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Quick Estimation of Seepage Discharge and Water Level Height Out of the Central Core in the Zoned Earth-fill Dam

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Abstract: This paper relates to the investigation of the amount of seepage discharge and the water level height out of the central core in the zoned earth-fill dam using the finite element procedure by Geo Studio-SEEP/W software. The investigation models were carried out in two shapes of the central core, the rectangular and the wedge shapes, by 200 miscellaneous models. For each model, seepage discharge and height of water level out were determined. Investigation results were examined using the artificial neural network technique (ANN) to demonstrate the influence weight of each independent variable (geometry and characteristics) on the output-dependent variables results using the statistical software SPSS. Core material hydraulic conductivity had the highest impact on seepage discharge and water level height while dam upstream slope had the least impact on them. Two statistical empirical equations were developed using multiple nonlinear regression for both the seepage discharge and the height of water level out using the SPSS software. The recommended equations were also verified by comparing their results with the results of 25% of the models analyzed by Geo Studio software. They showed great agreement that the coefficient of determination (r^2) was 97.3% for the seepage discharge equation and 96.6% for the height of the water level-out equation.

Keywords: Seepage, core, zoned dam, SEEP/W, ANN, nonlinear regression

1. Introduction

Seepage stands as the main element contributing to the failure of earth-fill dams. Jamel (2016) employed an artificial neural network to validate SEEP/W estimates of seepage through homogeneous earth dams, finding agreement with Casagrande and Dupuit solutions [6]. This infiltration can result in the erosion of the dam's structure, resulting in abrupt failure because of piping or sloughing. To avoid such failure and manage seepage, incorporating an impermeable zone or center in the earth-fill dam is critical [9].

. Salmasi et al. (2020) employed Limit Equilibrium Method (LEM) and Finite Element Method (FEM) to study inclined clay core impacts on seepage and stability of earth dams [14]. Alaa et al. (2020) conducted numerical and experimental modeling of seepage and slope stability in earth-fill dams [2].

Bredy and Jandora (2020) evaluated The Karolinka Dam body and foundation safety factors, dam height impacts on stability, and agreed with Plaxis results [7]. Kheiri et al. (2020) utilized SEEP/W to study an embankment Dam with a core, a cutoff wall, and horizontal drain, evaluating cutoff wall positioning and depth effects on subsurface seepage [10] . Asadi and Saba (2020) found raising clay core modulus of elasticity and lowering crust-core modulus differences significantly reduced dam crest vertical displacement [5]. Yang et al. (2020) presented formulas to simplify leakage estimation in clay core dams under varying groundwater levels above and below reservoirs [17]. Sánchez-Martín et al. (2020) provided evidence for optimal water height using impermeable cores consistent with downstream intermediate permeability placement [15]. Farhadian et al. (2021) conducted an evaluation of optimal cutoff wall depths for sealing clay cores in Peygham-chay dams [8]. Several studies have rigorously examined earth dam seepage characteristics.

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Sazzad and Alam (2021) utilized SEEP/W to model seepage through "Heterogeneous, zoned.", and diaphragm core dams [16]. Al-Hadidi and Hashim (2021) employed finite element analysis of Kongele earth dam seepage in GeoStudio concluding dam safety against piping, uplift, and heave for normal and maximum water levels [3]. Shen and Mostafa (2021) reported trapezoidal cores minimizing seepage discharge with linear phreatic line drops for chimney drains depending on rock toes [11]. Abdel-Kawy et al. (2021) determined wedge-shaped cores most effectively lower seepage due to factors impacting discharge quantity and phreatic surface location [1].When modeling downstream drain geometry impacts on earth-fill dam seepage, Refaiy et al. (2021) demonstrated experimental data provided sufficient accuracy [13]. Zaid and Basim (2022) performed tests comparing seepage in zoned dams using various core additives to determine sandy and silty soil permeability [18]. Arkan et al. (2023) numerically compared seepage responses to varied zoned dam core properties [4],. Collectively, these rigorous studies have compellingly advanced knowledge and modeling of critical earth dam seepage factors through empirical and numerical analyses. The cited works present strong evidence to inform optimized design for minimizing phreatic surface impacts.

The research contribution is the development of two general empirical equations for estimating the amount of seepage discharge and water level height out of the central core in zoned earth-fill dams. The equations were developed using a combination of flow analysis in porous media software (Geo Studio) and statistical software (SPSS). The research also examined the influence of various independent variables (geometry and characteristics) on the dependent variables (seepage discharge and water level height) using an artificial neural network technique. The recommended equations were verified by comparing their results with the results obtained from the Geo Studio software, showing a high level of agreement. This research provides a quick estimation method for seepage discharge and water level height in zoned earth-fill dams, which can be useful for dam design and management. The research contribution is the development of two general empirical equations for estimating the amount of seepage discharge and water level height out of the central core.

2. Methodology

To create the database of the zoned earth-fill dams necessary for the seepage flow analysis process, 200 models of these dams were made. One hundred models of these had a central core of a rectangular shape and the rest had a central core of a wedge shape with varied variables of dimensions and properties.Each dam model consists of three zones with a toe filter that impounds a reservoir and rests on an impervious foundation. Shell for zones (1 and 2) are composed of sand soil, central core is composed of mixed of sand clay, and triangular toe filter is composed of gravel, Figure (1).

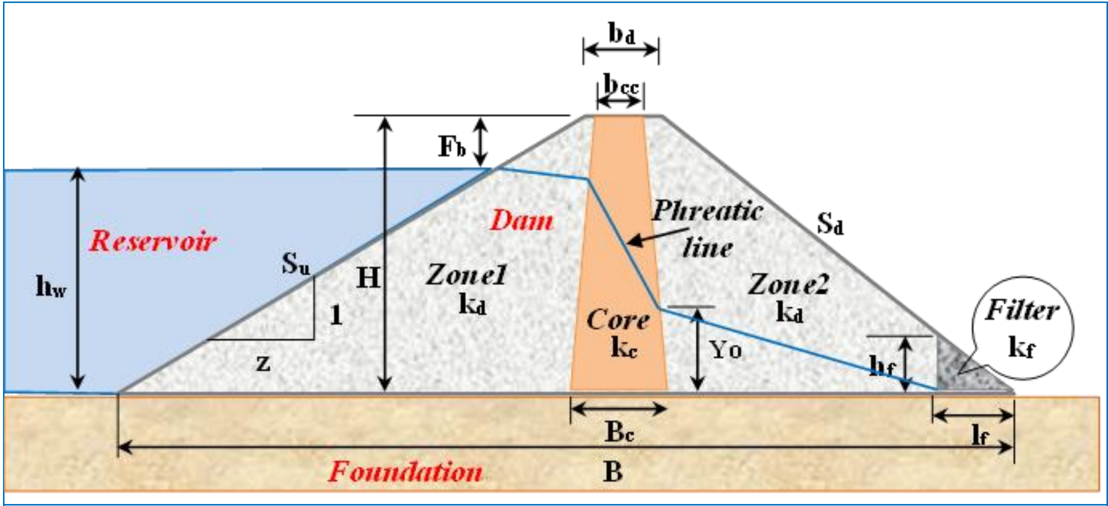


Fig. 1. General schematic section represent for zones of the zoned earth-fill dam models.

Where:

H = Total Dam height.
bd = Dam crest width.
Fb = Freeboard height.
Su = Dam upstream slope.
Sd = Dam downstream slope.
kD = Dam shell permeability.
bcc = Core crest width.
S_C = Core upstream slope.

kc = Core permeability.
kf = Filter permeability.
lf = Filter length.
hf = Filter height.
Yo= Phreatic line height out

The selection of variable ranges for dam models was determined based on the constraints within dam design practices and adhering to recommendations aimed at ensuring slope stability and effective control against sliding. For rectangular core shape, used (b_{cc}) equal to (B_c) to differentiate between it and the trapezoidal core shape. Identification of section geometry variables and material properties ranges are shown in Table (1).

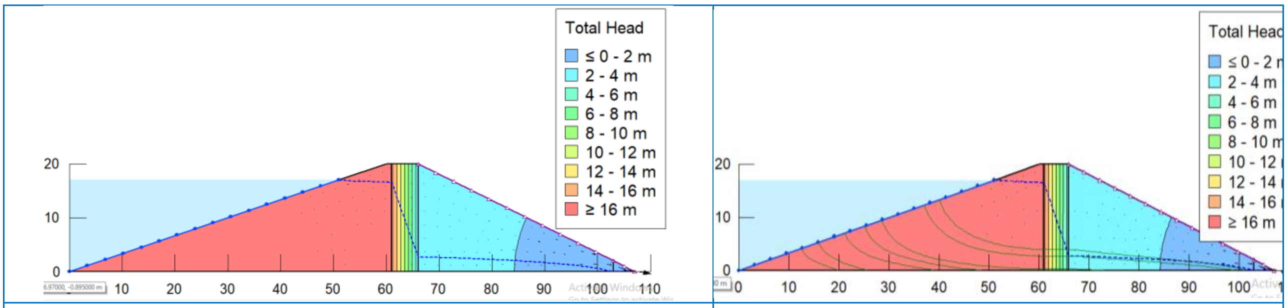
Geo Studio Application

The input variables that were adopted were used to create a set of 200 models with varied dimensions and properties. One hundred models have rectangular core and rest models have trapezoidal core. Therefore, to build a database of inputs and outputs variables quantities, each model (case) was analyzed using GS software (SEEP/W) to produce the seepage discharge value and the height of water level out of the core of the dam.

This software used a numerical method (finite element) to analyze flow in pores media of the dam section and produce phreatic line and seepage discharge after full saturation flow. As the Geo Studio's capabilities of graphical representation of the results are excellent, the depth of the water out of the core downstream can be monitored and record, Figures (2 and 3).

Table 1. Ranges of variables adopted for dam models International Commission on Large Dams (ICOLD 2012).

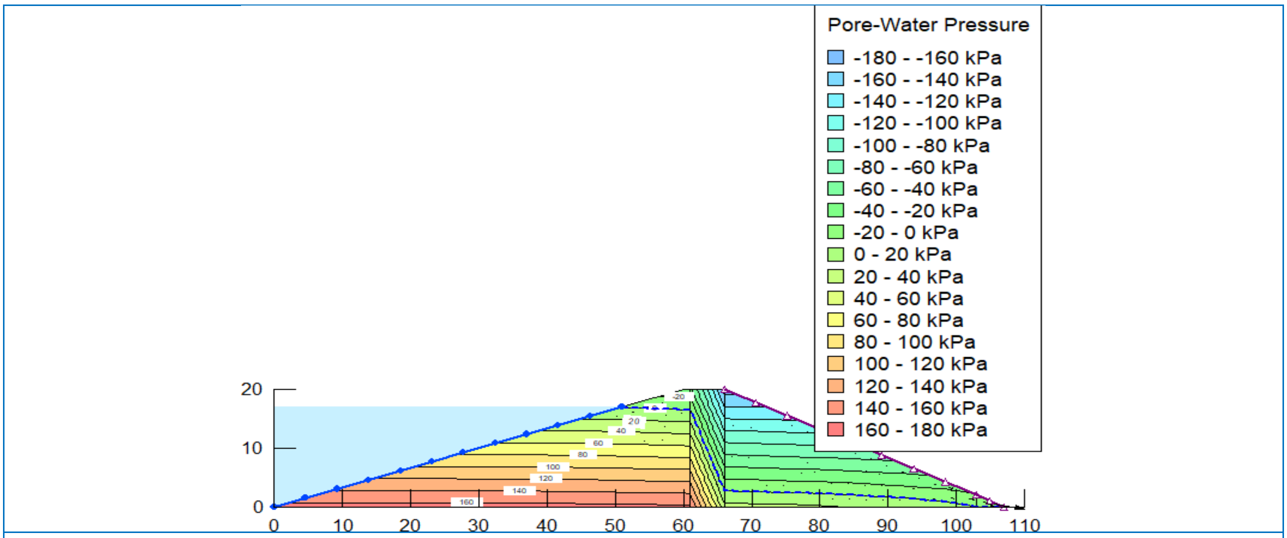
	Item	Range	Description			
Dam	Total dam height (m)	20-30	H	20	25	30
	Dam crest width (m)	6-9	bd	6	7	9
	Freeboard height (m)	2-3	Fb	2	2.5	3
	Dam Upstream slope (v:h)	1:2-1:3	Su	1:2	1:2.5	1:3
	Dam Downstream slope (v:h)	1:1.5-1:2.5	Sd	1:1.5	1:2	1:2.5
	Dam shell permeability (m/sec)	10-5-10-3	KD	10-5	10-4	10-3
	Soil type	Sand				
Core	Total core height (m)	20-30	H	20	25	30
	Core crest width. (m)	3-7	bcc	3	5	7
	Core upstream slope (v:h)	1:0.25-1:0.75	Sc	1:0.25	1:0.5	1:0.75
	Core permeability (m/sec)	10-8-10-6	kc	10-8	10-7	10-6
	Shape of core		Rectangular		Trapezoidal	
	Soil type	Clayey Sand				
Filter	Filter permeability (m/sec)	0.05	kf	0.05		
	Filter length (m)	3	lf	3	4	5
	Filter height (m)	2	hf	2		
	Soil type	Gravel				



(a) Phreatic line

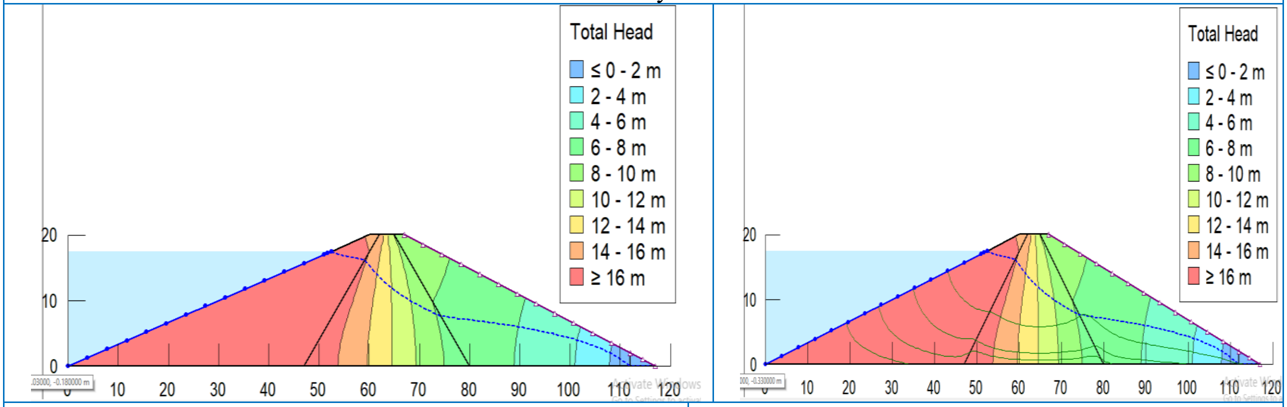
(b) Flow net

Fig. 2. Geo Studio output graphical results for one of the models have rectangular core used in this study.



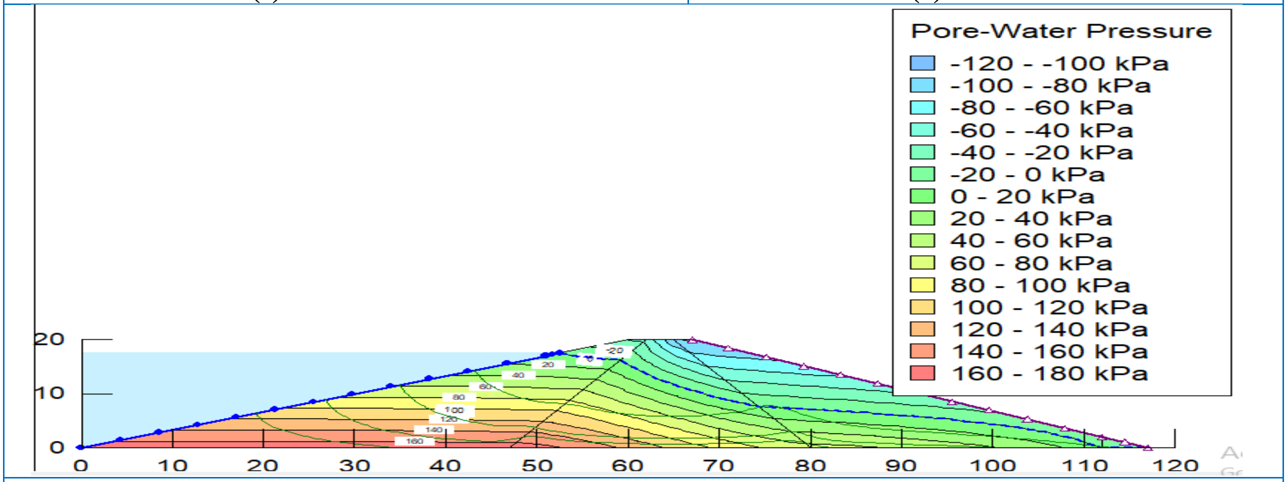
(c) Pore water pressure distribution

Fig. 2. Geo Studio output graphical results for one of the models have rectangular core used in this study.



(a) Phreatic line

(b) Flow net



© Pore water pressure distribution

Fig. 3. Geo Studio output graphical results for one of the models have trapezoidal core used in this study.

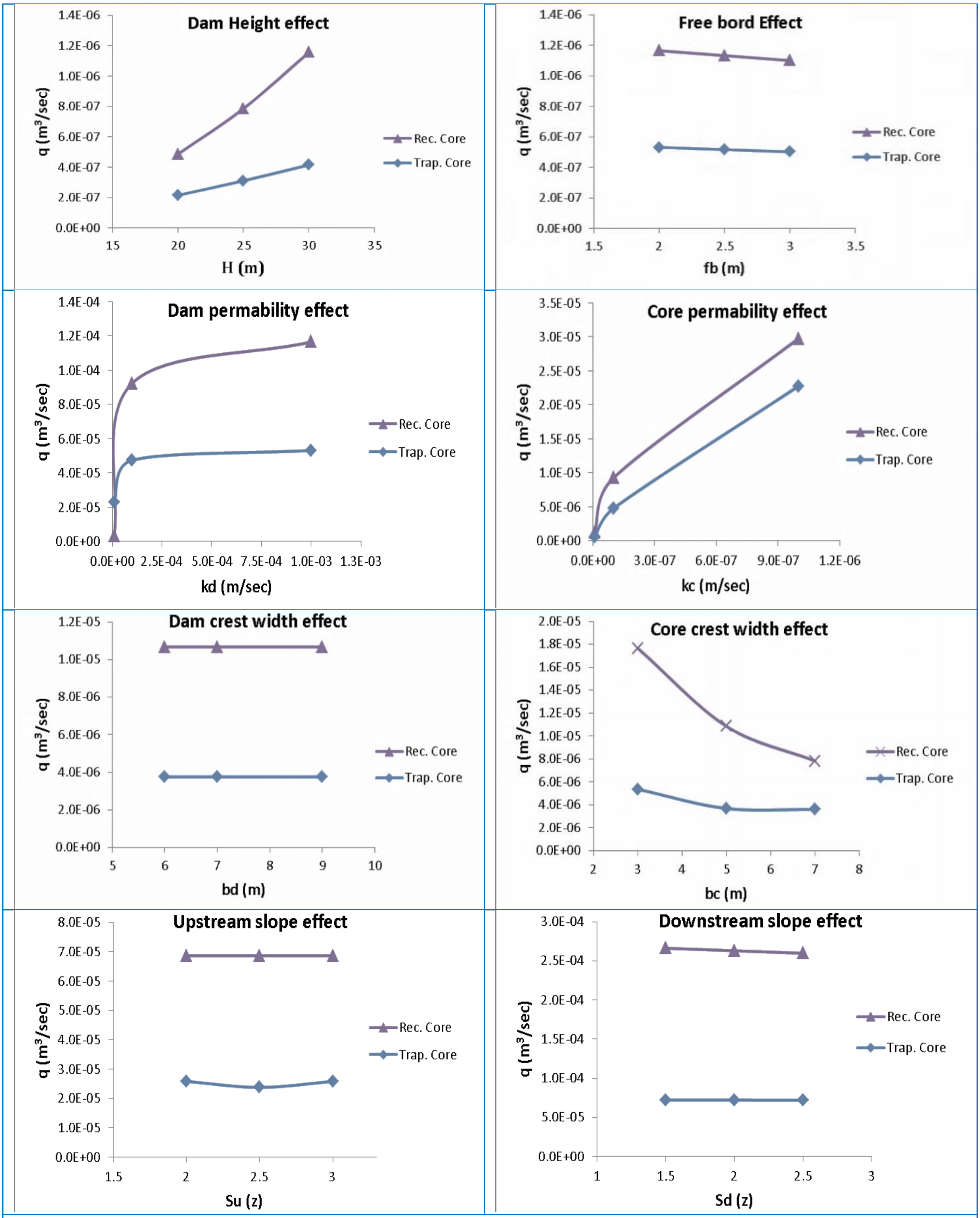


Fig. 4. The effect of dam dimensions and component materials properties on seepage discharge for a number of models adopted in this study.

3. Results

As previously mentioned, the estimation of seepage discharge quantity and core out-of-water level in a dam section necessitates understanding the impact of each input variable on the corresponding output variables. An effective way to establish this relationship is through the application of an Artificial Neural Network (ANN) model, which relies on a comprehensive database containing output variables corresponding to specific input variables. In this context, the utilization of the SEEP/W software application results in the creation of such a database. The IBM SPSS Statistics software is then employed to derive the parameter matrices and vectors for the ANN model using the developed database. To facilitate this process, the database is divided into three distinct subsample sets, namely training, testing, and holdout subsets, as part of the software utilization.

The case summary reveals that the optimal data allocation stands at (64%) for training, (28%) for testing, and (8%) for holdout purposes (verification). In addition, the software determines the ideal type of activation functions for the hidden and output layers as well as the optimal number of hidden nodes in the hidden layer. In this study, the modeling process is standardized, and the default activation functions are hyperbolic tangent for the hidden layers and identity for the output layers, which are used for automatic architecture selection.

Table (2) presents the error analysis derived from the software-selected final weights matrices and bias vectors. It outlines the minimum sum of square errors observed for individual subdivisions and details the relative error associated with each output variable in those subdivisions. for particular significance are the findings from the holdout subset, where the average overall error stands notably low at 0.045.

Figures (5) and (6) represent the contrast between the forecasted and observed output variables, (q, Y_o) with the correlation coefficients (r^2) of 97.0% and 96.4% respectively.

Table 2. Model summary.

Training	The sum of Squares Error		3.466
	Average Overall Relative Error		.027
	Relative Error for Scale Dependents	q	.032
		Y_o	.023
	Stopping Rule Used		1 consecutive step(s) with no decrease in error
Testing	The sum of Squares Error		2.699
	Average Overall Relative Error		.045
	Relative Error for Scale Dependents	q	.030
		Y_o	.075
Holdout	Average Overall Relative Error		.045
	Relative Error for Scale Dependents	q	.027
		Y_o	.086

a. Error computations are based on the testing sample.

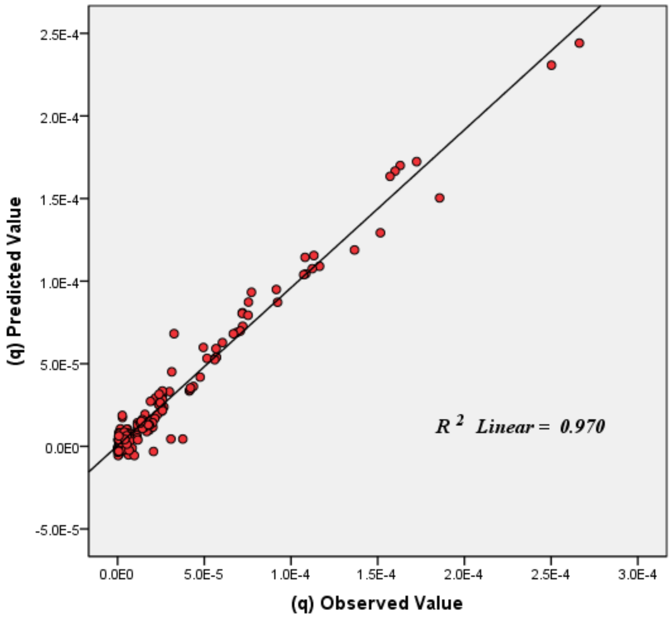


Fig. 5. Comparing the predicted and observed seepage discharge (q_a).

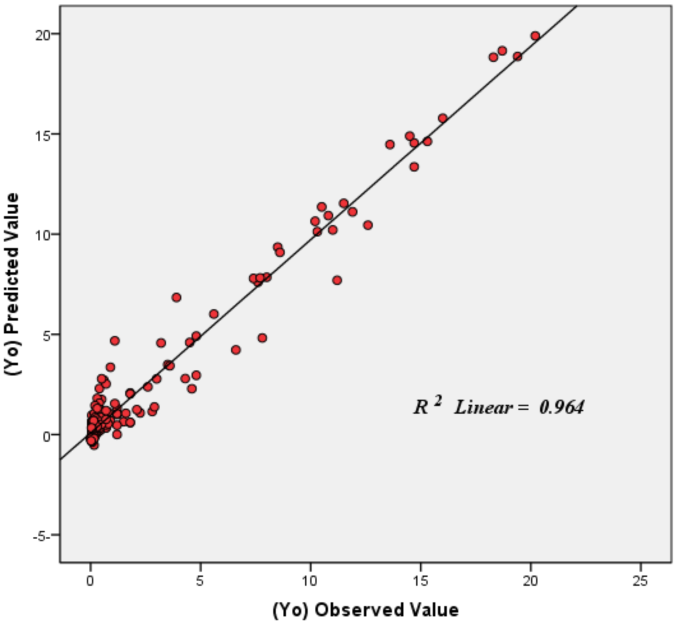


Fig. 6. Comparing the predicted and observed core out of water height (Y_o).

As shown in Table 3 core permeability exhibited maximum normalized importance of 100%, signifying it as the most determinative variable impacting model outputs. Crest width, meanwhile, demonstrated a minimum normalized importance of 8.7%, thus implying it was the least influential input. Figure 7 provides a graphical representation of these important analyses. It compellingly illustrates that core permeability far surpasses all other inputs in terms of the effect on the dependent variables targeted.

Table. 3. Independent variable importance.

	Importance	**Normalized Importance**
l_f	.040	15.7%
k_c	.256	100.0%
B_c	.052	20.4%
b_{cc}	.122	47.5%
k_d	.185	72.2%
S_d	.068	26.5%
S_u	.022	8.7%
b_d	.026	10.3%
B	.078	30.3%
h_w	.058	22.5%
H	.093	36.5%

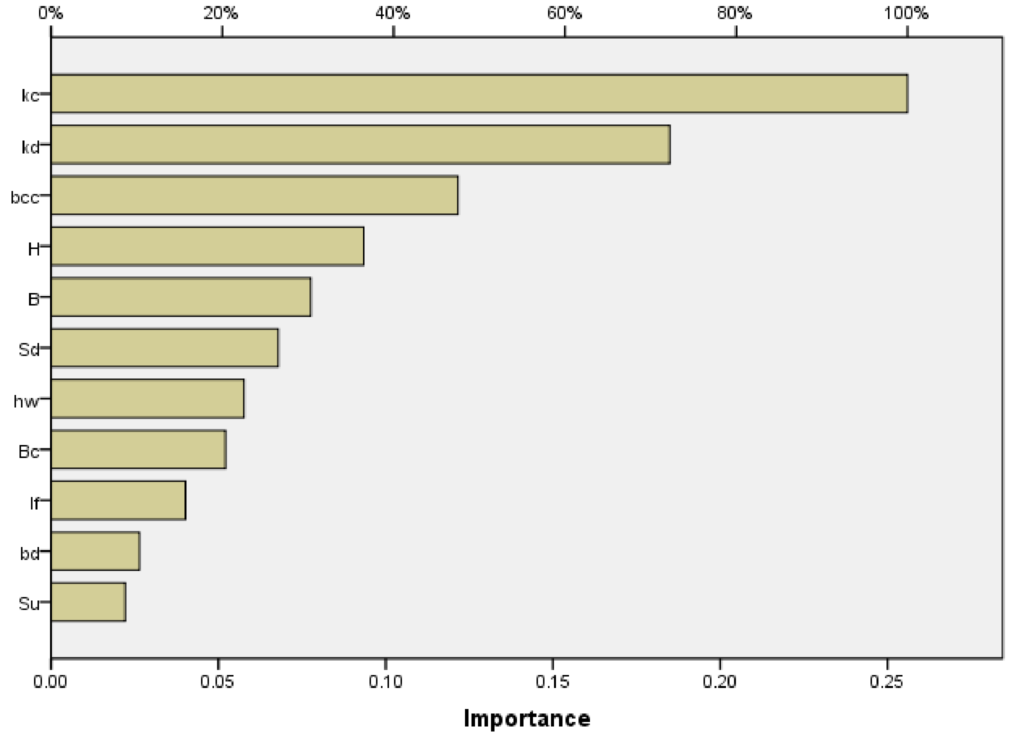


Fig. 7. Normalized importance for input variables.

Regression Model

One of the most important common statistical methods for creating an empirical equation to correlate a set of variables to demonstrate the relationship between them is the regression method. The equations that represent any case consist of a correlation between a dependent variable and several independent variables affecting its evaluation. This study aimed to evaluate key factors impacting critical seepage responses through rigorous computational modeling. The dependent variables examined - seepage discharge (q) and water level height outside the core (Yo) - provided quantitative metrics of performance. The independent variables incorporated encompassed both geometric design parameters defining dam configuration as well as material property inputs representing zone compositions. By systematically varying these predictor factors, their influence on the outcome variables could be compellingly determined. symbolized by (H, b_d, B, h_w, b_{cc}, B_c, S_u, S_d, l_f, h_f, k_d, and k_c).

The statistical analysis performed on the output data from the computational modeling trials indicated the relationships between the dependent and independent variables incorporated in the dam section models were non-linear in nature. Therefore, the multiple nonlinear regression method is used to establish this relationship in the form of two separate equations, the first to estimate the seepage discharge and the second to estimate the water level height emerging from the core by using statistical software (SPSS). We can wright the seepage discharge equation as:

$q = a0\ (H^{a1}\ h_w^{a2}\ B^{a3}\ b_d^{a4}\ S_u^{a5}\ S_d^{a6}\ k_d^{a7}\ b_{cc}^{a8}\ B_c^{a9}\ k_c^{a10}\ l_f^{a11}\ h_f^{a12})$

The parameters [a(0 to 12)] were estimated by using SPSS software for 75% of the database only (150 models) and then verifies with the residual 25% (50 models). Tables (4 and 5) show the parameters estimation, correlation of the parameters, and the analysis of variance for seepage discharge (q) which predict correlation coefficient (r^2 = 96.3%).

Table. 4. Parameter estimates.

Parameter	**Estimate**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	**Upper Bound**
a0	7.483E-6	11.123	-21.994-	21.994
a1	-14.447-	6.583	-27.466-	-1.429-
a2	.257	1.088	-1.896-	2.409
a3	17.191	7.066	3.219	31.163
a4	-1.561-	.575	-2.699-	-.424-
a5	-9.585-	4.019	-17.531-	-1.638-
a6	-6.704-	2.753	-12.147-	-1.260-
a7	.263	.013	.238	.289
a8	-.502-	.026	-.554-	-.450-
a9	-.607-	.081	-.767-	-.447-
a10	.770	.057	.658	.882
a11	-.055-	.322	-.691-	.581
a12	-4.574-	2143644.207	-4238913.538-	4238904.390

Table. 5. Analysis of variance (ANOVA).

Source	**Sum of Squares**	**df**	**Mean Squares**
Regression	.000	13	.000
Residual	.000	137	.000
Uncorrected Total	.000	150	
Corrected Total	.000	149	
Dependent variable: Q			
R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .963.			

Then the predicted equation in (m^3/sec) is:

$$q = \frac{7.483 \times 10^{-6} \times h_w{}^{0.257} \times B^{17.191} \times k_d{}^{0.263} \times K_c{}^{0.77}}{H^{14.447} \times b_d{}^{1.561} \times S_u{}^{9.585} \times S_d{}^{6.704} \times b_{cc}{}^{0.502} \times B_c{}^{0.607} \times l_f{}^{0.055} \times h_f{}^{4.574}}$$

Verification showed a high agreement between the observation results and the results obtained from the predicted empirical equation with a linear correlation coefficient ($r^2 = 97.3$ %), Figure (8).

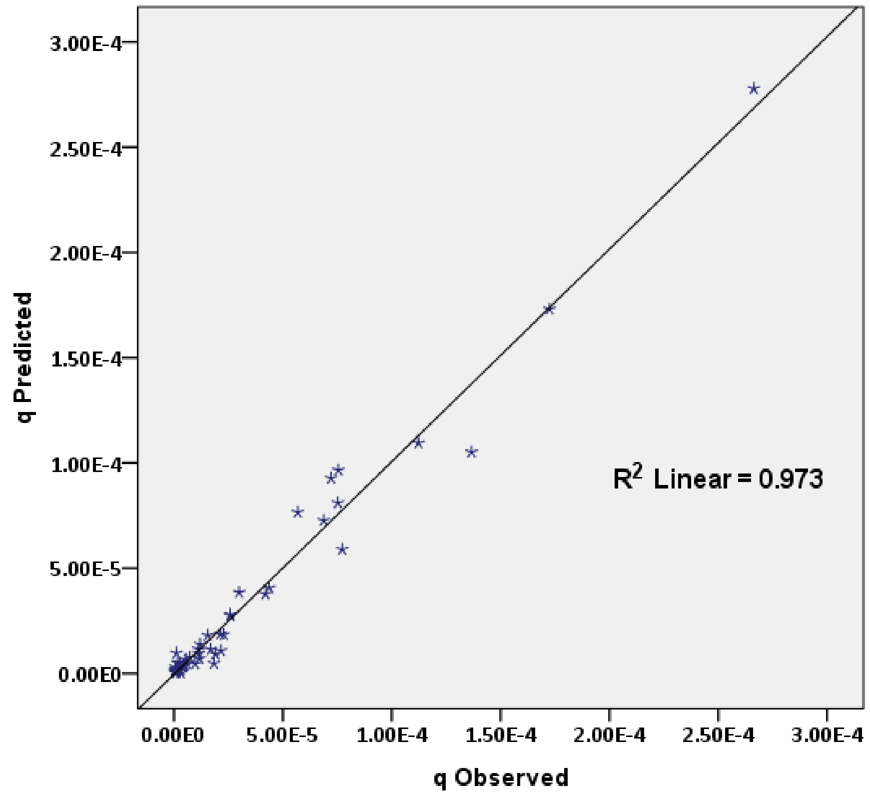


Fig. 8. Comparing the predicted and observed seepage discharge (q).

The same procedure repeated to create water level height out of the core zone (Y_o) equation. Tables (6 and 7) shows the parameters estimation, correlation of the parameters, and the analysis of variance for seepage discharge (q) which predict correlation coefficient ($r^2 = 98.5$%).
The predicted equation for outflow height from core in (m) is:

$$Y_o = \frac{0.007 \times B^{11.379} \times K_c{}^{0.652}}{H^{9.2} \times h_w{}^{0.045} \times b_d{}^{0.969} \times S_u{}^{6.436} \times S_d{}^{1.1113} \times k_d{}^{0.561} \times b_{cc}{}^{0.299} \times B_c{}^{0.174} \times l_f{}^{2.482} \times h_f{}^{2.441}}$$

Table. 10. Parameter estimates.

Parameter	**Estimate**	**Std. Error**	**95% Confidence Interval**	
			Lower Bound	Upper Bound
a0	.007	5356.174	-10591.458-	10591.473
a1	-9.200-	3.643	-16.405-	-1.995-
a2	-.045-	.604	-1.239-	1.149
a3	11.379	3.719	4.026	18.733
a4	-.969-	.253	-1.469-	-.469-
a5	-6.436-	2.067	-10.524-	-2.349-
a6	-1.113-	5.977	-12.933-	10.707
a7	-.561-	.016	-.592-	-.529-
a8	-.299-	.015	-.329-	-.269-
a9	-.174-	.066	-.304-	-.044-
a10	.652	.024	.604	.699
a11	-2.489-	5.782	-13.923-	8.945
a12	-2.441-	1079490.233	-2134620.120-	2134615.238

Table. 12. Analysis of variance (ANOVA).

Source	**Sum of Squares**	**df**	**Mean Squares**
Regression	3910.296	13	300.792
Residual	47.748	137	.349
Uncorrected Total	3958.044	150	
Corrected Total	3106.850	149	
Dependent variable: Y_o			
R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .985.			

The verification between the observed results and the results obtained from the predicted empirical equation is convenient and the linear correlation coefficient is ($r^2 = 96.5$ %), Figure (9).

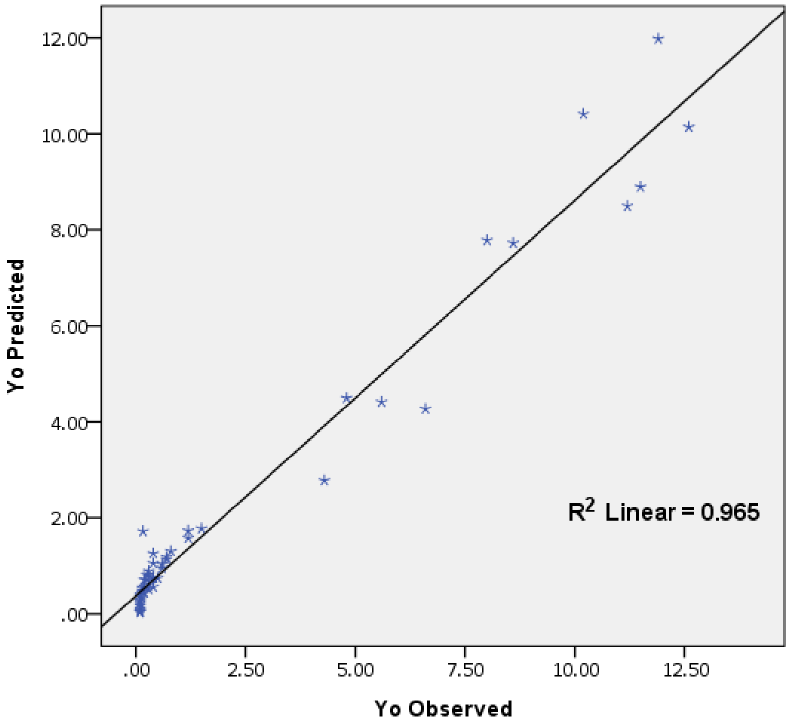


Fig. 9. Comparing the predicted and observed water level height out of the core zone (Y_o).

4. Conclusions

The following conclusions can be deduced:

a- Analyzing the models using Geo Studio software shows a high decrease in seepage discharge quantity for trapezoidal core shape in comparison with rectangular core shape, more than (50%).

b- Also shows direct proportion for seepage discharge with reservoir water level, dam permeability, core permeability, dam base width, and dam height and invisible effect for filter length, dam crest width, and dam upstream slope, while inverse proportion with the other variables.

c- The choice of the number of models adopted, (200) models, was appropriate and sufficient to represent the set of zoned earth fill dams and build the database. This was clear through analyzing the observed results using the artificial neural network (ANN) technique and comparing them with the results predicted and the correlation coefficient was greater than 96% for both seepage discharge and water level height out of the core.

d- Zone materials properties and core shape have the major influence on both seepage discharge and water level height out of the core and minor influence on the dam geometry. Core material hydraulic conductivity had the highest impact on seepage discharge and water level height out of the core while the dam upstream slope had the least impact on them

e- The mathematical equations obtained from the multiple nonlinear regression techniques for the database are considered suitable and accurate to use to estimate both the seepage discharge and the water level height out of the core in zoned earth fill dams easily. Analysis of variance for equations parameters estimation shows high correlation coefficient (r2 = 96.3%) for the seepage discharge equation and (r2 = 98.5%) for water level height out of the core equation.

f- In addition, verification of the predicted results of final equation showed high agreement with the observed results with a correlation coefficient greater than 96% for both, so they may be used directly without the need to use long indirect methods such as software.

g- The seepage estimation equation shows a direct proportion with the reservoir water level, dam permeability, core permeability, and dam base width and inverse proportion with the other variables.

h- Water level height out of the core estimation equation shows direct proportion with core permeability and dam base width only and inverse proportion with all the other variables.

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