



Comparison Analysis of Seepage Through Homogenous Embankment Dams Using Physical, Mathematical and Numerical Models

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Abstract

Embankment dams have many advantages; however, they frequently develop seepage problems which may cause dams' failure. In this study, comparison analysis of seepage through embankment dams was conducted using three different methods, namely experimental tests, mathematical calculations and numerical modeling. Three homogeneous embankment dam models with different downstream drainage filters were considered. Results revealed that SEEP/W model is inappropriate to compute the water flow volume if there is an intersection between the seepage flow line and the downstream slope of the embankment dam due to the appearance of pipes. Numerical modeling based on SEEP/W software was found to be compatible to the rest physical models. The findings also demonstrated that for all scenarios, both the Casagrande equations and the SEEP/W model produced seepage lines that closely matched the observed seepage lines. These results highlight the significance of managing the seepage line's location to ensure the stability of embankment dams through the implementation of horizontal drains.

Keywords Seepage · Embankment dam · Experimental tests · Numerical analysis · Dam safety

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1 Introduction

Embankment dams are widely constructed across rivers and valleys as an economical type of dams that utilizes the available materials in surrounding environment to retain water for several purposes such as water storage, water diversion and protection from floods [1–5]. Embankment dams can be homogeneous, in which one type of soil is used, or zoned constructed with different types of soil, rock, sand or clay compositions [6–8]. Although the benefits of embankment dams, they may cause some environmental changes and consequences due to the storing and leakage of water [9, 10].

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There are two processes in which embankment dams lose water from their reservoirs, namely evaporation and seepage [11–14]. Evaporation process cannot be controlled, while water losses due to seepage can be minimized by using some construction techniques [15–17]. Moreover, seepage flow causes internal erosion of embankment dam soil, which can result in dam failure [18]. Seepage line and discharge depend on various factors acting on water including the soil medium the dams' geometric conditions [16, 17, 19–22]. In order to avoid seepage-related problems on embankment dams, adequate seepage control in all construction stages and during dam operation must be insured [15, 23–26].

The large number of embankments failure that recorded in the last two centuries motivated the scientific studies on the matter [27, 28]. The emergence of a scientific approach to seepage control began in the eighteenth and nineteenth centuries, when advances in mathematics, physics and engineering provided new tools for understanding the behavior of water in the ground. Scientific researches started when Henri Darcy published his study regarding fluid flow through a porous media in 1856 [29]. He has developed his formula, which is well known today as Darcy's law, and it is widely used theoretical framework for seepage analysis. It can be defined as:

$$v_d = k i = Q/A \quad (1)$$

$$Q = k i A \quad (2)$$

where Q is seepage rate (m^3/s), v_d is velocity of discharge (m/s), i is hydraulic gradient (m/m), k is permeability coefficient (m/s) and A is cross-sectional area which is normal to the flow direction (m^2).

Following Darcy, Forchheimer found that Laplace differential equation can be considered as the governing equation to seepage flow, and then he introduced a robust graphical technique for approximating solutions to Laplace's equation [28]. Following its adoption [29], this method gained widespread popularity in the analysis of seepage for embankment dams, eventually evolving into the established procedure for such analyses [25]. Several improvements have followed the previous theories by Dupuit, Schaffernak–VanIterson and Casagrande [30–32]. Casagrande developed his formula to calculate the rate of seepage as:

$$q = k a \sin^2 \beta \quad (3)$$

where q represents the Darcy flux or flow rate (m^2/s), k stands for hydraulic conductivity or permeability (m/s), a denotes the seepage surface length (m), and β represents the downstream slope angle (See Fig. 1).

The calculation of the seepage surface length “ a ” with the use of the upstream head “ h ” is expressed as follows:

$$a = S - \sqrt{S^2 - \frac{h^2}{\sin^2 \beta}} \quad (4)$$

where S signifies the length of the $\bar{A}BC$ curve (in meters), and h represents the upstream head (in meters).

However, S can be approximated with about a 4–5% error, as a length of the $\bar{A}C$ straight line, then:

$$S = \sqrt{d^2 + h^2} \quad (5)$$

$$d = L + 0.3\Delta \quad (6)$$

The graphical method has a disadvantage of time-consuming due requiring long seepage line plotting procedure and it is subjected to personal skills [25]. To deal with this problem, analytical solutions were introduced by [30] to draw profile of phreatic line through an earth dam. Moreover [25] used analytical solutions for seepage analysis and determining the length of the drainage blanket and downstream slope cover of earth dams.

On the other hand, calculating the seepage rate and drawing the seepage line experimentally were performed by constructing scaled physical models [22, 26, 34–41], as they help to understand seepage behavior through embankment dams [16, 42, 43]. Nevertheless, due to the various limitations and constraints associated with physical modeling, numerical modeling has emerged as an alternative method widely employed by numerous researchers (e.g., [43–46]) to address highly intricate engineering problems, including seepage studies. As the numerical models are purely mathematical approach, their results may significantly differ from physical models [19, 44, 45].

Researchers usually validate numerical models by comparing to the field testing results [46, 47]. Reviewing literatures indicated that there is no sufficient studies on comparing results that may obtained from using the different methods (experimental, mathematical, graphical or numerical) as researchers usually use only one method in a study to estimate seepage rate and draw seepage line. Hence, although numerical modeling, nowadays, has widely employed by researchers, there is still no clear agreement on the conditions that affect suitability and accuracy of using such type of modeling.

In this research, an examination of the seepage line within embankment dams was conducted, and the seepage rate was assessed using three distinct methods: physical models, numerical models and mathematical calculations. Subsequently, comparison results have been conducted. The

Fig. 1 The solution proposed by Casagrande for the flow through an embankment dam [33]

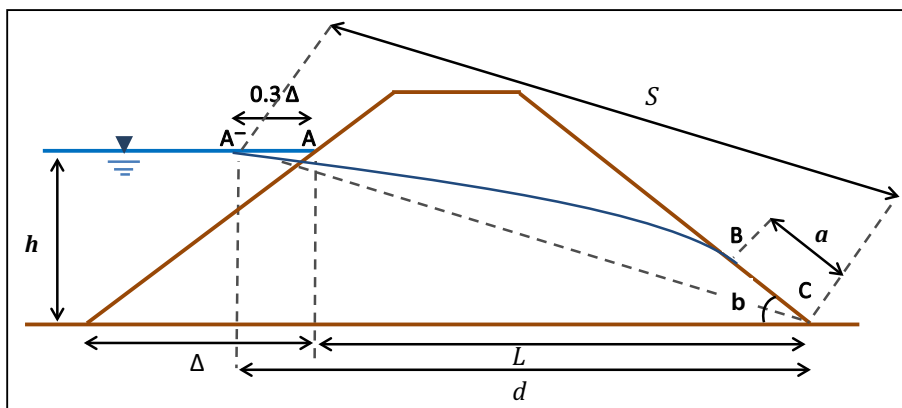
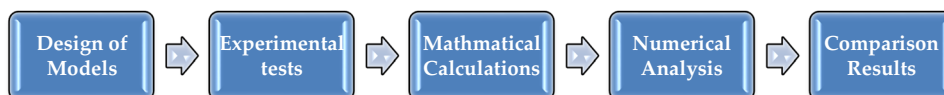


Fig. 2 Flowchart of the study



significance of the research can be summarized as an assessment for the ability and accuracy of numerical modeling based on SEEP/W software in predicting seepage line and seepage rate through homogenous embankment dams. The assessment involved three homogeneous embankment dam models with different downstream drainage filters (toe drain, minimum and maximum horizontal drain length). Hence, it gives a clear picture about conditions that make the SEEP/W model suitable or inappropriate to compute the seepage flow rates through embankment dams.

2 Materials and Methods

Comparison analysis of seepage through homogenous embankment dams was conducted using physical, numerical and mathematical models. For the comparison, conditions of experimental tests were considered for mathematical calculation and numerical analysis. Figure 2 illustrates the study flowchart.

2.1 Design of Embankment Dam Models

The study was conducted on a theoretical homogeneous embankment dam with a height of 0.36 m, crest width of 0.2 m, upstream slope (H:V) of 2.5:1 and downstream slope (H:V) of 2:1. Embankment dam dimensions were chosen based on the availability of space in the laboratory. Three homogeneous embankment dam models with different downstream drainage filters were considered. The three models are (a) model with toe drain; (b) model with minimum horizontal drain length; (c) model with maximum horizontal drain length. The minimum and maximum lengths of horizontal

drain were computed utilizing Chahar equation [48] which can be defined as:

$$L_{\min} = \frac{(1 + n^2)}{2n^2} \left[0.3m + n + F_b(m + n) + T - \sqrt{(0.3m + n + F_b(m + n) + T)^2 - n^2} \right] \quad (7)$$

$$L_{\max} = F_b(m + n) + T + h \frac{(1 + n^2)}{2n^2} \left[0.3m + n - \sqrt{(0.3m + n)^2 - n^2} \right] \quad (8)$$

where L_{\max} represents the horizontal drain length (in meters), F_b stands for free board (in meters), m denotes upstream slope (in meters), n represents downstream slope (in meters), T signifies width of crest (in meters) and h represents head of upstream (in meters) Fig. 3.

2.2 Materials and Experimental Setup

The body of the embankment dam models is made from soil, while the drainage filters, which are toe and horizontal drains, are made from gravel. We conducted laboratory tests to search the characteristics of the soil and gravel. The models were situated within a rectangular tank constructed from transparent Perspex acrylic sheets. The dimensions of the rectangular tank are length = 2.4 m, width = 0.5 m and height = 0.5 m (Fig. 4).

2.3 Experimental Tests

The experiments were conducted with a fully saturated soil and a constant value of upstream water level of 0.3 m. (Assuming that the freeboard of the dam is 0.06 m, hence the maximum water level is 0.3 m.) Four holes were drilled

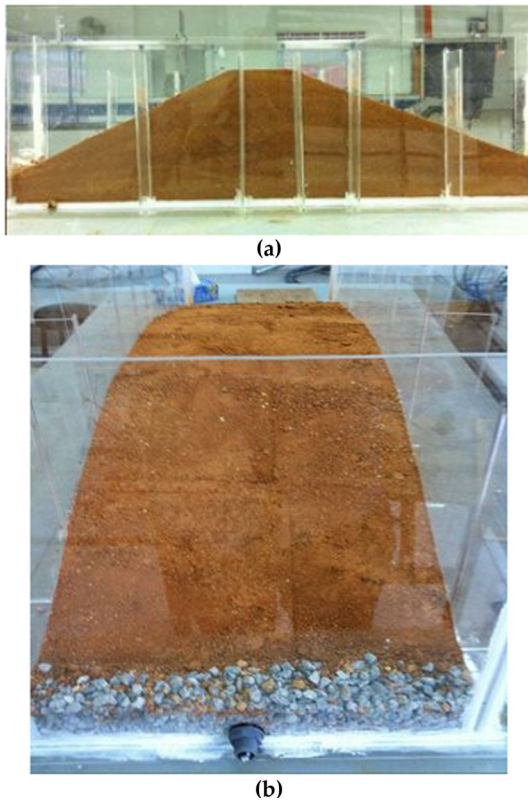


Fig. 3 Embankment dam model inside the rectangular tank **a** embankment cross section **b** downstream drainage

into the downstream slope of the dam at distances of 0.87, 1.04, 1.28 and 1.46 m from the upstream heel. These holes were used to monitor the seepage line by measuring the water height within them. Seepage rates were determined using the volumetric method, which involved measuring the volume of water that flowed out from the downstream outlet of the model per hour [49].

2.4 Mathematical Calculations

The mathematical method proposed by Casagrande (as shown in Fig. 1) was applied to depict the seepage line in all three embankment dam models. The calculations were conducted at the same four points that considered in the experimental tests. The seepage rate was mathematically determined by (3–6).

2.5 Numerical Modeling

SEEP/W software, which is a powerful widely used finite element-based geotechnical software, was used to model water flowing through soil of embankment dams [50]. SEEP/W software uses several mathematical equations of fluid such as Darcy's law, partial differential water flow equations, finite element water flow equations, etc. SEEP/W

software was applied to illustrate the seepage lines for the three models of embankment dam and to compute the associated seepage rates.

3 Results

3.1 Preexperimental Tests

Prior to experimental tests, laboratory tests for soil and gravel were conducted. Soil sample was found to be silty sand, and the hydraulic conductivities for soil and gravel was 3.493×10^{-6} m/s and 0.016 m/s, respectively. The minimum and maximum length of horizontal drain, which calculated using Eqs. (7) and (8), is 0.435 m and 0.63 m, respectively. Figure 4 presents the cross sections of the three models used in this study.

3.2 Experimental Tests

Experiments have been conducted using three embankments models. The values of water level of the seepage line at the four holes for three models are presented in Table 1.

Observations for the first model (Model a) showed that there was an intersection between seepage line and downstream slope and a portion of the seepage exited the embankment through the downstream face, flowing out between distances ranging from 1.41 to 1.48 m from the embankment's heel (as illustrated in Fig. 5).

The intersection between seepage line and the downstream slope poses a potential threat to the embankment dam stability due to the risk of piping. The use of volumetric method revealed that the discharge of seepage is $q = 1.77\text{E}-06$ m³/s/m.

The seepage line remains within the body of the embankment dam for the rest two models, i.e., models with minimum and maximum drain length (Fig. 6). The difference between the two models is the length of downstream cover. Thus, observations acknowledged that the use of horizontal drain prevents seepage from exiting the embankment model. The values of discharge of seepage are $q = 3.98\text{E}-07$ and $q = 6.11\text{E}-07$ m³/s/m for the models with minimum and maximum drain length, respectively.

3.3 Mathematical Calculations

The mathematical calculations (Casagrande equation) for seepage loss and seepage line are presented in Table 2. From Table 2, the seepage loss through the embankment dam for the model with toe drainage $q = 1.2924\text{E}-07$ m³/s/m, while for the models with minimum and maximum drain length are $q = 1.78\text{E}-07$ and $q = 2.253\text{E}-07$ m³/s/m, respectively.

Fig. 4 The cross sections of the three physical homogeneous embankment dam models **a** model with toe drain; **b** model with minimum drain length; **c** model with maximum drain length

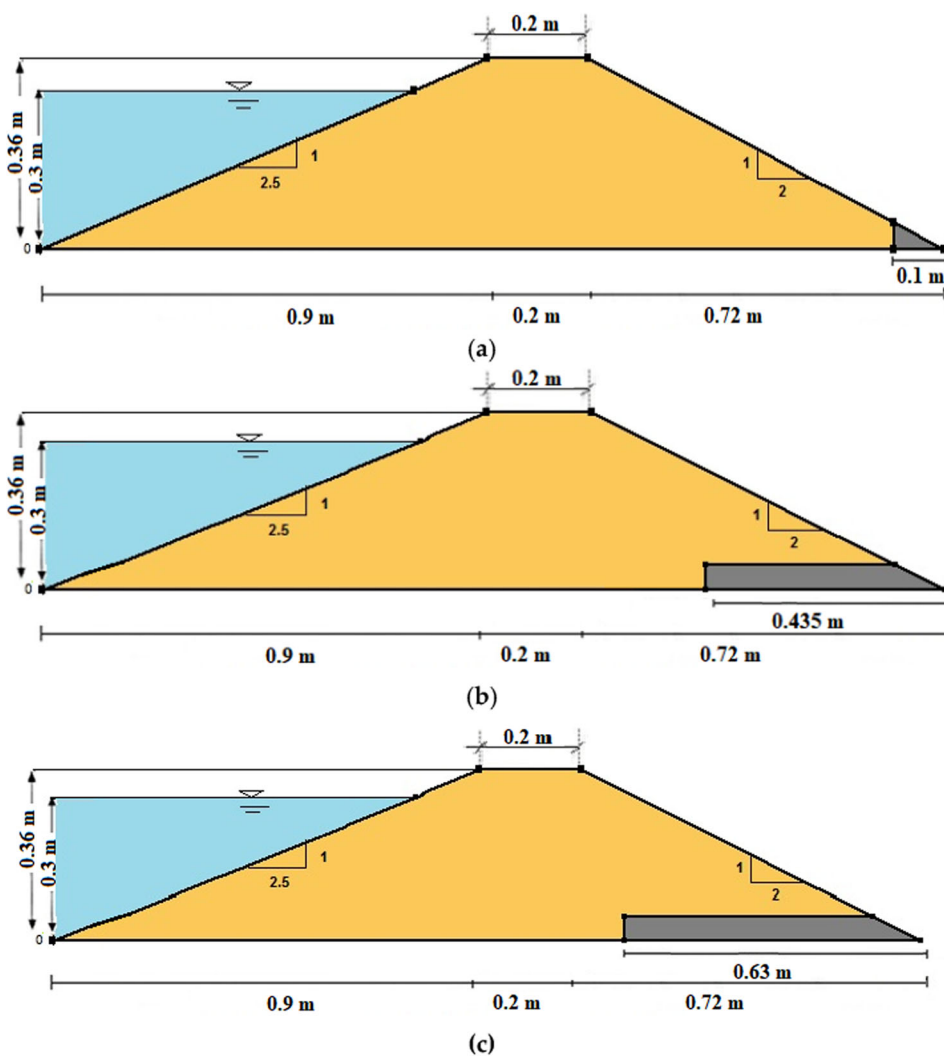


Table 1 Water level of the seepage line at the four holes

Model	Distance from the upstream heel x (m)	0.87	1.04	1.28	1.46	1.7	Seepage loss q ($m^3/s/m$)
a	Water height y (m)	0.27	0.24	0.193	0.175	0.05	$1.77E-06$
b	Water height y (m)	0.225	0.2	0.17	0.05	0.05	$3.98E-07$
c	Water height y (m)	0.21	0.146	0.05	0.05	0.05	$6.11E-07$

3.4 Numerical Modeling

Figure 7 shows the seepage line using SEEP/W model for the three models. From Fig. 7a, it is clear that there is an intersection between seepage line and the downstream face of the embankment model. The intersection was at the distances of 1.46–1.7 m from the embankment toe. According to the SEEP/W model, the seepage flow rates are $q = 1.62E-07 m^3/s/m$, $q = 2.88E-07 m^3/s/m$ and $q = 4.373E-07 m^3/s/m$ for the models a–c, respectively.

4 Discussion

Figure 8 presents the comparison of seepage lines through the three models (physical, mathematical and numerical). From the figure, it can be seen that both Casagrande equations and SEEP/W model have generated seepage lines that closely align with the observed seepage line, as the location of the seepage line was approximately consistent across all three techniques. (The maximum difference at any distance is less than 0.02 m.) However, while the water level of the seepage line for model b at the 1.28 m distance from the upstream

Fig. 5 Seepage line intersection with the downstream slope of the model with toe drain

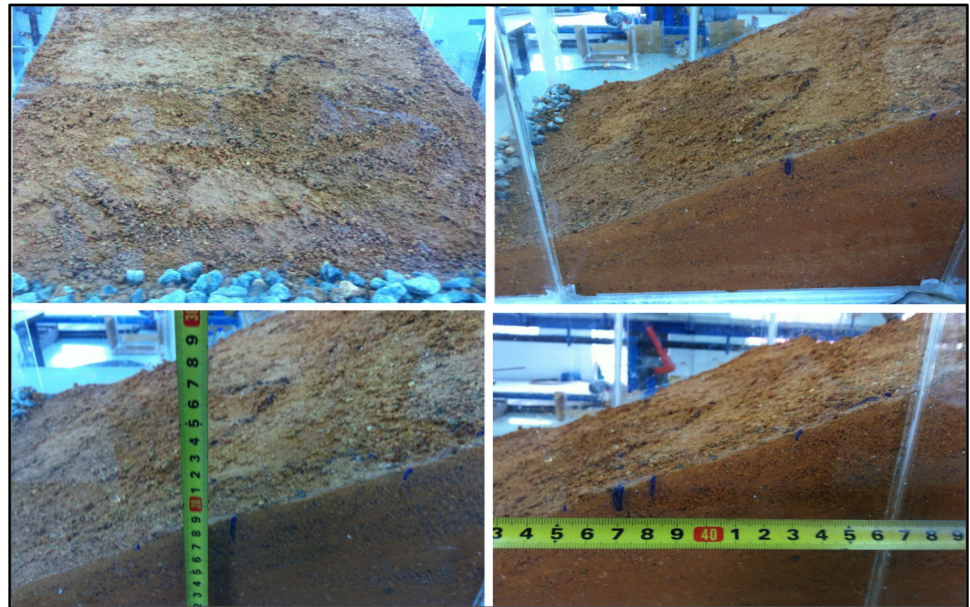


Fig. 6 Seepage line within the body of embankment models

heel is 0.155 as obtained from Casagrande equations and SEEP/W model (See Table 2 and Fig. 7), the water level of the seepage line measured from the physical model b at the same distance is 0.17 m (Table 1), which indicated that the actual seepage line through embankment dams follows the basic parabola approximately and not exactly. Furthermore, it can be noted from Fig. 8 that there is no significant change at 1.04 m distance from the upstream heel for these three models.

The above findings also indicated by [30, 51] from their comparison of the upper flow lines in a homogeneous and isotropic embankment, obtained using different methods. Comparisons that conducted by [30] acknowledged that the use of dimensional analysis to draw profile of phreatic line through homogeneous and nonhomogeneous earthen dams prove to be an easy and sufficiently accurate method when compared with conventional methods (such as Kozeny, A. Casagrande, & Stello) and also by centrifuge model test results conducted by [52]. Additionally, [30] found a fluctuation on the actual seepage line that measured through several homogeneous embankment dams. On the other hand, the comparisons that conducted by [51] acknowledged that analyzing free surface problems using numerical solution of finite difference equations provided similar results to those

Table 2 Mathematical calculations of water level of the seepage line

Model	Distance from the upstream heel x (m)	0.87	1.04	1.28	1.46	1.7	Seepage loss q ($m^3/s/m$)
a	Water height y (m)	0.26	0.235	0.194	0.156	0.081	1.2924E-07
b	Water height y (m)	0.235	0.194	0.115	0.05	0.05	1.78E-07
c	Water height y (m)	0.216	0.157	0.06	0.05	0.05	2.253E-07

Fig. 7 Seepage line using SEEP/W software, **a** model with toe drain; **b** model with minimum drain length; **c** model with maximum drain length

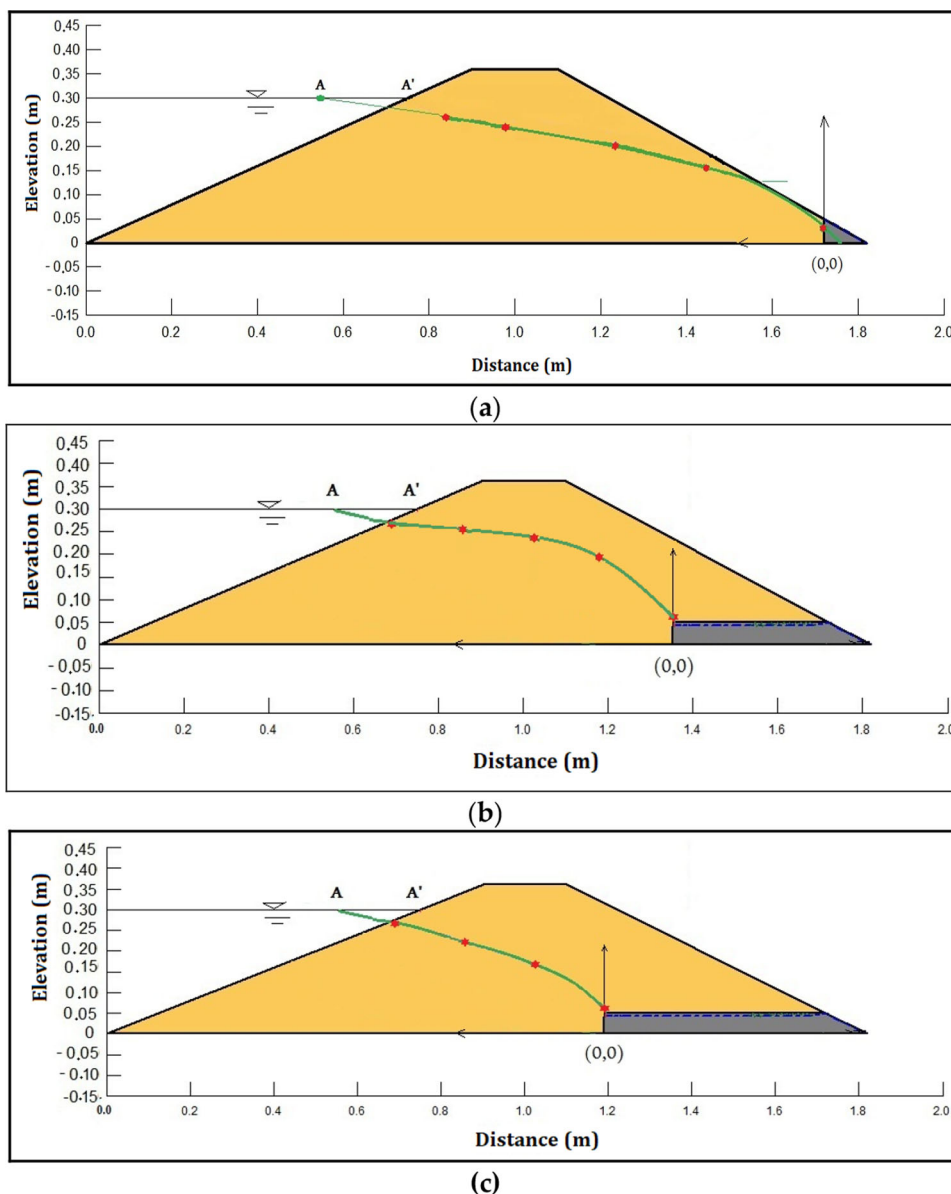


Table 3 Seepage flow rate obtained through the three models

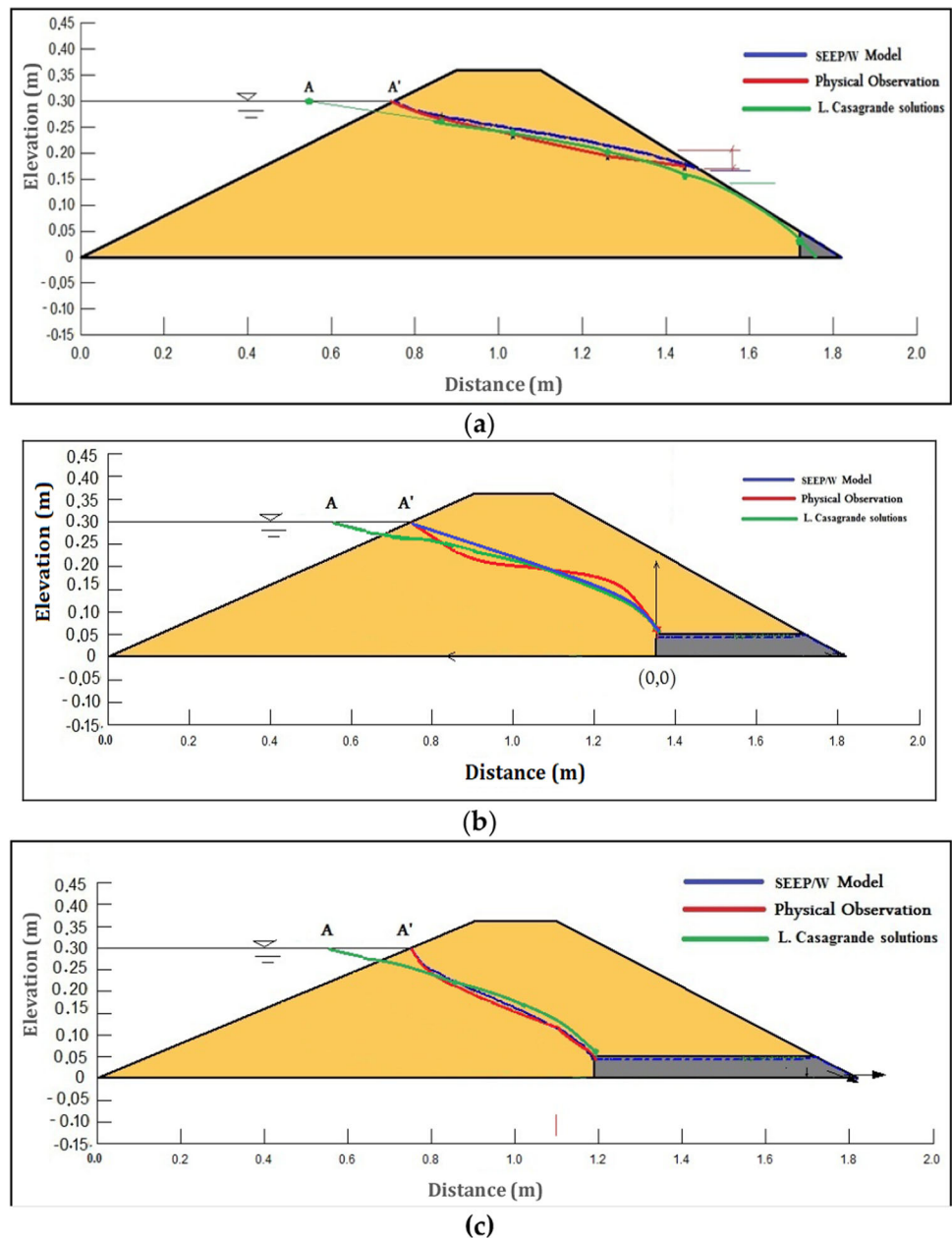
Models	q (m ³ /s/m)		
	Physical	Casagrande	SEEP/W
a	1.77E-06	1.292E-07	1.62E-07
b	3.98E-07	1.78E-07	2.88E-07
c	6.11E-07	2.253E-07	4.373E-07

obtained with the popular numerical methods, such as the finite element method.

The results of seepage flow rate using three models are represented in Table 3. From Table 3, seepage flow rate calculated from SEEP/W through model (a) is close to that

computed by Casagrande equations, while there is a big difference in the results of seepage rate comparing to that observed from the physical model. This observation suggests that when the seepage line intersects with the downstream slope, the likelihood of piping occurring within the embankment dam model increases, ultimately leading to a higher total seepage rate. In the case of models equipped with horizontal drains (models (b) and (c)), the seepage rate observed in the physical models is slightly greater than that obtained from SEEP/W software, and it surpasses the values calculated using Casagrande’s solution. The implementation of horizontal drains proves to be of paramount importance in controlling the seepage line’s position, which, in turn, enhances the stability of earth dams. Furthermore, an increase in the length of horizontal drains results in a larger cover for the seepage

Fig. 8 The seepage line using the three models **a** model with toe drain; **b** model with minimum drain length; **c** model with maximum drain length



line but concurrently leads to a higher seepage rate. These findings also indicated by [53] who conducted a comparison for seepage performance for different drainage systems. Moreover, the minimum and maximum lengths of horizontal drain that insure the dam safety were studied by [48]. Hence, an optimum length of horizontal drains should be conserved by designer engineers to obtain the best factors of dam safety. More studies on this matter using different type of soil, different physical model dimensions and different software are recommended.

5 Conclusions

To avoid seepage-related problems on embankment dams, adequate seepage control must be insured in all construction and operation stages. In this study, three different modeling approaches—experimental, mathematical and numerical were employed to examine the seepage flow within three homogeneous embankment dam models. The seepage lines and seepage flow rates obtained through these methods were compared with those derived from Casagrande's equations and the SEEP/W software. The comparisons acknowledged that the seepage lines are approximately at the same location for the three methods. (The maximum difference at any

distance is less than 0.02 m.) However, results obtained from physical models showed that the actual seepage lines through embankment dams were fluctuated and they approximately follow the basic parabola and not exactly. On the other hand, the results showed that there is a gap between results from physical and numerical modeling for the first model, and hence the SEEP/W model was inappropriate to calculate the volume of water flow when the seepage line intersected with the downstream slope due to the risk of piping occurrence. For the rest of models, SEEP/W obtained good matching results with physical and mathematical methods. Therefore, the use of numerical modeling is recommended for seepage analysis through homogenous embankment dams when sufficient downstream cover is available. The findings also underscore the significance of applying horizontal drains to control the seepage line position within an embankment dam. An adequate design of horizontal drains of embankment dam should be insured because while increasing the length of horizontal drains increases the cover of seepage line, it increases the seepage rate and water loss as well. Finally, numerical model users should keep in their mind that the results of seepage line and seepage rate obtain from the software are approximation results and not exact. Further studies and researches using different type of soil, different physical model dimensions and different software are recommended.

Authors' Contributions Conceptualization was presented by Saad Sh. Sammen, Ahmed Al-Janabi, Hayder Dibs and Badronnisa Yusuf; data creation was prepared by Hayder Dibs and Saad Sh. Sammen; formal analysis was conducted by Sabih Alzihairy, Rana Ikram, Hayder Dibs and Saad Sh. Sammen; investigation was done by Hayder Dibs and Ahmed Al-Janabi; methodology was provided by Saad Sh. Sammen, Ahmed Al-Janabi and Badronnisa Yusuf; software was developed by Saad Sh. Sammen and Badronnisa Yusuf; validation was approved by Saad Sh. Sammen and Badronnisa Yusuf; Writing—original draft was revised by Sabih Alzihairy, Rana Ikram, Ahmed Al-Janabi, Saad Sh. Sammen and Ozgur Kisi; Writing—review & editing was done by all authors.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

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References

- Graf, W.L.: Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. *Water Resour. Res.* **35**, 1305–1311 (1999)
- El, D.A.: Molla: Seepage through homogeneous earth dams provided with a vertical sheet pile and formed on impervious foundation. *Ain Shams Eng. J.* **10**, 529–539 (2019)
- Dibs, H.; Mansor, S.; Ahmad, N.; Pradhan, B.; Al-Ansari, N.: Automatic fast and robust technique to refine extracted sift key points for remote sensing images. *J. Civ. Eng. Archit.* **14**(6), 339–350 (2020)
- Hashim, F.; Dibs, H.; Sabah Jaber, H.: Adopting gram-schmidt and brovey methods for estimating land use and land cover using remote sensing and satellite images. *Nat. Environ. Pollut. Technol.* **21**, 867–881 (2022)
- Dibs, H.; Mansor, S.; Ahmad, N.; Al-Ansari, N.: Geometric correction analysis of highly distortion of near equatorial satellite images using remote sensing and digital image processing techniques. *Engineering* **14**, 1–8 (2022)
- Yener Ozkan, M.: A review of considerations on seismic safety of embankments and earth and rock-fill dams. *Soil Dyn. Earthq. Eng.* **17**, 439–458 (1998)
- Yaseen, Z.M.; Ameen, A.M.S.; Aldlemy, M.S.; Ali, M.; Abdulmohsin Afan, H.; Zhu, S.; Sami Al-Janabi, A.M.; Al-Ansari, N.; Tiyyasha, T.; Tao, H., et al.: State-of-the art-powerhouse dam structure and turbine operation and vibrations. *Sustainability* **12**, 1676 (2020)
- Jassam, M.G.; Abdulrazzaq, S.S.: Theoretical analysis of seepage through homogeneous and non-homogeneous saturated-unsaturated soil. *J. Eng.* **25**, 52–67 (2019)
- Yin, L.; Wang, L.; Keim, B.D.; Konsoer, K.; Yin, Z.; Liu, M.; Zheng, W.: Spatial and wavelet analysis of precipitation and river discharge during operation of the Three Gorges Dam. *China. Ecol. Indic.* **154**, 110837 (2023)
- Jia, S.; Dai, Z.; Zhou, Z.; Ling, H.; Yang, Z.; Qi, L.; Wang, Z.; Zhang, X.; Thanh, H.V.; Soltanian, M.R.: Upscaling dispersivity for conservative solute transport in naturally fractured media. *Water Res.* **235**, 119844 (2023)
- Richards, K.S.; Reddy, K.R.: Critical appraisal of piping phenomena in earth dams. *Bull. Eng. Geol. Environ.* **66**, 381–402 (2007)
- Calamak, M.; Yanmaz, A.M.: Probabilistic assessment of slope stability for earth-fill dams having random soil parameters. In: *Hydraul. Struct. Soc.: Eng. Challenges Extrem* (2014)
- Athani, S.S.; Shivamant Solanki, C.H.; Dodagoudar, G.R.: Seepage and stability analyses of earth dam using finite element method. *Aquat. Proc.* **4**, 876–883 (2015)
- Hashim, B.M.; Al Maliki, A.; Alraheem, E.A.; Al-Janabi, A.M.S.; Halder, B.; Yaseen, Z.M.: Temperature and precipitation trend analysis of the Iraq Region under SRES scenarios during the twenty-first century. *Theor. Appl. Climatol.* **148**, 881–898 (2022)
- Fell, R.; Wan, C.F.; Cyganiewicz, J.; Foster, M.: Time for development of internal erosion and piping in embankment dams. *J. Geotech. Geoenviron. Eng.* **129**, 307–314 (2003)
- Al-Janabi, A.M.S.; Ghazali, A.H.; Yusuf, B.; Mohammed, T.A.: Permeable channel cross section for maximizing stormwater infiltration and seepage rates. *J. Irrig. Drain. Eng.* **144**, 04018001 (2018)
- Al-Janabi, A.M.S.; Ghazali, A.H.; Yusuf, B.: Effects of cross-section on infiltration and seepage in permeable stormwater channels. In: *GCEC 2017*, vol. 9, pp. 1495–1509, Springer, Singapore (2019)



18. Su, H.; Dai, D.; Zhang, T.; Yang, J.; Mu, Z.: Experimental and DEM-CFD coupling investigations on the characteristics and mechanism of seepage erosion for cohesionless soil. *Water* **15**, 3085 (2023)
19. Özer, A.T.; Bromwell, L.G.: Stability assessment of an earth dam on silt/clay tailings foundation: a case study. *Eng. Geol.* **151**, 89–99 (2012)
20. Riahi-Madvar, H.; Dehghani, M.; Akib, S.; Shamshirband, S.; Chau, K.: Developing a mathematical framework in preliminary designing of detention rockfill dams for flood peak reduction. *Eng. Appl. Comput. Fluid Mech.* **13**, 1119–1129 (2019)
21. Erfeng, Z.; Ji, L.; Yufeng, J.: The seepage evolution law under the fault creep in right bank of Longyangxia Dam. *Eng. Fail. Anal.* **44**, 306–314 (2014)
22. Al-Janabi, A.M.S.; Ghazali, A.H.; Ghazaw, Y.M.; Afan, H.A.; Al-Ansari, N.; Yaseen, Z.M.: Experimental and numerical analysis for earth-fill dam seepage. *Sustainability* **12**, 2490 (2020)
23. Kermani, E.; Barani, G.: Seepage analysis through earth dam based on finite difference method. *J. Basic Appl. Sci. Res.* **2**, 11621–11625 (2012)
24. Hashim, F.; Dibs, H.; Jaber, H.S.: Applying support vector machine algorithm on multispectral remotely sensed satellite image for geospatial analysis. *J. Phys. Conf. Ser.* **1963**, 12110 (2021)
25. Chahar, B.R.: Determination of length of a horizontal drain in homogeneous earth dams. *J. Irrig. Drain. Eng.* **130**, 530–536 (2004)
26. Al-Janabi, A.M.S.: Study of Seepage Through Earth-Fill Dam Using Physical and Numerical Models. University Putra Malaysia, Malaysia (2013)
27. Baker, M.; Graham, W.: Dam failure investigation approaches (2008)
28. Dibs, H.; Ali, A.H.; Al-Ansari, N.; Abed, S.A.: Fusion landsat-8 thermal tirs and oli datasets for superior monitoring and change detection using remote sensing. *Emerg. Sci. J.* **7**, 428–444 (2023)
29. Hofmann, J.R.; Hofmann, P.A. Darcy's Law and Structural Explanation in Hydrology, vol. 1, pp. 23–35 (1992)
30. Phatak, D.R.; Pathak, S.R.; Birid, K.C.: Estimation of phreatic line using dimensional analysis. In: Fifth International Conference on Case Histories in Geotechnical Engineering (2004)
31. Stello, M.W.: Seepage charts for homogeneous and zoned embankments. *J. Geotech. Eng.* **113**, 996–1012 (1987)
32. Casagrande, A.: Seepage through dams. *J. New Engl. Water Work. Assoc.* **1**, 131–172 (1937)
33. Das, B.M.: *Advanced Soil Mechanics*. CRC Press ISBN 9781351215176 (2019)
34. Abnisa, F.; Wan Daud, W.M.A.; Athanassiou, M.; Zabaniotou, A.; Bridgwater, A.V.; Brown, D.; Rowe, A.; Wild, P.; Chen, D.; Yin, L., et al.: Manuscript-grant-writing. *Biomass Bioenergy* **5**, 1–10 (2014)
35. Cho, S.E.: Probabilistic analysis of seepage that considers the spatial variability of permeability for an embankment on soil foundation. *Eng. Geol.* **133**, 30–39 (2012)
36. Mansuri, B.; Salmasi, F.: Effect of horizontal drain length and cutoff wall on seepage and uplift pressure in heterogeneous earth dam with numerical simulation. *J. Civ. Eng. Urban.* **3**, 114–121 (2013)
37. Alekseevich, A.N.; Sergeevich, A.A.: Numerical modelling of tailings dam thermal-seepage regime considering phase transitions. *Model. Simul. Eng.* **2017**, 1–10 (2017)
38. Sivakumar Babu, G.L.; Vasudevan, A.K.: Seepage velocity and piping resistance of coir fiber mixed soils. *J. Irrig. Drain. Eng.* **134**, 485–492 (2008)
39. Malekpour, A.; Farsadzadeh, D.; Hosseinzadeh Dalir, A.; Sadrekarimi, J.: Effect of horizontal drain size on the stability of an embankment dam in steady and transient seepage conditions. *Turk. J. Eng. Environ. Sci.* **36**, 139–152 (2012)
40. Yusuf, B.; Al-Janabi, A.M.S.; Ghazali, A.H.; Al-Ani, I.: Variations of infiltration capacity with flow hydraulic parameters in permeable stormwater channels. *ISH J. Hydraul. Eng.* **28**, 234–242 (2022)
41. Al-Janabi, A.M.S.; Yusuf, B.; Ghazali, A.H.: Modeling the infiltration capacity of permeable stormwater channels with a check dam system. *Water Resour. Manag.* **33**, 2453–2470 (2019)
42. Pham-Van, S.; Hinkelmann, R.; Nehrig, M.; Martinez, I.: A Comparison of model concepts and experiments for seepage processes through a dike with a fault zone. *Eng. Appl. Comput. Fluid Mech.* **5**, 149–158 (2011)
43. Yaseen, Z.M.; Sulaiman, S.O.; Deo, R.C.; Chau, K.-W.: An enhanced extreme learning machine model for river flow forecasting: state-of-the-art, practical applications in water resource engineering area and future research direction. *J. Hydrol.* **569**, 387–408 (2019)
44. Al-Janabi, A.M.S.: Numerical analysis of seepage through earth-fill dams. In: Proceedings of the 4th International Conference on Architectural & Civil Engineering Sciences. pp. 32–38, Cihan University-Erbil (2023)
45. Dai, Z.; Li, X.; Lan, B.: Three-dimensional modeling of tsunami waves triggered by submarine landslides based on the smoothed particle hydrodynamics method. *J. Mar. Sci. Eng.* **2023**, 11 (2015)
46. Liu, C.; Cui, J.; Zhang, Z.; Liu, H.; Huang, X.; Zhang, C.: The role of TBM asymmetric tail-grouting on surface settlement in coarse-grained soils of urban area: field tests and FEA modelling. *Tunn. Undergr. Sp. Technol.* **111**, 103857 (2021)
47. Wei, W.; Xu, W.; Deng, J.; Guo, Y.: Self-aeration development and fully cross-sectional air diffusion in high-speed open channel flows. *J. Hydraul. Res.* **60**, 445–459 (2022)
48. Chahar, B.R.: Closure to “determination of length of a horizontal drain in homogeneous earth dams” by Bhagu R. Chahar. *J. Irrig. Drain. Eng.* **132**, 89–90 (2006)
49. Irwin, L.K.: Flow measurement in open channels and closed conduits. *Gaithersburg* **2**, 23–25 (1977)
50. GEO-SLOPE International Ltd. Seepage modeling with SEEP/W (2012)
51. López-Acosta, N.P.; González, J.L.: Study of water flow in dams using successive overrelaxations. *Water Technol. Sci. (Tecnología y Ciencias del Agua)* **6**, 43–58 (2015)
52. Resnick, G.S.; Znidarčić, D.: Centrifugal modeling of drains for slope stabilization. *J. Geotech. Eng.* **116**, 1607–1624 (1990)
53. Zakaria, S.M.S.; Mahmood, M.T.: Comparison seepage performance for different drainage systems of rainwater harvesting dam. *Int. J. Saf. Secur. Eng.* **13**, 301–306 (2023)