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Seepage Quantity Analysis Beneath Concrete Dams with Various Sheet Piles using Different Numerical Models

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Abstract: Seepage is a dangerous phenomenon under hydraulic structures and the main cause of failure and damage to dams when neglected and not processed. This study evaluates the numerical effects of the sheet piles' quantity, depth, and spacing beneath a concrete dam with isotropic and homogenous foundations on the seepage rate, pressure head, and exit gradient. The solutions were obtained using SEEP/W code in GeoStudio software 2018 for three configurations using single, double, and triple sheet piles. In addition, SLIDE software 6.02 was examined using single and double sheet piles. Dimensional analysis was applied to draw the dimensionless variables that affect the seepage rate and exit gradient, and all tests were repeated for three different sheet pile depths and distances from the heel of the dam. The findings showed that the seepage rate in all studied configurations reduced when sheet pile depth increased. The position of the sheet pile from the dam's toe significantly decreased the seepage rate in cases using single and double sheet piles, while in cases using three-sheet piles, the position of the middle sheet pile insignificant decreased seepage. It was recognized that when using a single sheet pile, the drop in pressure head increased with depths when the sheet pile was located at the heel and middle of the dam. In addition, in the case of a single sheet pile at the toe or using two and three-sheet piles, the pressure drop decreased as the depths increased. Also, the results showed that the middle sheet pile location in the case of three sheet piles slightly affected pressure reduction. Furthermore, the results showed that using two and three-sheet piles was more effective than using a single one in reducing the exit gradient, while the position of the middle one in the case of using three-sheet piles was insignificant. A nonlinear empirical equation was developed using SPSS 22 program, and the comparison of the seepage rate measured by SEEP/W and SLIDE software versus its quantity calculated from empirical equations showed a good agreement as the determinations (R^2) coefficients were equal to 0.9779 and 0.9928, respectively.

تحليل كميات التسرب تحت السدود الكونكريتية باستخدام الركائز العريضة المتنوعة وباستخدام نماذج عددية مختلفة

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الخلاصة
يعتبر التسرب ظاهرة خطيرة تحت المنشآت الهيدروليكية والسبب الرئيسي لفشل وتلف السد عند إهماله وعدم معالجته. تهدف هذه الدراسة إلى تقييم التأثيرات العديدة لكمية الركائز العريضة واطوالها وتباعدها تحت السد الخرساني مع أساسات متماثلة ومتجانسة على معدل التسرب وارتفاع الضغط الهيدروليكي والانحدار الهيدروليكي عند المخرج. تم تحليل النتائج بتطبيق برنامج SEEP/W على الركائز العريضة المفردة والمزدوجة وثلاثية الركائز، على التوالي. بالإضافة الي تطبيق برنامج SLIDE على الركائز العريضة المفردة والمزدوجة. تم تطبيق التحليل البعدي لرسم العلاقات بين المتغيرات التي بلا وحدات و التي تؤثر على معدل التسرب، و الانحدار الهيدروليكي عند المخرج، وتكررت جميع الاختبارات لثلاثة اطوال مختلفة من الركائز العريضة و لمسافات مختلفة عن مقدم السد.تظهر النتائج أنه ، في جميع التكوينات ، يتم تقليل معدل التسرب عند زيادة عمق الركيزة. موضع الركيزة من مقدم السد له تأثير كبير على تقليل معدل التسرب في الحالات التي تستخدم فيها ركائز مفردة ومزدوجة، بينما في الحالات التي تستخدم فيها ثلاثة ركائز ، فإن موضع الركيزة الوسطى ليس له تأثير كبير على معدل التسرب. بالإضافة إلى ذلك، في حالة وجود الركيزة في مؤخر السد، او استخدام اثنين، وثلاث ركائز فان انخفاض الضغط المؤثر يقل مع زيادة الأعماق. أظهرت النتائج أيضًا أن موقع الركيزة الوسطي في حالة استخدام ثلاث ركائز صفائحية له تأثير طفيف على تقليل الضغط المؤثر أسفل السد. علاوة على ذلك، أظهرت النتائج أن استخدام ركيزتين او ثلاثة ركائز كان أكثر فاعلية من استخدام ركيزة مفردة في تقليل الانحدار الهيدروليكي عند المخرج مع زيادة الأعماق، بينما لم يكن موضع الركيزة الوسطى في حالة استخدام ثلاثة ركائز فعالا. تم تطوير معادلة تجريبية غير خطية باستخدام برنامج SPSS 22، وأعطت مقارنة معدل التسرب المقاس بواسطة برنامج SEEP / W وSlide مقابل كميته المحسوبة من المعادلات التجريبية توافقًا جيدًا حيث إن معامل التحديد (R^2) كان يساوي 0.9779 و 0.9928 على التوالي.

الكلمات الدالة: تدرج المخرج، السدود الثقالية، شحنة الضغط، SEEP/W، SLIDE Seepage.

1.INTRODUCTION

Seepage problems represent a special weight in the concrete dams' safety considerations. Dams are usually subjected to various influences related to their safe operation and existence, such as the foundation deformation, the strength of their materials, stability conditions, and aging. Seepage, however, plays a special role in unison, with all these factors exasperating them in addition to its negative role [1]. The groundwater flow depends on the type of flow, the soil medium, and the boundary conditions [2]. To assess seepage through the foundation, the uplift pressure under the hydraulic structures should be estimated. Failure in the hydraulic structure is possible when seepage occurs over an extended period without protection, resulting in property damage and human casualties. Many researchers have investigated the quantity of seepage in different types of dams; the following are some of them. For a gravity dam with two sheet piles, (Ahmed and Elleboudy) [3] studied the impact of various sheet pile configurations on seepage losses, uplift pressure, and the exit gradient under the hydraulic structures using the finite element method that is based on the fixed mesh approach. It was concluded that the uplift force operating on the structure and the exit gradient at the end toe of the floor was unaffected significantly by the sheet pile being extended laterally through the canal's banks. (Mohammed-Ali) [4] evaluated the total uplift pressure under dams using a finite difference method and a relaxation technique for all cases of middle sheet piles of varying sizes and locations under the hydraulic structure. The results showed that when the middle sheet pile was positioned to converge downstream, the percentage of reducing uplift pressure increased and that the middle sheet pile length influenced how much uplift pressure dropped beneath hydraulic structures. (Zainal) [5] investigated the effect of the cutoff wall angle, which varied from 0° to 180° using the GeoStudio SEEP/W computer. The findings indicated that the optimum angle to reduce water flow was around 60°, the best angle to reduce uplift pressure was about 120° to 135°, and the best angle to reduce exit gradient was about 45° to 75°. (Alnealy and Alghazali) [6] tested the "SLIDE" program to analyze seepage flow under the hydraulic structure through single and multi-layers soils and its effect on structures with inclined cutoff downstream, upstream, and both of them. The minimum values of the uplift pressure and seepage quantity occurred when using a cutoff at the upstream side with an angle of 45°, and the minimum value of the existing gradient occurred when using a cutoff at the downstream side with an angle of 120°. (Uday and Hasan)

[7] adopted SEEP/W software and the SLIDE V.5.0 program to analyze the hydraulics of uplift pressure under the gravity dam and its effect on the gallery drain usage and without the gallery drain for different reservoirs and drain locations along the dam's base. They concluded that the uplift force was reduced by more than 40% and 20% when sheet pile and gallery drain, respectively, were used in the system. (Jamel) [8] studied the effect of using upstream and downstream sheet piles in a double soil layer on the seepage and uplift pressure exit gradient at the toe of the hydraulic structure using SEEP/W and verified the suggested equations. with an artificial neural network (ANN). The verification showed differences of less than 5%, 2%, and 6% for exit gradient, discharge, and uplift pressure, respectively, at the toe of the hydraulic structure. (Nourani, et al.) [9] examined how the drain pipes' placement from the dam's upstream face, the distance between them, and the drain's diameter affected the uplift force reduction. According to the findings, installing a drain system reduced the uplift forces generated beneath the structure's floor; however, the uplift may be ineffectively reduced if the drain was located close to the dam's face. (Saleh) [10] developed two artificial neural network (ANN) models for seepage quantity and exit gradient, respectively, using SEEP/W software. The variables considered were the difference in the head, the distance between piles, the downstream pile length, the upstream pile length, and the downstream and upstream inclined angles of the sheet piles. According to the findings, the soil permeability coefficient significantly impacted the seepage rate, and in terms of exit gradient, the distance between piles significantly impacted the exit gradient. (Rasool) [11] evaluated the uplift pressure and exit gradient effect of mutual interference piles on seepage phenomena using the finite element program ANSYS. It was found that the use of the pile upstream reduced the uplift pressures by 8.36%, and the use of the pile downstream increased them by 11.66%; the flow rate was reduced by 66.8%, and the exit gradient of the hydraulic structures was reduced by 28%. Seepage and piping are serious problems threatening dam safety, particularly uncontrolled ones. They can erode the dam's base and cause it to fail. This study aims to investigate and fill gaps explored in earlier research, particularly for gravity dams, by considering more configurations and geometries of sheet piles that affect uplift pressure and exit gradient. Also, to illustrate the ability of the SEEP/W code in (GeoStudio software 2018) and (Slide software 6.02) to simulate the process of analyzing data. The goals of this study extend to develop a nonlinear empirical equation for seepage rate using (SPSS 22) program.

2. METHODOLOGY AND APPLICATION

2.1. Dimensional Analysis

The present study's numerical modeling of SEEP/W 2018 and SLIDE V.6.02 program for water seepage through homogenous and isotropic soil foundation and steady-state flow is based on the partial differential equation Laplace's equation [12].

$$k_x \frac{\partial^2 h}{\partial^2 x} + k_y \frac{\partial^2 h}{\partial^2 y} + k_z \frac{\partial^2 h}{\partial^2 z} = 0 \quad \textbf{(1)}$$

Moreover, for two-dimensional flow and homogeneous isotropic soil with respect to permeability, $k = k_x = k_y$, and the continuity equation is simplified to Eq. (2), usually referred to as Laplace's equation.

$$\frac{\partial^2 h}{\partial^2 x} + \frac{\partial^2 h}{\partial^2 y} = 0 \quad \textbf{(2)}$$

In this study, a dimensional analysis using Buckingham's π theorem was applied to predict the dimensionless parameters that affect the seepage rate under the homogenous and isotropic foundation of a proposed concrete dam. The geometric parameters of the dam model are presented in Table 1 and shown in Fig. 1.

The variables that might have an impact on the seepage rate are:

q	Seepage rate (L³/T/L)
X	The horizontal distance of the sheet pile center from the dam heel (L).
B	Base width of the dam (L).
D	Depth of previous layer (L).
H	Water head (L).
d_1, d_2, d_3	Depth of u/s,d/s and intermidiate sheet piles respectivily (L).
K	Coefficient of hydraulic conductivity (L/T).
G_H	Exit hydraulic gradient in the case of a cutoff wall downstream (toe) of the dam.
G_{Ho}	Exit hydraulic gradient without a cutoff wall downstream (toe) of the dam.
ρ	Density of water (M/L³), and g: gravity acceleration (L/T²)

$$\emptyset\,(q, B, D, H, X, d_1, d_2, d_3, k, \rho, g, G_{HO}, G_H) = 0 \quad \textbf{(3)}$$

B and D are constants; one of them will be considered, as in Eq 4.

$$\emptyset\left(\frac{q}{kH}, \frac{X}{B}, \frac{d_1}{B}, \frac{d_2}{B}, \frac{d_3}{B}, \frac{G_H}{G_{HO}}\right) = 0 \quad \textbf{(4)}$$

Table 1 The Dam Model's Parameters.

Parameters	Values (m)
Upstream water head behind the dam (H)	25
Depth of impervious layer (D)	25
Base width of the dam (B)	23
Width of sheet piles	1
d_1 depth of upstream (u/s) sheet pile	5, 10 and 15
d_2 depth of downstream (d/s) sheet pile	5, 10 and 15 for (case I) 6.5m, 11.5m and 16.5m for (case II) and (case III)
d_3 depth of intermediate sheet pile	5, 10 and 15
Horizontal distance of the sheet pile center from the dam heel (X)	0.0 for (u/s) sheet pile 11.5 for (middle) sheet pile 23 for (d/s) sheet pile 8, 11, 14, 17 and 20 for middle sheet pile in (case III)
Gravity dams are applicable in rigid foundations hydraulic conductivity (k) for the saturated, homogeneous, and isotropic foundation [13].	1 x 10^{-11} m/s

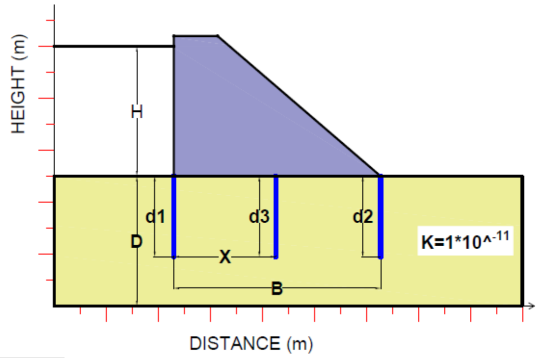

Fig.1 Schematic Diagram of the Gravity Dam.

2.2. Mesh Distribution

The grid size was determined through trial and error to test mesh dependence on the seepage discharge volume, and the variations in the seepage amount were very slight. Based on these results, all the calculations were performed using the best approximate element size for SEEP/W software, 1 m with 1823 nodes and 1725 elements in the mesh region. In addition, for SLIDE software triangles, only 657 nodes and 1212 elements were selected in all runs due to the minimum seepage rate.

2.3. Implementation of Numerical Models

The seepage rate (q) was determined for each run for both Geostudio (SEEP/W)) and SLIDE software, and the dimensionless parameters, as stated in Eq. 4, were then calculated and compared with the condition of no sheet piles supporting the gravity dam. The impact of these variables on seepage rate, uplift pressure head, and exit gradient was investigated in 25 tests for SEEP/W and 13 tests for SLIDE software using three cases, with the tests repeated for three different sheet pile placements and depths. As in Case I, a single sheet pile was upstream (u/s). Then, Case II represents two sheet piles located upstream (u/s) and downstream (d/s) of the dam. Finally, Case III indicates three sheet piles located upstream (u/s), downstream (d/s), and the intermediate sheet pile. All results are summarized in tables; all percentiles were for the best conditions.

3. RESULTS AND DISCUSSIONS

In this section, all figures are repeated for three different sheet pile depths and positions using the Geostudio (SEEP/W) for three cases and the SLIDE software for two cases.

3.1. Flow Net Patterns (Case I, Case II, and Case III)

In Case I, one single sheet pile was considered upstream of the dam, and the tests were repeated for three different distances from the heel of the dam (X = 0.0, 11.5, and 23 m, respectively), and three different sheet pile depths (d_1 = 5, 10, and 15 m). Fig.2. shows the net flow patterns for a single sheet pile with a depth of 15 m at locations at the dam's heel and toe for SLIDE and SEEP/W software, respectively. In case II, two sheet piles, one upstream and the other downstream of the dam, were considered, as shown in Fig 3. All tests were repeated for three distinct sets of depths (d_1 = 5 and d_2 = 6.5 m; d_1 = 10 and d_2 = 11.5 m; and d_1 = 15 and d_2 = 16.5 m). In case III, three sheet piles were considered at the dam's heel, toe, and midsection. The three sets of sheet pile depths (d_1 = 5, 10, and 15 m; d_2 = 6.5, 11.5, and 16.5 m; and d_3 = 5, 10, and 15 m, respectively) were used in all tests. As shown in Fig.4, the center one was situated at various distances from the dam's heel (X = 8, 11, 14, and 17 m, respectively).

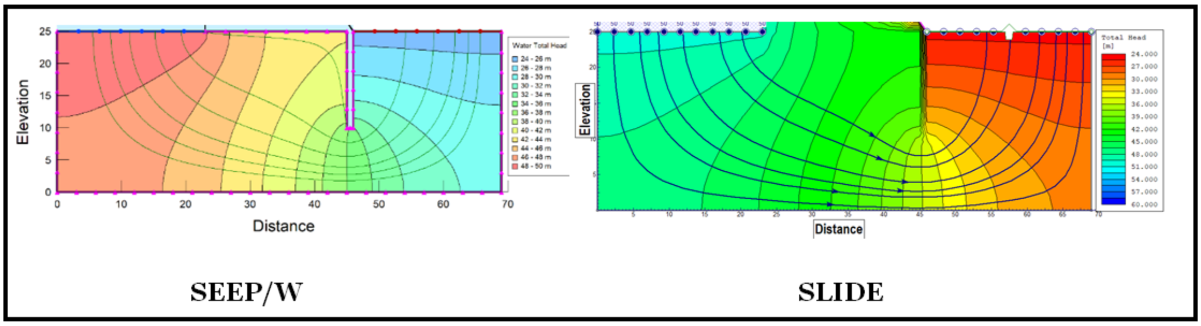

Fig.2 Flow Net Pattern for Case I (d1=15 m).

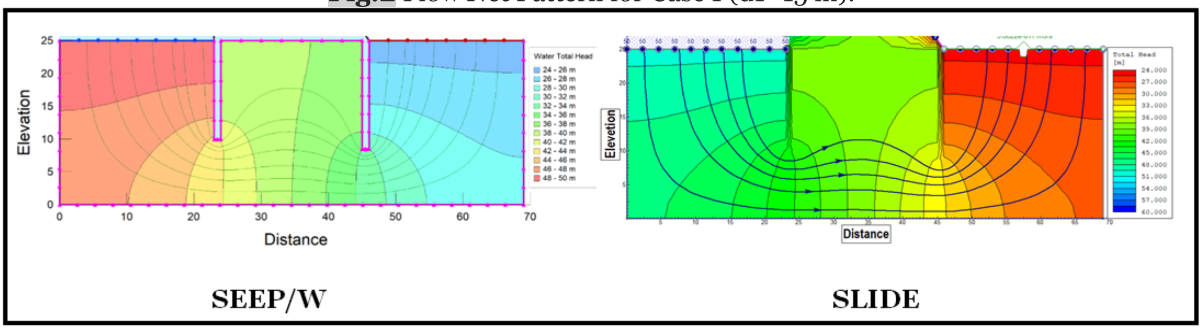

Fig.3 Flow Net Pattern for Case II (d_1=15 and d_2=16.5 m).

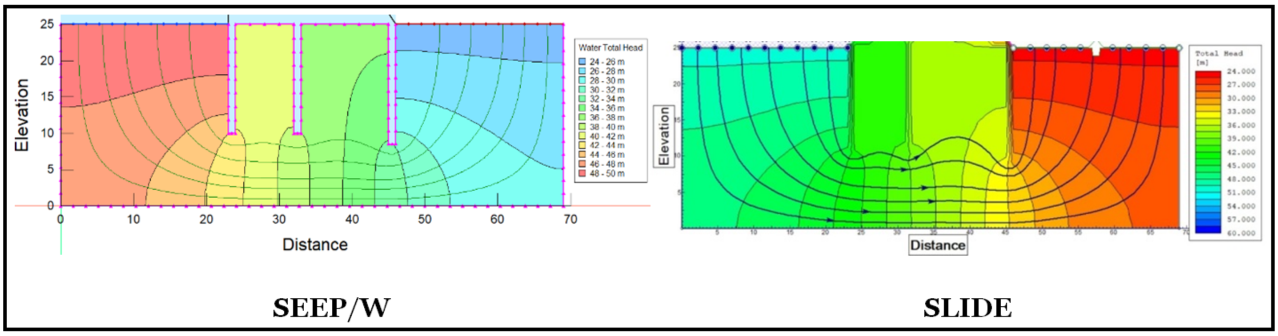

Fig.4 Flow Net Pattern for Case III (d_1=15, d_2=16.5 and d3 = 15m; X=8 m).

3.2 Impact of Sheet Pile Location and Depth

Fig.5 (a, b, c) and Table 2 demonstrate that the seepage rate decreased for Case I and Case II as the sheet pile depths increased. Also, it was emphasized that the sheet pile position relative to the dam's toe potentially affected decreasing seepage. Furthermore, it was recognized that the middle sheet pile location, when adding a third sheet pile in Case III, insignificantly impacted the seepage rate reduction. The results were consistent for both SEEP/W and SLIDE programs.

3.3 Effect on relative exit gradient

Fig. 6 (a, b, c) show that as the sheet pile depth increased and when its position approached the dam's toe, the relative exit gradient increased. While for Case III, it was confirmed that the middle sheet pile location unaffected the exit gradient reduction, see Table 3.

3.4 Variation of pressure head (p/γ) with the sheet pile depth and position.

For both SEEP/W and Slide software, Fig.7 (a) shows that for Case I, as the sheet pile depth increased, the percentage of uplift pressure reduction increased when the single sheet pile was located at the heel and middle of the dam, while it decreased when located at the dam toe. It concluded that the sheet pile at the dam's heel was highlighted as having the most significant impact on reducing pressure head. Fig.7 (a, b) demonstrate that as the sheet pile depth increased, the pressure head drops decreased, and the sheet pile location in Case III unmeasurably impacted pressure head reduction, as tabulated in Table 4.

3.5 Empirical Equation for Determining the Seepage Quantity

The seepage quantities obtained from SEEP/W and Slide software were compared using dimensionless parameters of Eq. (4) results in the SPSS 22 program and an empirical equation of seepage rate were predicted for both programs. Eqs. (5, 6), as shown below, were derived from a specified range of independent variables, $0.022 < \frac{X}{B} < 0.978$ and $0.217 < \frac{d}{B} < 0.652$, considering a single sheet pile for both software.

$$\frac{q}{kH} = 0.512 - 0.258\left(\frac{d}{B}\right) - 0.092\left(\frac{d}{B}\right)^2 + 0.208\left(\frac{X}{B}\right) - 0.278\left(\frac{X}{B}\right)^2 \quad \textbf{(5)}$$

$$\frac{q}{kH} = 0.369 - 0.054\left(\frac{d}{B}\right) - 0.271\left(\frac{d}{B}\right)^2 + 0.217\left(\frac{X}{B}\right) - 0.289\left(\frac{X}{B}\right)^2 \quad \textbf{(6)}$$

The coefficients of (R^2) were 0.9779 and 0.9928, respectively, as shown in Fig. 8 (a, b), which shows a good agreement between the calculated discharge from Eqs. (5, 6) and those from the SEEP/W model and slide accordingly.

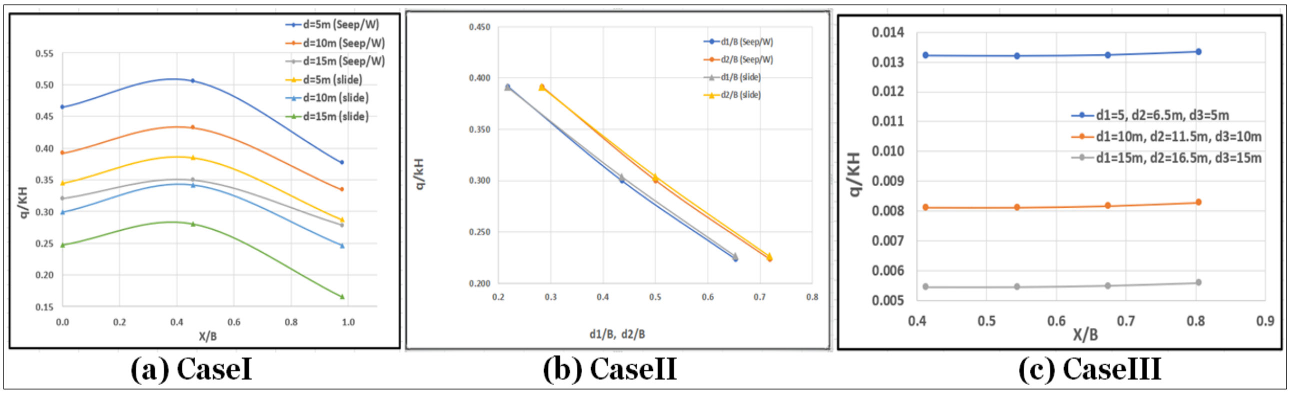

Fig.5 Variation of Seepage Rate (q/kH) with Respect to the Sheet Pile's Depths and Distances from the Heel of the Dam(X/B) **(a)** Single Sheet Pile, **(b)** Double Sheet Piles, and **(c)** Triple Sheet Piles.

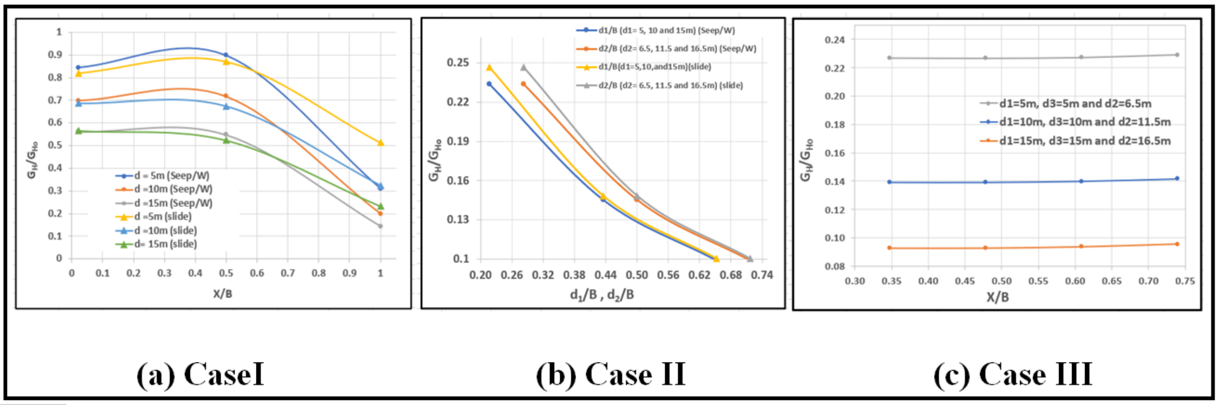

Fig.6 Variation of the Relative Exit Hydraulic Gradient under the Dam for Different Sheet Pile Depths and Locations **(a)** One Sheet Pile, **(b)** Two Sheet Piles, and **(c)** Three Sheet Piles.

Table 2 Variation of Seepage Rate (q/Kh) at the Best Condition with Depths and Position of the Sheet Pile at the Dam's Heel.

Case No.	Sheet pile depth	Max drop in q/kH % SEEP/W			Max drop in q/kH % SLIDE		
		heel	middle	toe	heel	middle	Toe
Case I	15	12.73	22.69	35.65	29.14	39.26	59.26
Case II	15, and 16.5		48.15			44.20	
Case III	15, 15, and 16.5	X=8m: 51.25	X=11m: 51.18	X=14m: 50.76; X=17m: 49.83		-	

Table 3 Relative Exit Gradient with Respect to the Sheet Pile's Depth and Location.

Case No	Sheet pile depth	Relative exit gradient (G_H/G_{Ho})%SEEP/W			Relative exit gradient (G_H/G_{Ho})%SLIDE		
		heel	middle	toe	heel	middle	Toe
Case I	5	71.18	69.32	89.38	55.68	52.93	72.30
	10	76.12	75.50	93.20	62.87	63.56	82.52
	15	80.85	81.30	95.07	69.45	71.72	87.43
Case II	5, and 6.5		92.02			86.68	
	10, and 11.5		95.04			91.98	
	15, and 16.5		96.63			94.58	
Case III		X=8	X=11	X=14; X=17		-	
	5,5, and 6.5	92.25	92.25	92.25; 92.18			
	10,10, and 11.5	95.26	95.26	95.22; 95.15			
	15, 15, and 16.5	96.83	96.83	96.80; 96.74			

Table 4 Variation Pressure Head with the Depth and Position of the Sheet Pile.

Case No.	depth	Pressure head SEEP/W			Pressure head SLIDE		
		heel	middle	toe	heel	middle	toe
Case I	5	89.65	89.03	55.58	93.65	93.28	56.17
	10	91.45	91.32	40.96	94.7	94.83	41.03
	15	93.36	93.42	30.82	95.8	96.25	30.63
Case II	5 and 6.5		56.97			59.24	
	10 and 11.5		51.60			53.9	
	15 and 16.5		49.19			51.3	
Case III		X=8	X=11	X=14; X=17			
	5,5, and 6.5	59.28	60.05	61.21; 62.84		-	
	10,10, and 11.5	56.45	57.99	59.66; 61.16			
	15,15, and 16.5	55.88	57.73	59.47; 60.84			

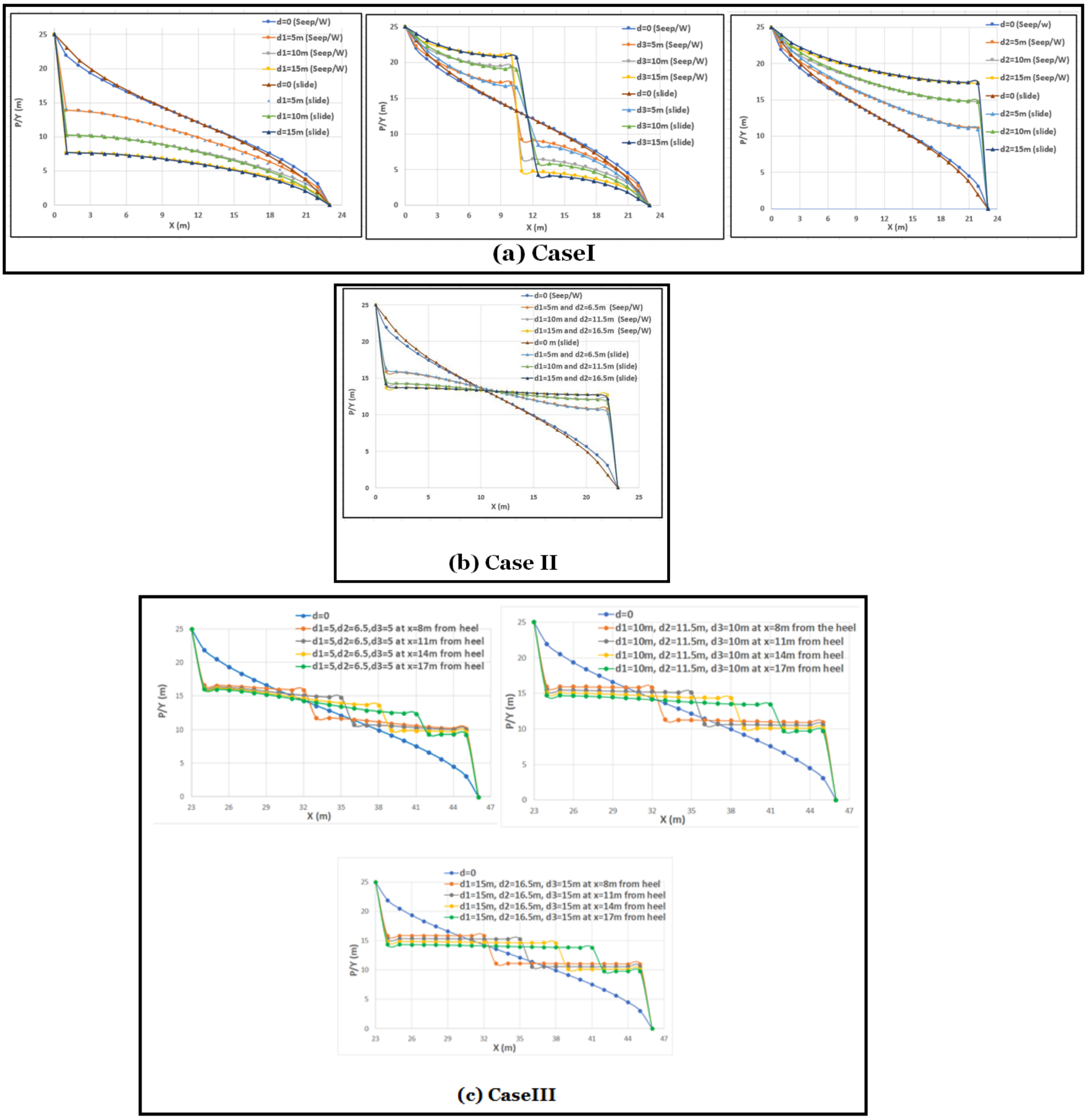

Fig.7 Uplift Pressure Head Distributions Beneath the Dam for Various Sheet Pile Depths and Locations For **(a)** Single Sheet Piles, **(b)** Double Sheet Piles, and **(c)** Triple Sheet Piles.

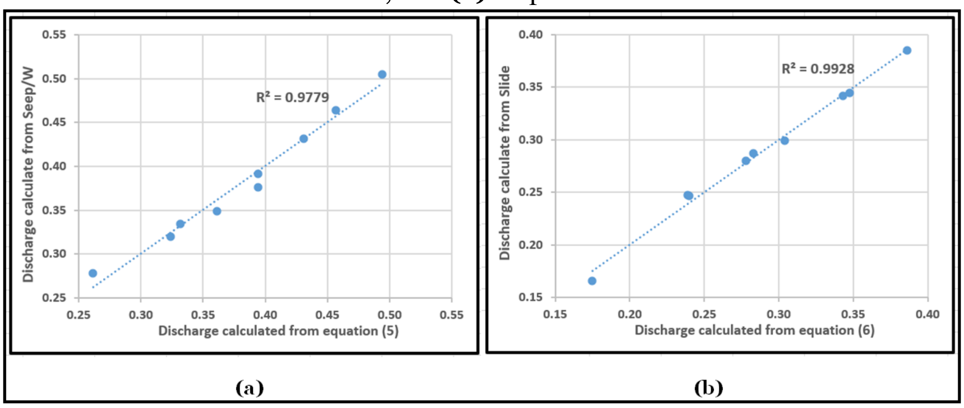

Fig.8 Comparison Between **(a)** The Seepage Rate Eq. 5 for SEEP/W, **(b)** The Seepage Rate Eq. 6 for SLIDE.

4. CONCLUSIONS

In this study, the following points are summarized

1. When the sheet pile depths increased, the seepage rate (q/kH) for Case I and Case II decreased, and the sheet pile position relative to the dam's toe had a significant potential effect on decreasing the seepage rate. In addition, for Case III, the middle sheet pile position has unmeasurably affected on dropping the seepage rate. The maximum reductions in q/Kh% were 35.65%, 48.15% at the toe, and 51.25 % at X= 8 m from the heel for the SEEP/W program, respectively, while 59.26, and 44.20% at the toe for the SLIDE program, accordingly.
2. Additionally, for Cases I, II, and III, the highest percentiles of the exit gradient reduction were 80.85, 81.30, and 96.79%, respectively, for SEEP/W, while 69.45, and 71.72% for SLIDE, which indicates that the exit gradient significantly dropped as the sheet pile depth increased. The middle sheet pile position in Case III immeasurably affected the pressure reduction.
3. For Case I, when the sheet pile was at the heel and middle, the drop in pressure head increased with the sheet pile depth. Also, the drop in pressure head reduced as the pile depth increased for Case I as the pile was located at the toe, Case II, and Case III. The sheet pile position at the dam's heel was highlighted as having the most significant impact on reducing pressure head.
4. The results showed that the R^2 coefficients were 0.9779 and 0.9928, respectively, showing a good agreement with accepted ranges.
5. The results were consistent for both the SEEP/W and SLIDE programs.
6. The Lack of monitored data limits the performance of effective statistical analysis. It is strongly advised to carry out this research on actual gravity dams using actual data to validate these numerical models thoroughly.

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