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The Simulation of Seepage Through the Foundations: Hilla Canal Main Regulator as Case Study

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Abstract. This abstract describes a study on the Hilla Canal regulator using the SEEP/W program. The study aims to simulate and validate hydraulic head values obtained from the field. It provides information about the soil properties and mesh sizes used in the simulation and the governing equation used in the SEEP/W program. The simulation results are presented in the form of observed and simulated hydraulic head statistical and computational data, including RMSE, ME, and Maximum Relative Error. The study concludes that the model's performance is good, with an efficiency of 99.999%, and that the comparison of observed and simulated hydraulic head values confirms the model's validity. Overall, the study demonstrates the accuracy and applicability of the SEEP/W program for modeling hydraulic systems.

Keywords: Seepage, SEEP/W program, Numerical analysis, Hydraulic head, Hilla Canal

1. INTRODUCTION

Seepage is the flow of water under the structure or inside it. Under pressure, the water is in contact with both sides of the structure, variations in water level in the structure upstream and downstream, and seepage from the canal body and foundation are significant for technical and economic considerations. Water in arid climates is considered acceptable to have water losses due to seepage from the bodies and foundations of canals and earth structures [1]. After the development of engineering programs, many numerical methods, such as finite element, are widely used using Geo-Studio software in the branch (SEEP/W). Seepage analysis is vital to designing and managing hydraulic structures such as canals, dams, and reservoirs [2]. The Hilla Canal is a crucial component of the irrigation network in Iraq, and any issues with the canal's structure could have severe consequences for the agricultural sector and the livelihoods of the local population. The canal's design was intended to be a component of a larger effort to conserve water resources and reduce maintenance and operational expenses associated with the canal in the future [3]. The distribution of the pore pressure due to the gravity seepage is determined using the flow grid method to ensure the security of the source in the upstream and downstream of structures, and the GeoStudio is used to determine the amount of seepage ratio that occurs under the canal body. This program can estimate flow net parameters such as seepage discharge, exit gradient, seepage velocity, pore pressure, and lifting pressure at any desired point in the flow net [4]. SLOPE/W can analyze a wide range of complex scenarios, such as variations in geometry, soil strength, pore water pressure, analysis methods, and loading conditions. It can effectively analyze steady-state seepage under different soil conditions, elevations, and rapid or sudden drawdown conditions applied on a canal's upstream and downstream sides [5].

The analysis helps evaluate the rate and direction of water flow through the soil and identifies areas where seepage may lead to structural instability or erosion. The penetration ratio (Kx/Ky) in the horizontal and vertical directions was tested on the basic elements to determine how it affected seepage [1]. The safety of the dams is an important part of protecting national exploration. Therefore, it is important to ensure canal safety at all times, the factor of safety against uplift pressure and heave different methods and under different soil conditions and elevations, and the analysis results show that under 3 cases [6]. With Geo-Studio, engineers can analyze water flow through soil layers, estimate seepage rates, and assess the stability of slopes and embankments. In this way, seepage analysis with Geo-Studio can provide critical insights into the behavior of soil-water systems and inform design decisions for engineering projects. By mimicking the intricate interplay among soil components, Geo-Studio software is a powerful tool used to simulate soil behavior and predict the movement of water through it, allowing engineers to identify potential seepage hotspots and optimize the design of hydraulic structures [7]. Several factors affect the stability of an earth canal, including the strength of its bed and bank materials, as well as the flow characteristics. The safety factor is a critical parameter in determining the stability of a hydraulic structure, and the analysis aimed to ensure that the canal could withstand the forces of uplift and heave pressure. This study's results can help improve the canal's water management efficiency and minimize potential structural issues [8]. Therefore, ensuring the safety of canals and dams is crucial for protecting national investments [9]. This paper aims to share information about seepage analysis of canals, including numerical methods and available software, and present various case studies in the literature [10].

2. HILLA CANAL MAIN REGULATOR

Hillah Canal is a canal in Iraq that diverts water from the Euphrates River to Hillah city and its surrounding agricultural lands in Babylon Governorate, southern Iraq. The Hillah Canal Regulator likely refers to the system or structure that controls the water flow in the canal and regulates water distribution to various users. The length of the Hillah Canal is approximately 120 kilometers (75 miles), as shown in Figure 1.

Figure 1: Hilla Canal Main Regulator

The x-axis of point A is measured from the face of the cut-off to the position of the piezometer number 27 in the u/s. The y-axis of this point A is measured from the base of origin down to the start rising height of the piezometer 18.5 in the soil and likewise, for point B, the same method is followed with point A, the difference being point B in the d/s as shown in Figure 2 which shows the locations of the 27 and 28 piezometers.

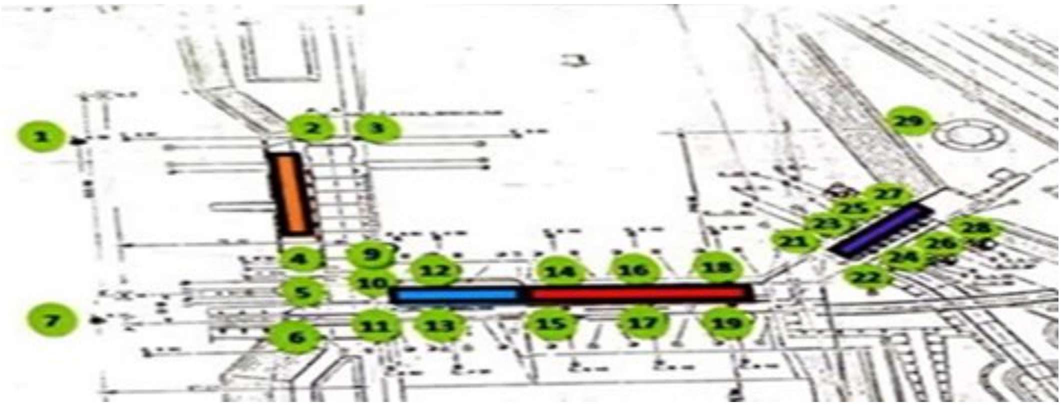

Figure 2: Locations of piezometers 27 and 28.

3. GEO-STUDIO PROGRAM

The primary objective of this paper is to investigate seepage in the foundation of the Al-Hilla Canal main regulator. The canal is analyzed under various circumstances, including the lowest and highest water levels. The subsequent procedures were used to simulate seepage through the dam:

a) Establish the steady state analysis type [19-20].
b) Knowing the locations of the piezometers distributed in the front and back.
c) Drawing Al-Hilla canal regulator.
d) Definition of hydraulic conductivity for the foundation soil layers.
e) Assign material properties defined and boundary conditions.

In the study area, the groundwater is predominantly located in the lower Mesopotamian region, specifically in the Quaternary deposits. These deposits are typically composed of silt, sand, and gravel layers. Silt and shale constitute the bulk of the groundwater deposits in the study area, which exhibit good hydraulic connectivity. Table 1 summarizes the properties of the construction materials used in the Hilla Canal.

Table 1: Soil properties materials for Hilla canal regulator

Material	γ (kN/m³)	k (m/s)	Ø	c (kPa)
Fine to medium silty sand	19.7	0.1	40	0
Plio-Pleistocene deposits	20	0.001	33	10
Very weak calcareous sandstone	20	0.00001	40	0
Clay carbonate mud /siliceous carbonite silt	18.5	0.001	33	0
Concrete protection slab	25	-----	------	----
Transition and filter layer	200	-----	40	0

Geo-Studio used Several meshes to check porewater pressure at the same point as in Table 2.

Table 2: Mesh size checking for the Hilla canal regulator.

No.	Meshes size (m)	Total water head (m)
1	0.5	30.7062
2	0.25	30.7163
3	1.0	30.6875

The variation of the difference between 1 and 2 = (0.03) and 3 and 2= (0.09), generally finer mesh sizes provide more accurate results but require more computational resources and longer analysis times. Using 0.5 mesh in the case study achieved the highest accuracy in the analysis, and observing that the percentage difference in readings is not more than 5% when analyzing meshes of different sizes.

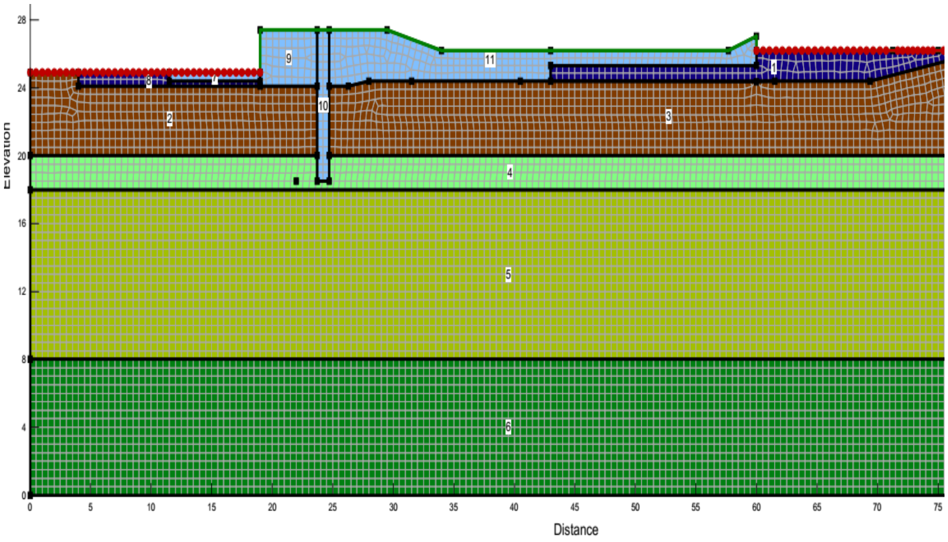

Figure 3: General mesh formation for Hilla canal regulator.

4. GOVERNING EQUATION

The following partial differential equation (PDE) is the governing equation used for the modeling of SEEP/W program [9]:

$$\frac{\partial}{\partial x}\left(kx\,\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(kx\,\frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t} \qquad (1)$$

Where H = Hydraulic head (m) and kx and ky = hydraulic conductivity values in the x and y directions, respectively.

4.1 Observed and Simulated Hydraulic Head Statistical Computational

The hydraulic head refers to the water height above a reference point in a hydraulic system. It is often used to calculate the pressure and flow in groundwater or subsurface flow systems. Observed hydraulic head refers to the measured hydraulic head values, while simulated hydraulic head refers to values calculated using computer models. The simulation of hydraulic heads typically involves using mathematical models and statistical techniques to account for the complex interactions between water flow and the subsurface environment. Table 3 demonstrates that validating a model involves comparing its simulated results with the observed data. The purpose of this comparison is to ensure that the model is applicable and accurate simulation model through various statistical parameters such as RMSE (Root Mean Squared Error), ME (Mean Error), and Maximum Relative Error. The model's performance is considered good, with an efficiency of 99.99%, as shown in Table 4. The model's validity is further verified by comparing the observed values in the field with those extracted from the Geo-studio SEEP/W program and by comparing the readings with changing water total head. The comparison shows that the difference is slight, which confirms the correct performance:

$$\mathrm{ME} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Hsi} - \mathrm{Hoi}) \tag{2}$$

$$\mathrm{RMSE} = \left[\frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Hsi} - \mathrm{Hoi})^2\right]^{0.5} \tag{3}$$

$$\mathrm{EF} = 1 - \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Hsi}-\mathrm{Hoi})^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{Hoi}-\mathrm{Hoa})^2} \tag{4}$$

Table 3: Observed and simulated hydraulic head for Hilla canal regulator.

Upstream	Downstream	result	from site	HOi	HSi	Error	HSi - HOi
31.65	29.5	30.020	30.45	30.45	30.020	1.412	-0.430
31.95	30.7	31.002	31.15	31.15	31.002	0.474	-0.147
31.90	30.5	30.839	31.13	31.13	30.839	0.936	-0.291
31.80	30.1	30.511	30.82	30.82	30.511	1.002	-0.309
31.75	30.4	30.727	30.90	30.90	30.727	0.561	-0.174
31.65	29.5	29.966	30.29	30.29	29.966	1.069	-0.324
31.95	30.7	30.971	31.02	31.02	30.971	0.158	-0.049
31.90	30.5	30.804	31.01	31.01	30.804	0.666	-0.207
31.80	30.1	30.469	30.67	30.67	30.469	0.657	-0.202
31.75	30.4	30.693	30.77	30.77	30.693	0.252	-0.077

Where HSi is the value of the simulated head, (Hoi) is the value of the observed head, and (Hoa) is the average or mean of the observed head.

Table 4: Summary of Statistical Parameters Showing Model for Hilla canal regulator.

Statistical parameters	Value
Mean Error (ME)	-0.221
Root mean Square Error (RMSE)	0.248
Model Efficiency (EF)	99.159
Maximum relative error	1.412

The comparison between the observed and simulated values has shown that the difference between the two does not exceed 1%. This result is considered safe, indicating that the simulation model is accurate and reliable.

4.2 Seepage Flux and Maximum Seepage Velocity

Seepage Flux is the rate at which water flows through a unit area in a porous medium. It measures the volume of water that passes through a specific area in a given time. Seepage flux is an important parameter in seepage analysis because it helps to understand water flow through the soil. Maximum Seepage Velocity is the maximum velocity water flows through a porous medium. It is an important parameter in seepage analysis because it can help to determine the potential for erosion or scouring of soil or other materials due to high water velocities for three studied cases are shown in Table 5, and Figures 4 and 5 show the relationship between actual water level and seepage flux and seepage velocity. Maximum state: upstream 31.95, downstream 30.7. Normal state: upstream is 31.75, downstream is 30.4. Minimum state: upstream is 31.65, downstream is 29.5.

Table 5: Computed seepage flux, Max seepage velocity model for Hilla canal regulator.

Parameter	Maximum state		Normal state		Minimum state	
points	A	B	A	B	A	B
Seepage flux (m^3/sec/m) ×10^{-7}	1.68	1.66	1.81	1.79	2.88	2.85
Max seepage velocity (m^2/sec) ×10^{-20}	1.29	1.02	1.55	0.11	5.21	0.19

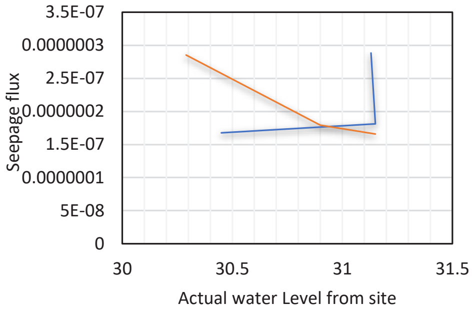

Figure 4: Simulated seepage flux versus surface actual water level from the site.

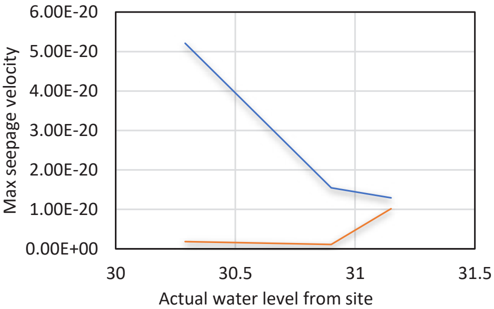

Figure 5: Simulated max seepage velocity versus actual water level from the site.

5. SEEPAGE ANALYSIS

Firstly, seepage analysis is conducted to determine the steady-state seepage. Then, the upstream and downstream slopes are assessed when conducting seepage analysis. It is common first to establish the steady-state seepage condition, which refers to a situation where water flows through the soil or rock has reached a relatively constant state. This is typically done by simulating the seepage over an extended period until the flow rates and pressures have stabilized. Once the steady-state condition has been established, it is important to check the slopes of the structure's upstream and downstream sides being analyzed. This is because the terrain's slope can significantly impact the seepage flow and pressure distribution. On the upstream side, it is important to note that a steep slope can result in faster water flow and higher pressure on the structure, while a gentle slope can lead to water spreading out and reduced pressure. Regarding the downstream side, it is worth noting that a steep slope can cause water to accumulate and increase pressure, whereas a gentle slope can facilitate easier drainage and decreased pressure. By checking the slopes of both the upstream and downstream sides, the engineer can ensure that the seepage analysis accurately reflects the actual conditions and identify any areas where additional measures may be needed to mitigate the risks initially. The maximum water level is shown in Table 6 (a-Water total head, b-Pour water pressure, c-Pressure head, d-Water flux, e-Water XY gradient).

Table 6: Water total head, porewater pressure, pressure head, water flux, and water xy gradient for a maximum water table for the Hilla canal regulator.

Parameter	**Water total head (m)**		**Porewater pressure (m)**		**Pressure head (m)**		**Water flux × 10^{-07}**		**Water XY gradient**	
Points	A	B	A	B	A	B	A	B	A	B
	31.01	30.97	120.16	118.58	12.25	12.09	1.676	1.791	0.163	0.166

6. THE HYDRAULIC GRADIENT

Checking the hydraulic gradient is crucial for seepage analysis. It determines flow direction and rates through porous media, ensuring consistency and acceptability. Figures 6 to 9 show XY gradient, water total head, porewater pressure, and pressure head for the maximum water table.

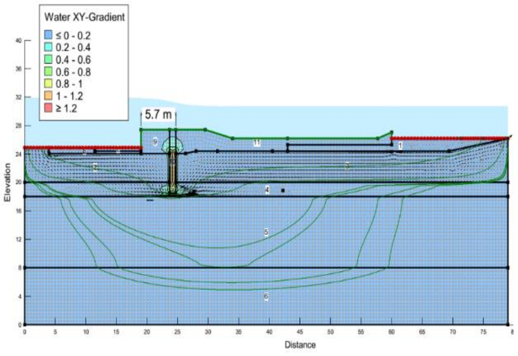

Figure 6: XY gradient for max water table.

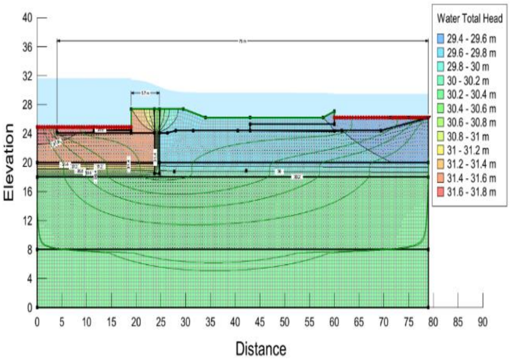

Figure 7: Water total head.

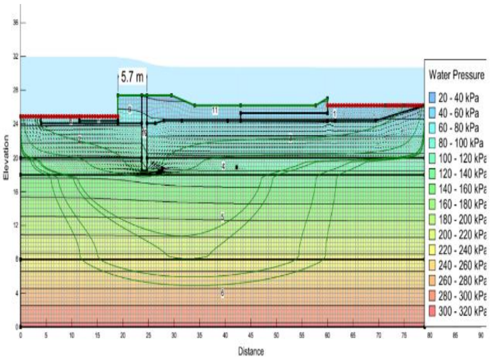

Figure 8: Porewater pressure.

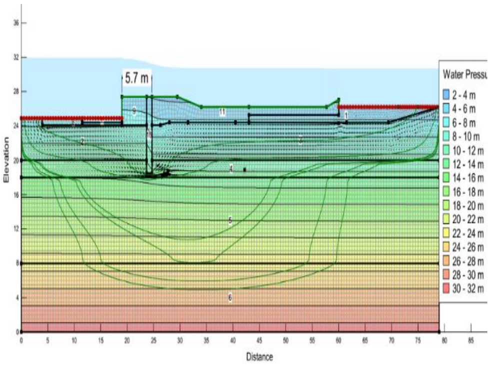

Figure 9: Pressure head.

All these figures in upstream 31.95 and downstream 30.7. From Figure 6, it found the maximum exit hydraulic gradient (i_e) is (0.2), (1/0.2) = 5. For different cases, the factor of safety against heave is calculated as below equation:

$$\mathrm{Fs} = \mathrm{i_{cr}}/\mathrm{i_{ave}} \qquad \mathrm{Fs} = 1/(\mathrm{head}/\mathrm{length}) \tag{6}$$

For minimum water level=1/(5.75/75)=13.04, for normal water level =1/(6.85/75)= 10.94 and for maximum water level=1/(7.05/75)=10.6.

Table 7: The results of the hydraulic safety criteria according to the (USBR,2014) for Hilla canal regulator.

Safety factor	Value	(USBR, 2014) limits	Safety state
Against heave	5	Not less than 4	Acceptable
Against uplift	10.60	Not less than 2	Acceptable
	10.94		
	13.04		

7. CONCLUSIONS

In this paper, a simulation has been made for the Al-Hilla canal regulator to check the seepage in the foundation. The Geo-studio SEEP/W program has made this simulation, and after reviewing its reliability with the observed piezometer reading, an analysis has been made for maximum, moderate, and minimum water levels upstream, and the following results are found:

- Due to the water pressure underneath it, the minimum safety factor against uplift on the base of the regulator was 10.6, and the values exceeded the minimum acceptable threshold of 2.
- The safety factor against heave is 5, higher than the minimum acceptable value of 4.
- The variation in seepage flux before and after the sheet pile was about 1.04% when the water was at a maximum level upstream.
- The variation in the Water XY gradient before and after the sheet pile was about 1.84% when the water was at a maximum level upstream.
- All these conclusions prove that the Al-Hilla canal regulator is considered structurally safe and acceptable for its intended purpose.

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