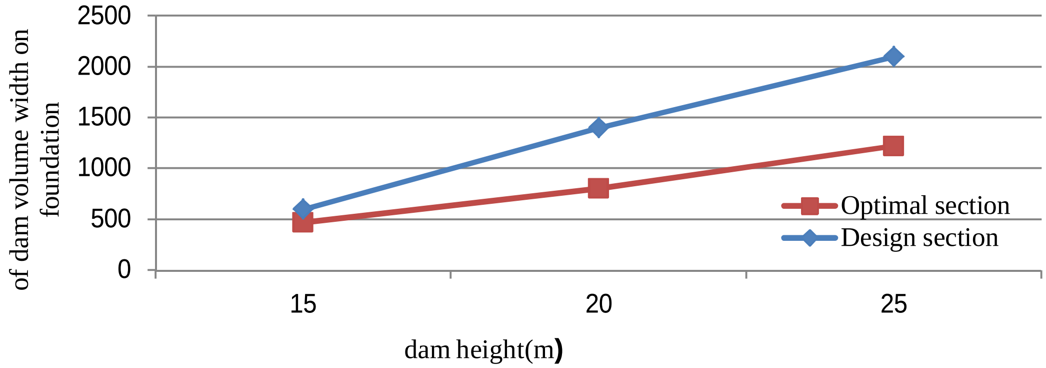

Figure 7. comparison of dam volume width on foundation in optimized section rather than engineering design.

From the above figures dimension and volume that obtained from designing by use of model are lower than their values in engineering design. That indicated that core and shell dimensions decreased rather than previous dimensions. As result core volume and affected by that, shell volume decreased. The volume of hesar sangi core dam was obtained 103.5 m^3 in length unit whereas after determination of optimized dimension, this volume decreased to 81.75 m^3 in length unit. That in fact 21 percent of it's primary volume decrease. Decrease of volume of clay core cause the volume of functional operations, compact operations and operational costs of dam decreased. Thus the operation volume of core construction (preparation, carry and operate) decrease from 25875 to 2037.5 and affected the shell operations that decrease in 12.3 percent rather than primary costs.

Cost of operation of Hesar Sangi Dam body

Cost of operation of shell and core of Hesar Sangi dam body based on designed dimension by consultant and developed model, represented in table (5) and (6).

Table5. Costs of operation of shell and core of Hesar Sangi dam based on designed dimensions.

	Unit	Unit price	Amount	Price
Operation of shell dam	M^3	14706	126000	1852956000
Operation of core dam	M^3	36580	25875	946507500
Sum	2799463500			

Table6. costs of operation of shell and core of Hesar Sangi dam based on optimized dimensions.

	Unit	Unit price	Amount	Price
Operation of shell dam	M^3	14706	116062.5	1706815125
Operation of core dam	M^3	36580	20437.5	747603750
Sum	2454418875			

As it indicated from table(5) and (6) of current costs for construction of core and a dam shell that design with optimization program decreased to 345044625 and costs, in comparison with past, decreased 12.3 percent. We can conclude that, here minimizing the dimensions of clay core by providing suitable conditions such as: seepage, hydraulic gradient and earth dam stability caused decrease in costs that is the most important characteristic of selection of a good plan. Also because of polar effect between different regions of dam. Decrease of core dimensions affected the other components of dam and may result in decrease of these components volume and operational costs. There for consideration of the effect of core dimensions decrease on each components of zone dam and analysis of current conditions are essential that need extensive study. For considering the accuracy of model safety stability factor, hydraulic gradient and seepage calculated from program with the similar obtained values from direct operation of software models, for several section of dam with height of 15, 20, 25 and 42 compared. Table (7) as it observed calculated values from program operation and operation of Geo Studio software models for dam section s with different height, relatively near and there isn't significant parameters between them.

Table7. Safety stability factor, Hydraulic gradient and Seepage calculated from MATLAB and Geo Studio software models for several section of Hesar Sangi Dam.

Dam height(m)		Hydraulic gradient	Seepage(m^3/year.m)	Stability factor
15	Geo studio	0.5	1.3	1.68
	MATLAB	0.46	1.3	1.68
20	Geo studio	0.56	1.82	1.69
	MATLAB	0.53	1.8	1.69
25	Geo studio	0.6	2.33	1.69
	MATLAB	0.59	2.3	1.69
42	Geo studio	0.67	4.02	1.69
	MATLAB	0.66	4	1.69

Conclusion

In this paper, new regression models including leaking from dam body model ,hydraulic gradient model , and stability safety factor model were developed to calculate the designing variables. The results indicated the high performance of new regression models for determining coefficient of stability, leakage from the body, and hydraulic gradient. For developing the necessary model, hydraulic gradient and stability safety factor were considered as constraints Also, the multi objective function was expressed as reduction of seepage through dam body, and the volume of core material is minimized. This problem was optimized using the SA. The results of modeling were compared with actual geometry of Birjand Hesar Sangi earth fill dam. The values of the core dimensions, coefficient of stability, leakage from the body, and hydraulic gradient obtained from a models development were compared with actual values of the dam. The results of performances indicated that SA algorithms produced 12.8 percent reduction of the dam cost. Development of SA algorithm was proven remarkably prosperous capability in form of 21 percent reduction for material type in dam core and 8 percent in shell dam.

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