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Optimum Size for Clay Core of Alavian Earth Dam by Numerical Simulation

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Abstract: Seepage in embankment dams is one of the important factors in stability and dam's maintenance. Core in earth dam is essential for waterproofing and controlling of seepage. Therefore, selection of proper materials and sizes for core of earth dam are very important. Thick clay core is proper for waterproofing but because of low shear strength of the clay, it would be dangerous for dam's stability. The optimal core would be the core which has proper waterproofing, stability safety factor and also with economic condition. In this study, the aim is to determine the optimum size for clay core of Alavian dam near Maragheh city in steady state seepage condition. For this purposes, Geo-Studio pack is used for numerical simulation. In addition, simulation of seepage and slope stability for the built maps of the dam, 11 more models of the dam with different size of cores were tested to find the optimum core thickness. From these models, data required for objective function and constraints using regression techniques for seepage, hydraulic gradient and stability safety factor were provided. Results showed that optimized volume of the core is 35% smaller than the present core.

Key words: Earth dam · Optimization · Clay core · Excel solver · Geo-Studio

INTORDUCTION

Dams are one of the most important structure made by human that destruction of it may caused excessive costs and sometimes irreparable. Destruction of the dams may be due to seepage from dam is one of the most important ones. Seepage itself is not a destructive phenomenon and happens in all dams. But the point that makes it dangerous is lack of proper controlling and forecasting of dam resistances. In non-homogeneous earth dams, waterproofing is a task for dam core. Use of clay core for waterproofing the dam is most common. In the other hands, shear strength of the fine materials like clay is low and it would decrease the stability of the dam against slope sliding. Therefore, use of thick cores is a good choice for minimizing seepage and prevention from internal erosion; on the other hand, thick core would decrease dam slope stability [1]. In another study by Fadaei Kermani and Barani [1], finite difference method (FDM), the five-point approximation technique, has been demonstrated to deal with seepage problem in earth dams. The grid system, with computational boundary being coincident with the physical boundary, was numerically obtained by solving Laplace equation. The method was applied to analyze the steady seepage in an earth dam. In this study, three different grid types were considered and the results were compared with ones obtained by analyzing with Geostudio [2] software. It showed that by choosing small enough increments, the results are satisfactory. Hasani *et al*. [3] used geo-studio software for seepage analysis in Ilam earth fill dam. In order to evaluate the type and size of mesh on total flow rate and total head through the dam cross section, four mesh size such as coarse, medium, fine and unstructured mesh were considered. Results showed that average flow rate of leakage under the different mesh size for Ilam dam equal to 0.836 liters per second for the entire length of the dam [3].

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Many researchers had effectively investigated in this field. Investigation on optimization of the dam core took place in 1979 to 1985 [4]. Kasim and Jusoh [5] studied seepage analysis using Seep/w program. Relation between seepage discharge and reservoir water level was nonlinear and for different input data; also the function of hydraulic conductivity were different [5]. Abdul Hossain *et al*. [6] for optimizing homogenous earth dam used multiple target function optimization by weighted method. Optimization is based on stability restrictions and distance between upstream water levels and downstream water levels. Function of seepage discharge, permeated surface and design restrictions are virtual functions of design parameters [6].

Salmasi and Mansuri [7] studied on effect of homogeneous earth dam hydraulic conductivity ratio (K_x/K_y) with horizontal drain on seepage. Results showed that the provision of the filter nearer the upstream side results in higher seepage losses and an increment in the required filter length. If the filter is located away from upstream face, i.e., near the downstream toe, though seepage gets reduced, the saturated zone is increased, resulting in a reduction of the dry zone. Mansuri and Salmasi [8] studied the effectiveness of using horizontal drain and cutoff wall in reducing seepage flow from an assumed heterogeneous earth dam. Seepage analysis, hydraulic gradient and uplift pressure, are computing by numerical simulation, using Seep/w software. Results showed that increasing horizontal drain length, caused slightly in increasing seepage rate and increasing hydraulic gradient. Optimum location of cut off wall for reduction of seepage rate and piping is in the middle of dam foundation. Different location of cut off wall in dam foundation has little effect on exit hydraulic gradient and always it is less than unity. Installation of cut off wall in middle of foundation, results in 19.68 percent decrease in hydraulic gradient respect to existent of cut off wall in upstream of dam.

In a study, Gotvand-Olya dam seepage analysis was numerically performed using 2-D FEM transient analysis [9]. As a particular boundary condition for an analysis, the water level fluctuation was incorporated to simulate the daily changes. As a result, various seepage phenomena were quantified such as hydraulic gradient, seepage vector and pore water pressure distribution at the corresponding time of interest as the water level rises and recedes. At steady state analysis, the seepage flux at high water level in downstream area was predicted to be 78 l/s. The result of this study proves that there was no sign of hazardous sources contributing to the possibility of piping, internal erosion and excess leakage through the dam body [9]. In another study, critical hydraulic gradient for sediment transport through rockfill dam was determined [10]. Results from dynamic pressure fluctuations in stepped three-side spillway showed that the proposed form of ogee profile caused a significant reduction in turbulence intensity within the side channel. On the other hand, the stepped Ogee profiles of three-side spillways caused to simple construction and ease of operation [11]. Other materials in this subject can be found in the reported literature [12, 13].

The aim of present study is to determine the optimal sizes for core within consideration of enough upstream slope stability safety factor. The executive restrictions are controlled seepage, acceptable hydraulic gradient, safety factor against sliding for upstream slope of dam and proper dam crest width. For this purpose, two part of Geo-Studio package, i.e. Seep/w and Slope /w programs were used for numerical simulation. The data required for regression modeling was obtained and regression models provided by SPSS software. In addition, optimization for minimizing the core volume was successfully carried out by Solver tool in Excel.

MATERIAL AND METHODS

Geo-Studio Software Pack: With Geo-Studio software pack analysis such as stress-strain, seepage, stability of slopes, dynamical analysis and condition of sudden drop of reservoir water level were preformed. In this study, Seep/w program for seepage analysis and Slope/w program for slope stability were used.

Finite element numerical methods are based on the concept of subdividing a continuum into small pieces, describing the behavior or actions of the individual pieces and then reconnecting all the pieces to represent the behavior of the continuum as a whole. This process of subdividing the continuum into smaller pieces is known as discretization or meshing. The pieces are known as finite elements.

In Geo-Studio Seep/w, the geometry of a model is defined in its entirety prior to consideration of the discretization or meshing. Furthermore, automatic mesh generation algorithms have now advanced sufficiently to enable a well behaved, numerically robust default discretization often without additional effort by the user. Of course, it is still wise to view the default generated mesh but any required changes can easily be made by changing a single global element size parameter, by changing the number of mesh divisions along a geometry line object, or by setting a required mesh element edge size.

The information required like dam geometry, property of material geotechnical parameters for dam and foundation are gathered from Regional Water Authority of Eastern Azerbaijan, RWAEA [14]. Selected dam is Alavian earth dam located in Eastern Azerbaijan in Iran near Maragheh city.

Seep/w program: Seep/w is geotechnical software based on finite element method. Equation (1) represents seepage discharge based on Darcy's law.

$$q = -kA(\partial h / \partial l) \quad (1)$$

where, q is seepage (m^3/s), k is hydraulic conductivity of soil (m/s), A is cross-section area of seepage flow (m^2) and $\partial h/\partial l$ is hydraulic gradient of flow (dimensionless).

Combining continuity equation with Darcy' law results in Poisson equation.

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} = q \quad (2)$$

where k_x and k_y are horizontal and vertical hydraulic conductivities of soil (m/s), h is water potential head in soil (m) and q is input or output discharge of soil mass ($m^3/s.m^2$). Solving Poisson equation is a difficult problem in mathematics and so numerical methods are used to solve this differential equation. Seep/w uses finite element method.

Slope/w program: This program unlike the other program of Geo-Studio is not based on finite element. This program includes graphical method for analysis of stability of slopes. The process is done by limited equilibrium methods. The Slope/w has ability to analyses within most of the equilibrium methods such as Morgenstern-price, Bishop and etc. One of the cons of this program is possibility of direct modelling of common reinforcements like geo-fabrics, bearing rein and nailing for improving the safety of slopes.

Location of Alavian Earth Dam: Alavian dam is an earth dam with clay core, made on Sufi-Chay River 3.5 km of northern west of Maragheh city in eastern Azerbaijan, Iran. The main aim from Alavian dam construction is to collect surface river flows and controlling Sufi-Chay River for purposes like supplying drinking water of Maragheh city, development agriculture lands and hydroelectric uses as well. Fig. 1 shows a view of the Alavian earth dam.

The height of dam from bed rock is 76 meters, the dam has 935 meters length, the width of crest is 10 meters, total volume of dam's soil material is 4.8 million cubic meters, the crest elevation is 1572 meters from mean free surface of sea, the reservoir volume in normal level is 60 million cubic meters and dead volume is 3 million cubic meters [14].

Required Information for Modeling: The required information for numerical modeling and analysis of the cross sections of dams are listed as the following items:

- Dam layout map and cross-section profiles
- Permeability of all materials used in dam
- Strata under the dam (alluvium of the river) with its hydraulic conductivity
- Saturated and dry specific weight of materials
- Soil shear strength parameters, like internal friction angle and soil cohesion

Fig. 2 is the biggest cross-section view of the Alavian earth dam with finite elements mesh generation. Hydraulic conductivity of the different materials is shown in Table 1.

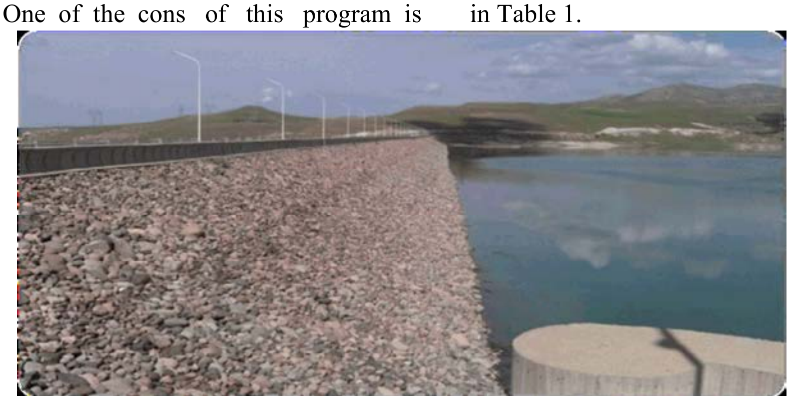

Fig. 1: Upstream slope of Alavian reservoir dam

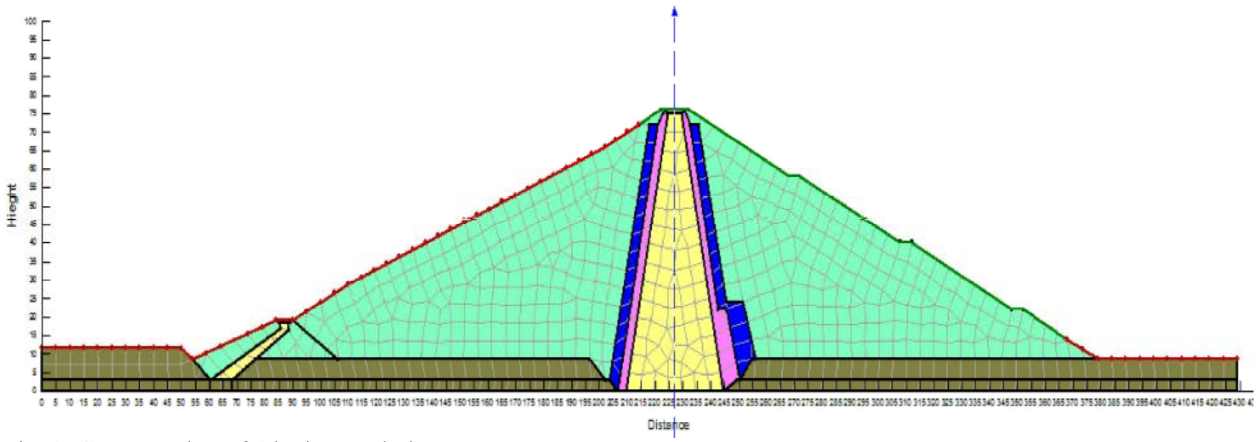

Fig. 2: Cross-section of Alavian earth dam

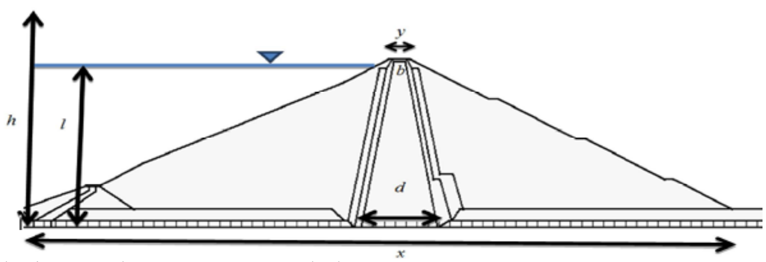

Fig. 3: Geometry of the Alavian non-homogeneous earth dam

Table 1: Hydraulic conductivity of different materials used in Alavian dam [14]

Layer	Hydraulic conductivity (*m/s*)
Core	$2 * 10^{-10}$ to $5 * 10^{-11}$
Filter 1	$1.8 * 10^{-5}$ to $4.5 * 10^{-6}$
Filter 2	$1.8 * 10^{-4}$ to $4.5 * 10^{-5}$
Shell	$1.1 * 10^{-4}$ to $4.1 * 10^{-5}$
Foundation	$2.69 * 10^{-9}$ to $3.32 * 10^{-10}$

Table 2: Shear strength proprieties of the material used in Alavian earth dam

Material	$\gamma_w (kN/m^3)$	$\gamma_{sat} (kN/m^3)$	φ_{UU}(Degree)	φ_{CU}(Degree)	φ_{CD}(Degree)	C_{UU} (kPa)	C_{CU} (kPa)	C_{CD} (kPa)
Core	19	20	10	22	28	50	37	0
Filter 1	21	22	35	0	0	0	0	0
Filter 2	21	22	40	0	0	0	0	0
Shell	21	22	43	0	0	0	0	0
Foundation	19	20	25	0	0	170	0	0

The values of soil specific wet weight, specific saturated weight, internal friction angle and cohesion of the materials in the studied dam are presented in Table 2, which is used for numerical simulation.

Fig. 3 shows the non-homogeneous embankment dam within needed parameters. In Fig. 3, h is the dam's height (m), l is upstream water level (m), d is the core width on foundation (m), b is the core crest width (m), x is the dam width on the foundation (m) and y is the crest width of the dam (m).

Initially, the Alavian dam was modeled in Seep/w and Slope/w just like how it built in reality. Then 11 more assumed models with different core sizes (thicker and thinner than the normal condition) and according to design criteria and the same material were created. The assumed geometrical data of the simulated models is in Table 3. After simulating 12 models, the required data for seepage regression equation, hydraulic gradient and stability of safety factor are obtained via SPSS software.

Table 3: Geometrical data of the 12 simulated models according to Fig. 3

Model	b (m)	d (m)	l (m)	h (m)
1	3	33	72	76
2	4	34	72	76
3	6	36	72	76
4	7	37	72	76
5	5	42.5	72	76
6	5	50	72	76
7	5	27.5	72	76
8	3	35	72	76
9	8	35	72	76
10	5	35	72	76
11	5	72	72	76
12	3	25	72	76

Numerical simulation with Seep/w and Slope/w resulted in for seepage, *q;* (m^2/s), hydraulic gradient (i*)* and stability safety factor (*SF)*. The dimensionless design parameters were selected are *q/kl, b/h, b/l, d/l, SF and d/x*.

Optimizing by Solver in Excel: Solver has capability for optimization when target function and constraints are known. For obtaining optimum Maragheh dam core, definition of target function and constraints are stated as following:

Target Function: Because of the need for less permeability of core, it is required to be made of fine-grained materials and because of this fact, shear strength of the core is less than the other parts of the dam. Sometimes while determining the proper sizes for the core, due to important design parameters and factors like: *q, i* and *SF*, the geometry would not be economic. For this reason, determining the optimized core size while observing the design criteria, physical and geo-technical characteristics of the material, should be economically justified. In order to minimize the volume of the clay core for embankment dams matching the design criteria, a model using *Solver* tool has been created in *Excel* to optimize the issue. In this study, volume of the clay core material is considered as target/objective function. For minimizing volume of clay core, Eq. 8 is used.

$$\mathrm{V} = \left(\frac{d+b}{2} * \mathrm{h}\right) \quad (3)$$

Constraints: Most of the designers believed that acceptable seepage in full reservoir condition must be less than a cubic foot per second or 30 liters per second. For minimizing the seepage from dam and its foundation, Eq. 4 is introduced using regression technique by SPSS software.

$$\frac{q}{kl} = -49791\frac{b}{h} + 7942.4 \quad (4)$$

To prevent soil particle migration in dam and piping, hydraulic gradient (*i*) constraint was applied according to Eq. 5.

$$i = 1.624 - 1.96\frac{b}{l} - 0.346\frac{d}{l} \ \ and\ \ 1 \le i \le 3 \quad (5)$$

Safety factor (*SF*) of stability against sliding derived in total simulated 12 models. Usually in earth dam design, *SF* was select more than 1.5. Eq. 6 is used for this purpose.

$$SF = 2.792 - 2.271\frac{d}{x} - 0.139\frac{b}{y} \quad , \ SF \ge 1.5 \quad (6)$$

RESULTS AND DISCUSSION

Simulated model of the Alavian dam (in present condition) is shown in Fig. 4. The phreatic line, equpotential lines and seepage amount are also shown on Fig. 4.

For analysis of the stability safety factor of the 12 models of Alavian dam, these models are simulated according to the design criteria. According to Fig. 5, stability safety factor of the upstream slope of Alavian dam at steady state condition is 2.488.

In this study, the optimized sizes of the clay core for Alavian dam are analyzed in steady flow condition. As it is mentioned in optimization part, the aim is to minimize the core's volume for dam unit length. Comparison between Tables 4 and 5 demonstrate that in optimized condition, volume of Alavian dam core would be 35% less than the present one. So it could be mentioned as a conclusion that optimizing the clay core of Alavian dam while observing design criteria would be more economic.

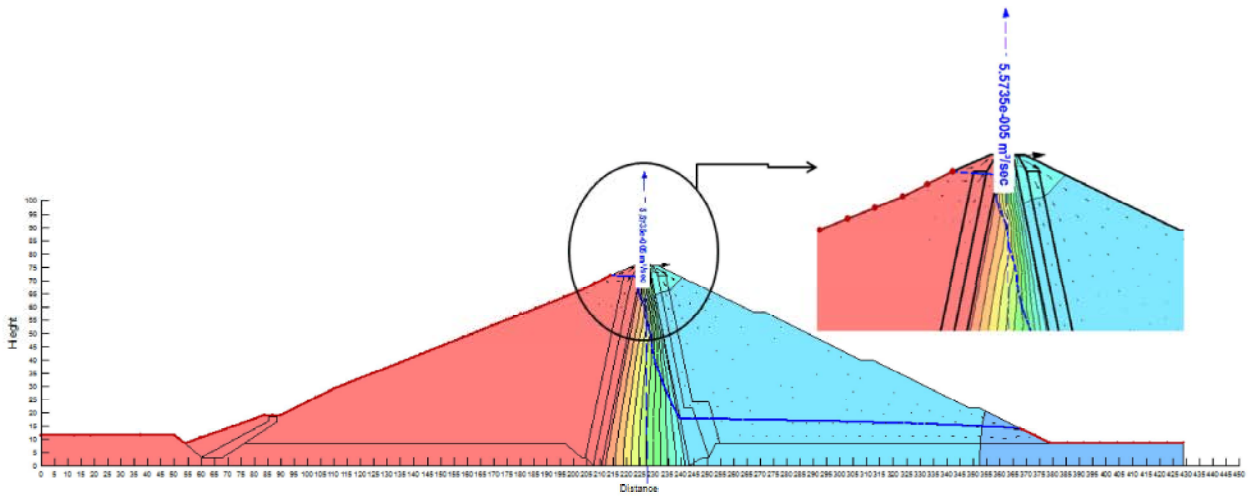

Fig. 4: Simulated model of the Alavian dam

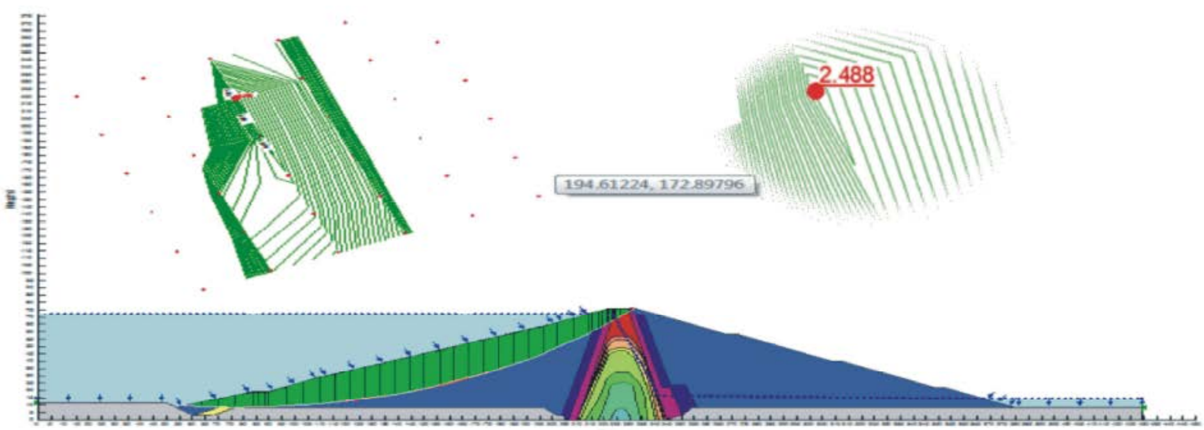

Fig. 5: Simulated model of Alavian dam and stability safety factor (present dam)

Table 4: Optimized sizes of the Alavian core dam

b (m)	*d (m)*	*h (m)*	*l (m)*	*x (m)*	*y (m)*	*i*	*q* $(m^3/s/m)$	*SF*	*Volume* (m^3/m)
3	22.8	76	72	10	329	1.43	0.000054	2.59	980.4

Table 5: Present sizes of the Alavian core dam

b (m)	*d (m)*	*h (m)*	*l (m)*	*x (m)*	*y (m)*	*i*	*q* $(m^3/s/m)$	*SF*	*Volume* (m^3/m)
5	35	76	72	10	329	1.37	0.00004	2.49	1520

CONCLUSION

In design of an earth dam, thicker clay core results less seepage amount and less hydraulic gradient due to low permeability of clay. This condition is proper for dam from prevention of piping phenomenon view point. In other hands, thicker clay core causes to reduce upstream slope safety factor against sliding (because of clay's low shear strength). The purpose of this study was to introduce a method for optimum design of an earth dam by taking consideration of the following criteria:

- Having minimum volume of clay as an objective function (Eq. 3).
- Safety factor against upstream sliding be more than 1.5, i.e., $SF>1.5$ (Eq. 6).
- Hydraulic gradient be less than 3 and more than unit, i.e. $1<i<3$ (Eq. 5).

- Seepage (q) from dam and foundation has to be less than 30 lit/s.m (Eq. 4).

Results demonstrate that in optimized condition for dam clay core, volume of Alavian dam core will be 35% less than the present condition. So in design of earth dams, using optimization technique with consideration of all hydraulic or geo-technique criteria, resulted in economic plan.

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Persian Abstract

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چکیده

یکی از مهمترین عوامل موثر در پایداری و نگهداری از سدهای خاکی مسئله نشت از بدنه و پی سد می باشد. معمولا هسته رسی مرکزی در سد خاکی کنترل کننده حد مجاز نشت از بدنه است. لذا انتخاب مصالح رسی مناسب و نیز ضخامت هسته جزو پارامتر های مهم طراحی هستند. هسته با ضخامت زیاد از نظر کاهش مقدار نشت مفید است ولی به دلیل مقاومت برشی کم مصالح رسی، هر چقدر هسته نازک تر باشد مناسب تر خواهد بود. تصمیم گیری در مورد ضخامت بهینه هسته رسی جزو کار طراحان این گونه سدها بوده و دارای اهمیت زیادی است. در این تحقیق هدف یافتن ضخامت بهینه هسته رسی سد علویان در نزدیکی شهر مراغه می باشد. برای این منظور از بسته نرم افزاری Geo-Studio جهت شبیه سازی عددی استفاده شده است. ابتدا بر اساس نقشه های همچو ساخت سد خاکی علویان، مقدار نشت و ضریب اطمینان در برابر لغزش شیب بالادست سد بررسی شده و سپس ۱۱ مقطع فرضی دیگر با ضخامت های مختلف هسته رسی شبیه سازی گردید. پس از شبیه سازی عددی این ۱۲ مدل از سد خاکی، معادلات مربوط به میزان نشت، گرادیان هیدرولیکی و پایداری شیب بالادست توسط تکنیک رگرسیون بدست آمده و به صورت تابع هدف و قید ها بکار رفتند. نتایج نشان دادند که حجم هسته رسی بهینه شده حدود ۳۵ درصد نسبت به وضعیت کنونی آن کاهش می یابد.