Numerical Analysis of Seepage through Earth-Fill Dams

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Abstract—**Uncontrolled seepage through earth-fill dams may cause of dam failure. Seepage analysis, therefore, is an essential study required before construction for a safe and sustainable dam operation. In this study, numerical analysis of seepage through a theoretical case of an earth-fill dam was applied using SEEP/W program. Five different dam models, two with homogenous and three with zoned cross sections, have been studied. The study consists normal and maximum reservoir water levels, different drainage lengths and thicknesses, different percentages of permeability between shell and core. Total of 26 tests were conducted and the best model based on seepage behavior was chosen. Seepage analysis acknowledged that with availability of required soil quantity, the homogeneous model that has medium length of drainage with thickness of 0.5 m is the most appropriate model for the case study. Otherwise, zoned model with core at the centre with 1:0.5 (H:V) slope is recommended.**

Keywords—**Earth-fill dams, Numerical analysis, Seepage, SEEP/W model.**

I. INTRODUCTION

Earth-fill dams are widely used as an economical option that utilizing locally available materials. Earth-fill dams can be built to any height because of the less rigorous foundation requirements comparing to other types of dams [1]. The successful design of an earth-fill dam requires a comprehensive study which should include the hydrological and geological conditions of the site [2]. However, the concern of dam designers is mostly on stability and seepage as they are the most reasons of dams' failure [3–5]. Seepage, which is the water movement through the body of earth-fill dams [6], causes water waste, internal erosion and piping, and the decline of dam stability [7]. Hence, adequate control of seepage is required to minimize its rate, in order to avoid seepage-related problems [2,3,8,9].

The rate of seepage depends on the characteristics of soil medium and the dams' geometric conditions [10–13]. Different types of earth-fill dams, such as homogenous and non-homogeneous, can be used, each with advantages and disadvantages [14]. The most important factor in choosing the type of an earth-fill dam is the economic factor as this type utilizes the available soil in the site. If the available soil has accepted permeability, no need for complex design which leads to increase construction cost. When the soil with accepted permeability is not sufficiently available in the site, earth-fill dams with different zones are preferred for construction; hence, zoned earth-fill dam is a practical type that can overcome the seepage-related problems [15].

Many studies have been conducted (wither experimentally, mathematical or numerical) to locate the seepage line and to calculate its rate, seeking for minimizing its amount [15–23]. However, the study that conducted by Henri Darcy in 1856 was the first study explained the flow of fluid through porous media [24], and an empirical equation was developed to explain the relationship between velocity and hydraulic gradient:

$$v_d = k\,i = Q/A \tag{1}$$

$$Q = k\,i\,A \tag{2}$$

where vd is velocity (m/s), i is hydraulic gradient (m/m), k is coefficient of permeability (m/s), Q is seepage rate (m3/s), and A is cross-sectional area normal to the direction of flow (m2).

Many studies were conducted after Darcy, one of them was conducted by Forchheimer in 1880's which explained how the seepage behavior follows Laplace equation. Later, he developed a graphical method to solve Laplace's equation [25], which became widely accepted for seepage analysis after acknowledgement by Casagrande researches [3,18].

Numerical analysis has been applied by many researches for solving complex mathematical problems (e.g., [22,29–32]), and it has been used for seepage studies as well. Moreover, the applications of soft computing methods for dealing with water engineering problems were widely used by many researchers (e.g., [33–36]), and its application for seepage modeling was studied by [7].

In this study, the seepage line through an earth-fill dam with different models and the rate of seepage through them were investigated. Numerical models created by SEEP/W software were used to analyze the seepage through five different models of earth-fill dams (Two homogenous models and three zoned models) and then a comparison among models have been subsequently conducted.

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II. MATERIALS AND METHODS

A. *Discription of the Case Study*

A theoretical case of an earth-fill dam was proposed, and the seepage analysis includes different models of the dam. The dam height is limited to 9 m with reservoir storage volume = 2.5x106 m3, hence it is considered as a small dam. For small dams,

design criteria and construction methods are generally focus upon economic factor, by producing a satisfactory functional structure at a minimum total cost [15]. The dam crest width is 5 m, and the slope of upstream and downstream for the homogeneous models of the dam are 2.5:1 and 2:1 respectively, while the slope of upstream and downstream sides for the zoned models are 2:1 for both. Soil used for the dam body of homogenous models and for the core of zoned models is Silty Sand. The characteristics of the soil and drain material used for the dam is presented in Table 1.

The normal water level NWL in the reservoir is 7.5 m and the maximum water level MWL is 8 m (minimum freeboard is 1m). The dam has an impervious foundation; hence the seepage moves through the dam body while there is no seepage under the dam. Two methods of drainage system are used in this study. They are: Horizontal drainage and Chimney and Horizontal drainage combination. Min and Max length of Horizontal drain calculated by equations proposed by [3], and they are 2.5m and 16m respectively.

TABLE I
PROPERTIES OF THE SOIL AND THE DRAIN MATERIAL

Soil Type	Optimum Moisture of Soil %	Hydraulic Conductivity (m/s)		Drain Type	Hydraulic Conductivity (m/s)
		Well compacted soil	Low compacted soil		
Silty Sand (SM**)**	20	1.74562E-08	3.493E-06	Poorly Graded Gravel (GP)	0.016

B. *Earth-fill Dam Design Models*

The study includes evaluating seepage through five selected models of earth-fill dam. Total of 26 tests were conducted and the best model based on seepage analysis were chosen. The five models consist of two homogeneous and three zoned configurations (Figure 2). The details of test trails are presented in Table II.

The two homogenous models (Figure 2 a, b) consist of:

1) Earth-fill dam with horizontal drain of L= 16 m, and

2) Earth-fill dam with horizontal drain of L=12 m.

For each model, the analysis has considered two deferent drainage thicknesses (1.25 and 0.5 m), and for each drainage thickness two reservoir water levels of 7.5 and 8 m were considered.

The three zoned models (Figure 2 c, d, e) consist of:

1) Earth-fill dam with central core that has slopes of 1:1,

2) Earth-fill dam with central core that has slopes of 1:0.5, and

3) Earth-fill dam with inclined core that has slopes of 1:1 for upstream and 1:0.5 for downstream.

For each zoned model, three deferent shell material values of permeability Kshell were considered. The values of shell material permeability were 10, 102 and 103 times of core material Kcore. Moreover, the analysis has considered two upstream water levels for each value, which are normal and maximum reservoir water levels.

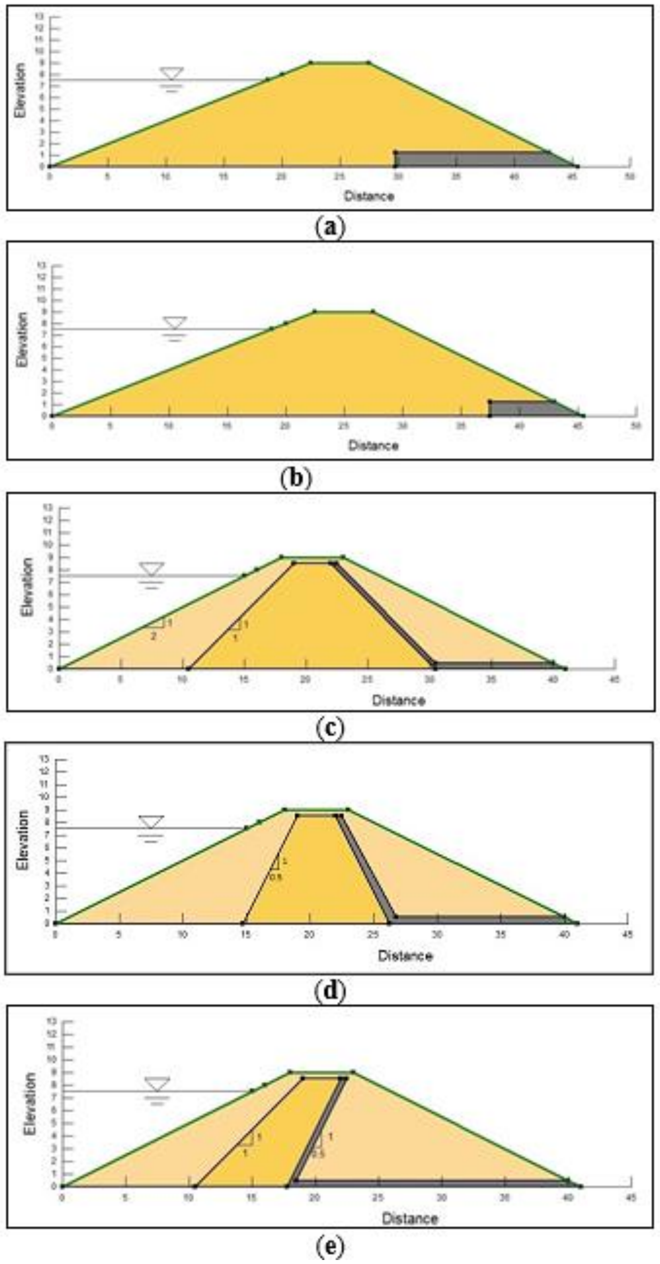

Fig. 2. *Cross section of five dam models*

TABLE II
DETAILS OF TEST TRAILS

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Model	Type	Drainage length (m)	Drainage thickness (m)	Water level (m)
a	Homogenous	$L_{Max} = 16$	1.25 and 0.5	7.5 and 8
b	Homogenous	$L_{Mid} = 12$	1.25 and 0.5	7.5 and 8
		K_{shell}/K_{core}		
c	Zoned	10, 100, and 1000		7.5 and 8
d	Zoned	10, 100, and 1000		7.5 and 8
e	Zoned	10, 100, and 1000		7.5 and 8

C. *Numerical Modeling*

SEEP/W software is a two-dimensional model can simulate seepage using many related mathematical equations [15]. It has been used in this study to sketch the seepage line through the earth-fill dam models and to calculate its rate through them. The fundamental components of numerical modeling by SEEP/W are:

- The dam Geometry which includes dimensions, cross-section, location and dimensions of filter.
- Material properties (permeability, pore water pressure, water content)
- Boundary conditions (upstream and downstream water level)
- Discretization, subdivision of space.
- Type of flow.

III. RESULTS AND DISCUSSION

A. *The Homogenous Earth-Fill Dam Models*

Figure 3 (a) and (b) shows the seepage lines, flow rates and contributions of total head for model (a) and (b) respectively at different cases. From the figure, the seepage line of model (a) is within the body of dam for all cases, with adequate downstream slope cover. The downstream cover of the dam with 1.25m drainage thickness is a bit lesser than the drainage with 0.5 m thickness, and its seepage flow rates are lower. Figure 3 (b) shows that the seepage line of model (b) is within the body of dam for all cases as well, however, the downstream slope cover is lesser than model (a). The downstream cover of the dam with 1.25m drainage thickness is also lesser than the 0.5m drainage thickness, and its seepage flow rates are lower.

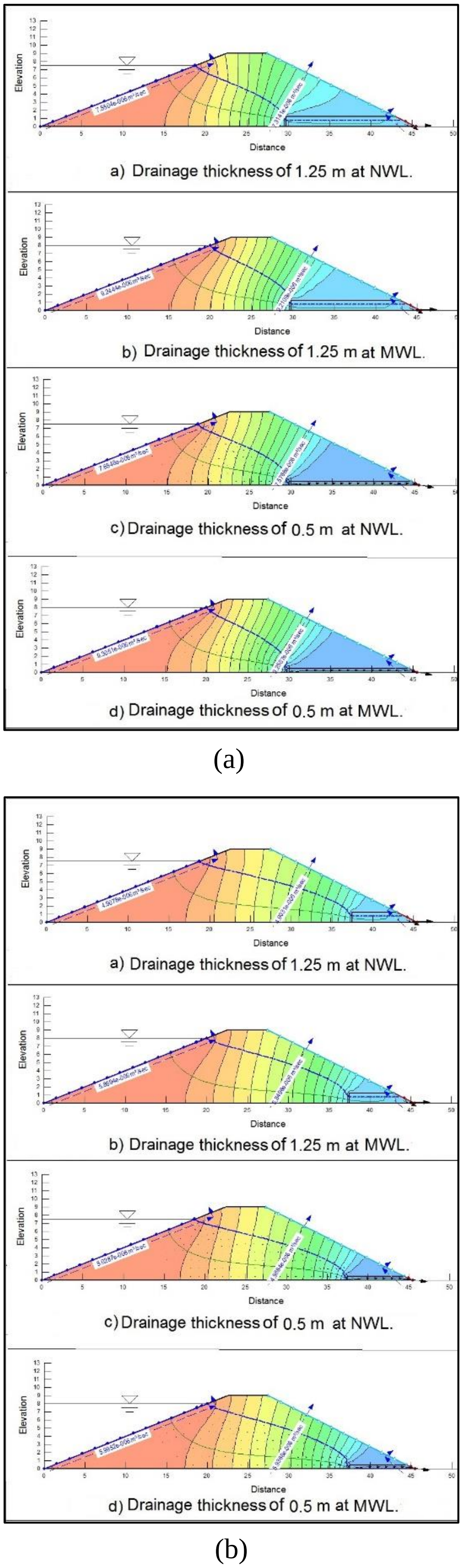


Fig. 3. Seepage line, flow rate and contribution of total head for models (a) and (b) at different cases

The values of seepage rates are presented in Table 3. It can been recognized that Model (a) has higher seepage flow rates and lower downstream cover in all cases comparing to Model (b). For both models, drainage with thickness of 0.5 m is adequate as the difference in seepage rate between the two thicknesses is insignificant.

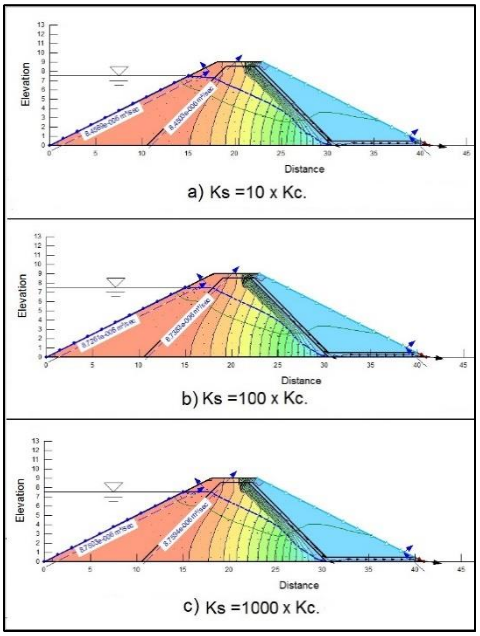
TABLE III
SEEPAGE RATES OF HOMOGENOUS MODELS

Model	Drainage thickness	Seepage *q* ($m^3/s/m$)	
		Normal water level	**Maximum water level**
a	1.25 m	7.55E-06	9.244E-06
	0.5 m	7.655E-06	9.3E-06
b	1.25 m	4.9E-06	5.86E-06
	0.5 m	5.02E-06	5.99E-06

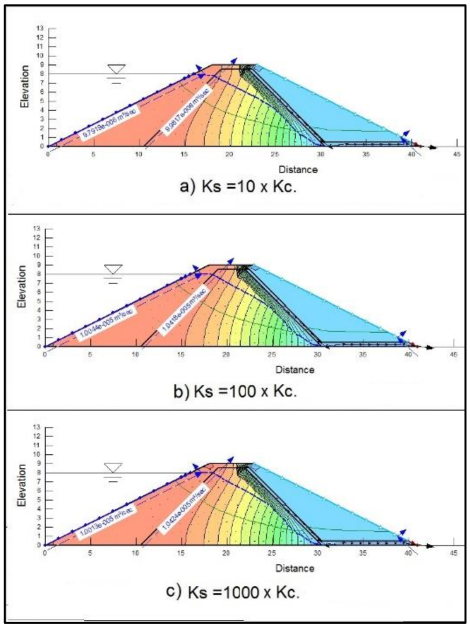
B. The Zoned Earth-Fill Dam Models

Three design models of Zoned dam were studied (see Figure 2 c, d, e). Silty sand soil has been used for the core of the dam with permeability K =3.493E-06. For each model, three types of soil were used for shell with permeability of 10 times, 100 times, and 1000 times of core permeability.

Figure 4 shows the seepage lines, flow rates and contributions of total head for Model (c) at different cases. From the figure, the seepage line for all cases is within the core of the dam for NWL and MWL, even if K for shell is 1000 times K for the core. The seepage flow rates do not change very much when increase K of shell. Moreover, in Model (c), the cross sectional area of silty sand soil is 97.75 m2 and the volume of soil needed for core is then 97.75 m3 per meter length. This means that the reduction of cross sectional area is 129.5 m2 and the reduction of the volume is 129.5 m3 per meter length (from 227.25m2 to 97.75m2).



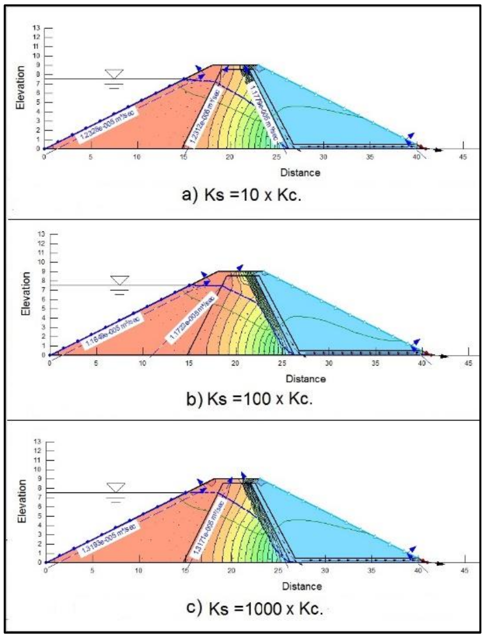
NWL



MWL

Fig. 4. Seepage line, flow rate and contribution of total head for model (c) at different cases.

Figure 5 shows the seepage lines, flow rates and contributions of total head for Model (d) at different cases. From the figure, the seepage line for all cases is within the core of the dam for NWL and MWL, even if K for shell is 1000 times K for core, and the seepage flow rates do not change very much when we increase Ks. In this model the cross sectional area of silty sand soil is 61.625 m2 and hence the volume of soil needed for core is 61.625 m3 per meter length. This means that the reduction of cross sectional area is 165.625 m2 and the reduction of the volume is 165.625 m3 per meter length (from 227.25m2 to be 61.625 m2).



NWL

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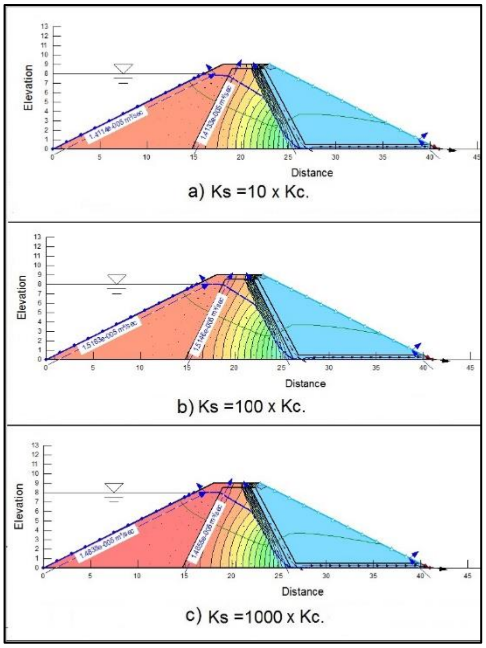


a) Ks =10 x Kc.

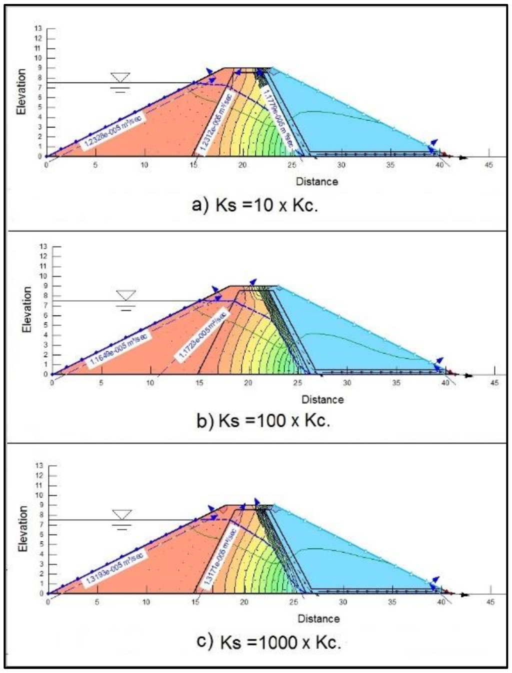
b) Ks =100 x Kc.

c) Ks =1000 x Kc.

MWL

Fig. 5. Seepage line, flow rate and contribution of total head for model (d) at different cases

Figure 6 shows the seepage lines, flow rates and contributions of total head for model (e) at different cases. From the figure, inclined core model is also sufficient to keep the line of seepage within the dam's core for all cases. Seepage flow rates increased slightly when Ks increased. In this model the cross sectional area of silty sand soil is 43.56 m2 and the volume of soil needed for core is 43.56 m3 per meter length. This means that the reduction of cross sectional area is 183.68 m2 and the reduction of the volume is 183.68 m3 per meter length (from 227.25m2 to be 43.56 m2).

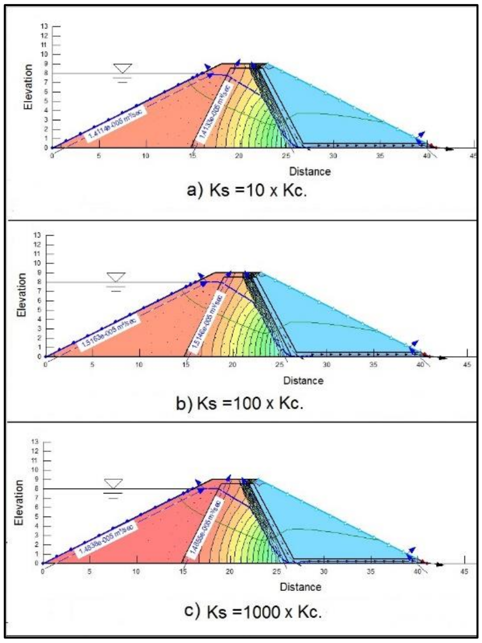


a) Ks =10 x Kc.

b) Ks =100 x Kc.

c) Ks =1000 x Kc.

NWL



a) Ks =10 x Kc.

b) Ks =100 x Kc.

c) Ks =1000 x Kc.

MWL

Fig. 6. Seepage line, flow rate and contribution of total head for Model (e) at different cases.

The values of seepage rates and required core material of Zoned dam models with different percentage of shell to core permeability (Kshell / Kcore) are presented in Table IV. It can be noticed that the model with inclined core (i.e. Model (e)) requires smallest volume of core, however, the rate of seepage is very high comparing with other models. Moreover, the rate of seepage for Model (d) is slightly higher than Model (c), while the difference in required volume of core is much less, so it is considered preferable.

TABLE IV
SEEPAGE RATES AND REQUIRED CORE MATERIAL OF ZONED MODELS

Model	**The details of core**		**Required core material (m^3/m)**	K_{shell} / K_{core}	**Seepage q ($m^3/s/m$)**	
	Place	**Slope** (H:V)			**Normal water level**	**Maximum water level**
c	Central	1:1	97.75	10	8.45E-06	9.85E-06
				100	8.73E-06	1.01E-05
				1000	8.75E-06	1.02E-05
d	Central	0.5: 1	61.63	10	1.23E-05	1.41E-05
				100	1.16E-05	1.51E-05
				1000	1.32E-05	1.48E-05
e	Inclined	1:1 U/S, 1:0.5 D/S	43.56	10	2.75E-05	3.05E-05
				100	2.9E-05	3.24E-05
				1000	2.62E-05	3.41E-05

C. Comparision of Models

Based on seepage analysis, if adequate quantity of low permeability soil is available, the homogeneous model with medium length of drainage is the ideal design model. The reason behind this preference is (1) sufficient downstream cover (2) lower seepage rate. Moreover, drainage with thickness of 0.5 m is adequate as the difference in seepage rate between the two thicknesses is insignificant. If adequate quantity of low permeability soil is not available, Zoned model with core in the centre of the dam and with 1:0.5 slopes would be the preferable model with reasonable seepage flow rate and required core material.

CONCLUSION

Seepage analysis is an essential study required before earth-fill dams' construction for ensuring sufficient control of seepage through the body of dams for safe and sustainable operation. In this study, numerical analysis of seepage through earth-fill dam models was conducted by applying SEEP/W program. Five different dam models, two with homogenous cross section and three with zoned cross section, have been studied. Moreover, the study consists the normal and maximum reservoir water levels, different drainage length and thickness, different percentage of permeability between shell and core in order to find the most appropriate model according to seepage behavior. Seepage analysis acknowledged that with adequate availability of low permeability soil, homogenous dam model with drainage of medium length and 0.5 m thickness is the best model. Otherwise, Zoned model with core in the centre of the dam and with 1:0.5 slopes would be the preferred.

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