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ADVANCED MULTIPLE REGRESSION FOR SEEPAGE ESTIMATION IN AJDABIY RESERVOIR

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ABSTRACT

Seepage plays a critical role in the failure of earth dams, making the control of excessive seepage crucial to prevent such failures. This study aimed to quantify the seepage rate through a homogeneous earth dam equipped with a horizontal filter, utilizing multiple methodologies. The SEEP/W program was employed to analyze 64 models, calculating seepage discharge at varying water depths (5, 6, 7, and 8 meters) with hydraulic conductivity coefficients ranging from 0.000001 to 0.0001. The impact of different values of these essential factors on seepage volumes was evaluated. These results were further analyzed using statistical techniques, including Moderated Multiple Regression (MMR). When the seepage volumes predicted by MMR were compared to those obtained from SEEP/W, the correlation coefficients (R^2) at depths of 5, 6, 7, and 8 meters were found to be 0.985, 0.688, 0.689, and 0.712, respectively. These correlations exceeded those from the nonlinear empirical equations derived from SPSS.

Keywords: Seepage, SEEP/W, MMR, SPSS20, Horizontal Filter.

INTRODUCTION

Earth dams are essential man-made structures designed to create artificial reservoirs. To ensure their stability and prevent sliding and overturning stresses, these dams typically feature permeable materials on the upstream and downstream surfaces, while compacted, impermeable earth layers form the core. When water moves from the upstream reservoir to the downstream toe of a dam, this process is known as seepage, with the phreatic surface marking the highest limit of the percolating water (Singh, 1996).

Effective seepage management requires the careful design of various filter types. However, obtaining analytical solutions to the governing seepage equation, the Laplace equation, is challenging, except in specific cases with simple boundary conditions. Research suggests that numerical examples derived from these equations can complement standard flow net methods, aiding designers in verifying their work (Irzooki, 2016).

Additionally, the stability and seepage performance of earth dams have been evaluated using programs such as GeoStudio and Ansys. A notable difference between these two programs lies in their determination of the safety factor, with Ansys consistently providing more reliable results (Kamanbedast & Delvari, 2012)

Numerical simulations have been employed to evaluate the impact of cutoff walls and horizontal drain length on uplift pressure and seepage in heterogeneous earth dams (Mansuri & Salmasi, 2013) [4].

One notable case study focused on the "Hub" earthen dam in Karachi, Pakistan, where the SEEP/W simulation results were compared with field-collected data for seepage analysis. According to Arshad and Babar (2014), the material properties were calibrated by minimizing discrepancies between the observed and simulated hydraulic heads.

Further research on seepage under hydraulic structures was conducted by Alnealy and Alghazali (2015), who utilized the Slide software to examine the effects of single-layer and multi-layer soils, as well as sloped cut-offs.

Additionally, Mamand (2020) investigated seepage through a filterless homogeneous earth dam by testing various assumptions [6].

Irzooki (2016) developed a new equation for estimating seepage volumes by utilizing SEEP/W software to simulate uniform earth dams with horizontal toe drains.

Çalamak, Bingöl, and Yanmaz (2016) investigated the suitability and effectiveness of blanket and chimney drains in earth-fill dams, evaluating various aspects of the drainage system [7].

In their 2019 study, Li and Bricker analyzed the effects and control of seepage in earth-fill dams using the San Luis dam as a case study. They extensively examined unsaturated and transitory seepage, focusing on pore-water pressures at failure and the progression of the phreatic surface within the fine-grained core to assess drawdown stability [8].

RESERVOIR CONDITION ASSESSMENT

About 20 kilometers southeast of Ajdabiya city, the Libyan government constructed the Ajdabiya dam, an earthen embankment project with a sloping design. At its highest point of 98.4 meters (around mean sea level) and its lowest point of 91.92 meters, the reservoir can hold 4,000,000 m³ of water each day. On a daily basis, the highest recorded inflow is 3,680,000 m³, although the safe capacity is 4,500,000 m³. A 923.2-meter-diameter circular embankment surrounds the reservoir, which is devoid of any natural catchment region. The operational range of the reservoir is 6.48 meters, according to Great Man-Made River in November 2008.[9].

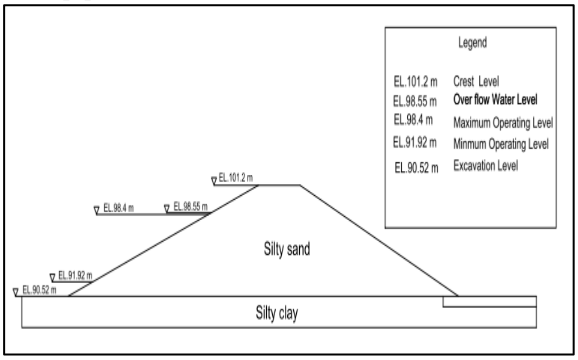

Fig. 1 Current State of the Dam (GMR,2008).

RESEARCH METHODOLOGY

Upstream of the horizontal homogeneous earth dam, the researchers modeled saturated and unsaturated flow under steady-state conditions using the Seep/W program. For this study, we measured seepage discharge through the dam at8,7,6, and 5 meters of water depth. The hydraulic conductivity coefficients, which varied between 0.000001 and 0.0001, were tested with two different slopes, 1/3 and 1/2.5. We ran 64 simulations with different values for each seepage quantity parameter.

Figure 2 illustrates the configuration of the finite element mesh and the boundary conditions used for the seepage analysis. The dam, along with other parts of the finite element model (FEM), was discretized using both triangle and quadrilateral elements. The main model contained 3,282 nodes and 3,114 components. For the steady-state seepage investigation, the boundary conditions were defined by the total head at the upstream and downstream limits

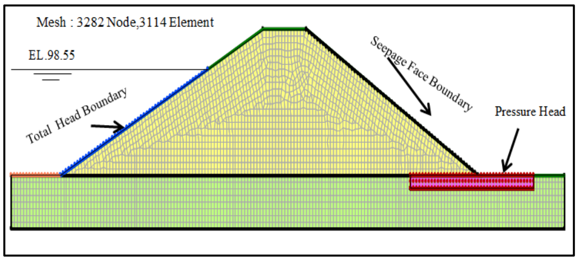

Fig. 2 Location of the boundary conditions

RESULTS OF SEEP/W SIMULATION

The table below display the software results for hydraulic conductivity (*K*) values of 0.0001.

Table 1. Hydraulic Conductivity and Depth Variation (*K* = 0.0001)

Depth	q (m3/day)		p (kpa)		i		v (m/s)	
(m)	Max	Min	Max	Min	Max	Min	Max	Min
8	0.1934	0.0063	78.46	67.32	0.48	0.16	$4.30x10^{-5}$	$1.46x10^{-5}$
7	0.1728	0.0055	68.65	58.13	0.45	0.15	$4.10x10^{-5}$	$1.38x10^{-5}$
6	0.1507	0.0048	57.29	49.67	0.39	0.13	$3.57x10^{-5}$	$1.20x10^{-5}$
5	0.1285	0.0041	45.67	38.81	0.34	0.12	$3.11x10^{-5}$	$1.05x10^{-5}$

DIMENSIONAL ANALYSIS IN SEEPAGE PREDICTION

We start with the idea that fundamental and derived quantities in the natural sciences have different dimensions. It is well-known that dimensional analysis is an effective tool for providing a consistent and methodical explanation of the connections between physical properties.

In this work, seepage volume through homogeneous earth dams with a horizontal drain (Figure 3) was empirically calculated using dimensional analysis. The study isolates the main factors influencing the seepage per unit width (q).

$$q = f\,(p, , i ,d, D) \qquad (1)$$

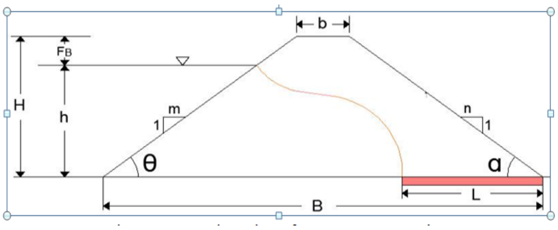

Fig. 3 General Cross-Section of the Earth Dam

OUTCOMES OF STATISTICAL DATA ANALYSIS

Prior to entering the data into the computer for analysis, it was first arranged in ascending order. By analyzing the factors in SPSS version 20, an empirical equation was created to estimate the seepage quantity through homogeneous earth dams with horizontal toe drains.

ANALYSIS USING MODERATED MULTIPLE REGRESSION (MMR):

This section examines the seepage quantity through the dam discharge at different depths, where certain moderating factors impact the internal distance within the dam. Pressure (*p*) and hydraulic gradient (*i*) can have their original connection modified by a moderating variable (*MV*), with distance (*d*) acting as a moderator. We aim to determine how much the linear combination of pressure and hydraulic gradient affects the dependent variable (*DV*), in this case, the amount of seepage (*q*). To further understand the impact of the moderating factor, researchers use multiple regression analysis to examine all independent variables (*IVs*) and the moderating factor through several models. The results regarding the effect of the distance variable on the pressure-hydraulic-gradient correlation are explained in the following sections.

A moderator is an independent variable that changes the conditions under which the relationship between a predictor and an outcome becomes apparent. It explains the context of the relationship between the dependent (DV) and independent (IV) variables. When a moderating variable is introduced, it alters the strength or direction of the link between the two variables, a phenomenon known as the interaction effect.

Moderation effects can be categorized in several ways:

(a) The effect of the predictor on the outcome is magnified when the moderator is enhanced.

(b) Buffering occurs when the moderator reduces the impact of the predictor on the outcome by increasing its own effect.

(c) An antagonistic effect arises when enhancing the moderator renders the predictor ineffective with respect to the outcome.

To evaluate the effect of the moderating variable, moderating multiple regression is used. The primary goal of moderation testing is to determine whether the interaction between the moderator (M) and the predictor (X) significantly predicts the outcome (Y) by analyzing this interaction

MODERATING ROLE OF DISTANCE FACTOR IN DEPTH

According to the theory, the distance factor modifies the connection between pressure and hydraulic gradient, affecting the quality variable at different depths. To test the hypothesis, the following method was used:

At different depths, the interaction between pressure and hydraulic gradient factors, influenced by the distance variable, affects the quality. The impact of pressure and hydraulic gradient, with distance acting as a moderator, is modeled to assess its effect on quality.

$$Y= \beta_0 + \beta_1 X_1 + \beta_2 X_2 + Z\,(\beta_3+\beta_4 X_1 + \beta_5 X_2) +e \qquad (2)$$

The previously mentioned model was used to assess the effect of pressure, hydraulic gradient, distance, and quality on the quality variable. If so, where exactly:

Y = quality variable (*seepage or q*);
β_0 = is the intercept;
$\beta_{i\ (i=1,\dots,5)}$ = the coefficients regression;
X_1 = pressure (*or p*);
X_2 = hydraulic gradient (*or i*);
Z = the moderating variable (*distance or d*).
e = is a residual term.

STEPS FOR RUNNING THE SPSS PROGRAM

Utilizing two models built upon the aforementioned framework, the impact of pressure and hydraulic gradient factors on the quality variable (q) was assessed, with the distance variable controlling these factors. Model 1 includes the moderating variable, while Model 2 does not. Below are the models used to conduct the analysis at depths of 5, 6, 7, and 8 meters.

Table 2. Overview of Models at Depths 5, 6, 7, 8

Depths (m)	Model	R	R^2	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
5	1	.806	.649	.637	.138	
	2	.994	.987	.985	.026	1.661
6	1	.806	.649	.637	.137	
	2	.839	.704	.688	.127	1.532
7	1	.807	.651	.639	.1356	
	2	.839	.705	.689	.1261	1.516
8	1	.805	.649	.636	.1354	
	2	.844	.712	.697	.1236	1.540

a. Predictors: (Constant), *i*, *p*
b. Predictors: (Constant), *i*, *p*, *d*
c. Dependent Variable: *q*

Table 2. Presents a summary of Model 1 and Model 2 for the following depths

1. At 5 depths, Model 2 explains more of the variation in the predictors (hydraulic gradient and pressure) than Model 1. Model 2 has an R^2 of 0.987 and an adjusted R^2 of 0.985, whereas Model 1 has an R^2 of 0.649 and an adjusted R^2 of 0.637. The increase in the variation explained by the modified R^2 is 54.6% for Model
2. Including the moderating variable greatly enhances the overall model fit. At depth 6, Model 2 explains a smaller percentage of the variation in the predictors compared to Model 1. Model 1 has an R^2 of 0.806 (adjusted R^2 = 0.637), while Model 2 has an R^2 of 0.704 (adjusted R^2 = 0.688). The increase in the variation explained by the modified R^2 is 8.0% in Model 2. The addition of the moderating component leads to a small improvement in the overall model fit.
3. At depth 7, Model 2's R^2 of 0.705 (adjusted R^2 = 0.689) shows a slightly higher predictor variation than Model 1's R^2 of 0.807 (adjusted R^2 = 0.651). The corrected R^2 for Model 2 has increased by 8.0%. However, the impact of the moderating factor on the model fit is insignificant.
4. At 8 levels of analysis, Model 2 performs better than Model 1 in adjusting for predictor variation, with an R^2 of 0.844 (adjusted R^2 = 0.712), while Model 1 has an R^2 of 0.805 (adjusted R^2 = 0.649). The adjusted R^2 in Model 2 increases by 9.6 percentage points. The overall model fit is only slightly affected by the moderating component.

To further assess the residuals for autocorrelation (homoscedasticity), the Durbin-Watson statistic is provided in Table 2. An autocorrelation score between 1 and 3 indicates no correlation between the items in the sample. Table 3 presents the coefficients for Model 2 at depths of 5, 6, 7, and 8 meters. Additionally, a comparison of seepage volumes at various depths between Seep/W and the Moderated Multiple Regression Model is also included.

Table 3.Moderate Multiple Regression – Model 2

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	T	p-value
Depth 5	(Constant)	-.472	.048		-9.929	.187
	p	.009	.001	.283	9.893	.000
	i	.037	.067	.110	2.550	.046
	D	.008	.000	1.216	38.814	.000
Depth 6	(Constant)	-1.295	.766		-1.690	.097
	p	.021	.012	.748	2.796	.040
	i	.473	.300	.149	2.578	.046
	D	.039	.012	1.473	3.215	.002
Depth7	(Constant)	-1.320	.779		-1.694	.096
	p	.018	.011	.780	2.715	.041
	i	.376	.265	.136	2.416	.045
	D	.040	.013	1.512	3.177	.002
Depth8	(Constant)	-1.550	.777		-1.996	.051
	p	.019	.009	.887	2.619	.047
	i	.308	.231	.127	2.333	.049
	D	.043	.012	1.619	3.521	.001

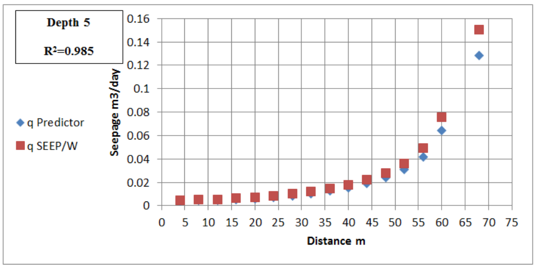

Fig. 4 Comparison at Depth 5

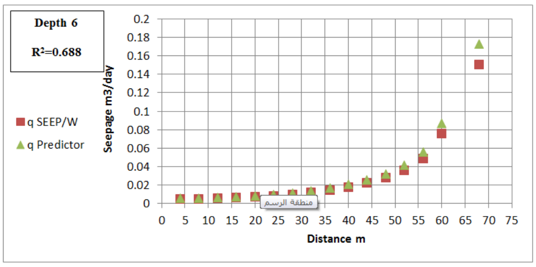

Fig. 5 Comparison at Depth 6

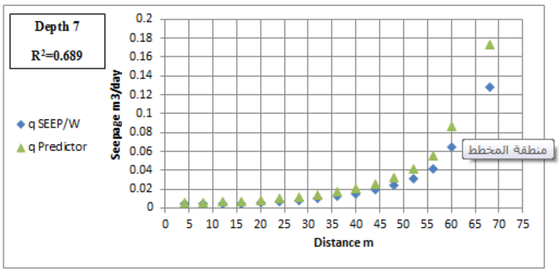

Fig. 6 Comparison at Depth 7

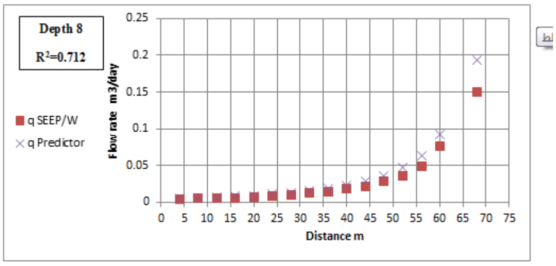

Fig. 7 Comparison at Depth 8

Models have been fitted, predictions made, and residual values typically obtained. The regression equation estimates provide the predicted values, while model diagnostics utilize raw residuals and ten other types, including cumulative residuals. Techniques are available to calculate standard errors for residuals, expected means, and individual predictions..

CONCLUSIONS

After calibrating the models, it is common practice to compute predicted values and residuals. The estimated regression equation provides predicted values, while various forms of residuals, including cumulative residuals, are used to generate raw residuals for model diagnostics. There are several methods available to determine standard errors for residuals, anticipated means, and individual predicted values

1..As one delves deeper into a homogeneous earth dam, the amount of seepage increases. Seepage also grows as the upstream water depth rises and the horizontal toe drain extends.

2.The amount of seepage through earth dams becomes increasingly significant as the hydraulic conductivity coefficient increases.

3.The accuracy of the geometrical equation variable related to seepage discharge is significantly affected by the median variable distance, as demonstrated by the MRR method.

4.We compared the exudation rates obtained using SEEP/W with those from the MRR method. The comparison revealed superior determination coefficients (R^2 = 0.985, 0.688, 0.689, 0.712) at depths of 5, 6, 7, and 8 meters, respectively, in contrast to the nonlinear empirical equations calculated using SPSS.

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