NUMERICAL PARAMETRIC SIMULATIONS FOR SEEPAGE FLOW BEHAVIOUR THROUGH AN EARTHFILL DAM

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ABSTRACT

A finite element method is practical and applicable for many fields including for geotechnical engineering structures. Seepage through earth dam is difficult to analyse especially dams with multiple zones. Therefore, finite element is the best tool for analyzing seepage flow in an earthfill dam. The main objective of the project is to simulate the seepage flow through an earthfill dam. Three sets of steady state numerical modeling are presented in the paper. Two sets of parametric studies on long-term steady state flow were conducted using homogeneous and zoned earthfill dams for studying the behaviour of seepage in the dams. The third set of the simulations is a case study, which is analysis of steady state seepage condition for Kuala Yong Dam, the main part of Pergau Hydroelectric Project, Tenaga Nasional Berhad (TNB). The seepage quantity at the core and the downstream section were determined for the steady state flow condition. The results of the parametric simulations show that the total fluxes at downstream changes with the coefficient of permeability value. The flux quantity changes linearly with maximum seepage velocity. Significant differences can be observed in the case study, for the analysis using the coefficient of permeability function (varies with matric suction) versus analysis using a constant coefficient of permeability. Relationship between flux quantity at downstream and maximum seepage velocity is non-linear when hydraulic conductivity function is introduced in seepage analysis.

INTRODUCTION

Embankment dams especially earthfill dam requires seepage control (Cedergen (1989), Fell et al (1992), and Singh and Varshney (1995)). It is reported that failure of embankment dam caused by seepage alone make up about 25% of the total failure besides overtopping, internal erosion, etc. The seepage control involves reduction of seepage quantity by introducing impervious zone (or often refer as core) or drainage systems in the embankment dams (Singh and Varshney, 1995). Excessive seepage through the earth dam may result piping or internal erosion, which could lead to a failure.

The drawing of flow nets in the determination of seepage quantity is relatively straightforward for simple embankment dams such as a homogeneous earthfill dam with simple configurations. However, the complexity of seepage behaviour increases immensely especially for zoned earthfill dams or embankment dams with different coefficient of permeability for each zone. Therefore, seepage modelling using a finite element analysis can help to solve the problem faster, thus saving time and monetary wise, but sacrificing a minimal reduction of accuracy. Several authors such as Papagianakis and Fredlund (1984), Lam et al (1988), Potts and Zdravkovic (1999), and Rushton and Redshaw (1979) had performed seepage analysis through an embankment dam using finite element method.

The effect of coefficient of permeability or hydraulic conductivity on flow of seepage through unsaturated soils has been investigated by several researchers (Leong and Rahardjo (1997) and Fredlund et al (1994)). Hydraulic conductivity, which varies with negative pore-water pressure (or matric suction) are referred as hydraulic conductivity function or permeability function (Fredlund and Rahardjo, 1993). The assumption of constant hydraulic conductivity for entire pressure range in any seepage analysis could results in a significant error. Therefore, seepage analysis must take account of the hydraulic conductivity functions.

OBJECTIVES AND SCOPE OF THE STUDY

The main objective of the study was to study seepage flow and flux patterns of a dam with respect to variations in coefficient of permeability of dam materials. In fulfilling the general objective, the specific objectives of the study were to:

- Determine the effect of coefficient of permeability on flux quantity of the core and of downstream of a homogeneous embankment dam.
- Determine the effect of disparity of coefficients of permeability between that of core and adjacent earthfill material of a zoned earthfill dam on pattern of seepage flow and flux quantity.
- Determine the flux quantity of embankment for soil with soil-water relationship and various coefficients of permeability using a case study of a zoned earthfill dam.

The study was limited to the flux quantity based on different coefficients of permeability of a soil. The changes of flux quantity within a certain section of the dam were investigated. Assumptions were made for the simulation works, which are as follows:

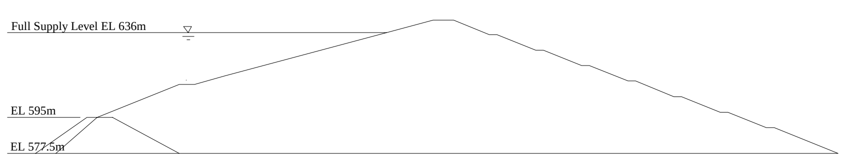
- The soils are assumed isotropic.
- Flux with respect to rainfall is excluded.
- There are no flows through the base of the dam or the foundation.
- The embankment dam constructed on top of a hard stratum (e.g., rocks) and settlement of the structure was ignored.

METHODOLOGY

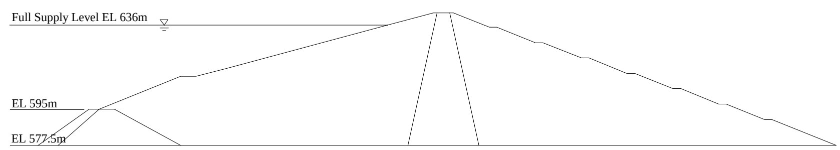
Seepage modelling using commercial finite element two-dimensional analysis software, SEEP/W, was performed. The study of the long term seepage through earth dam is divided into two categories of parametric simulations and a case study of Kuala Yong Dam. The parametric simulations consider constant hydraulic conductivity conditions only. For the case study, i.e., Kuala Yong Dam, both constant and non-constant coefficients of permeability are applied in the steady state simulation modelling. The unit of coefficient of permeability is meter per second (m/s).

Parametric Study

The parametric studies consist of a homogeneous (Category 1) and zoned earthfill dam (Category 2) as shown in Figure 1. The purpose of the parametric study is to determine the seepage fluxes at the core and downstream for various coefficients of permeability. The coefficient of permeability values considered for Category 1 and Category 2 are shown in Tables 1 and 2, respectively. The coefficients of permeability for Categories 1 and 2 are assumed constant for all range of pore-water pressures (see Figure 2(a)). Three different reservoir levels were analysed, i.e., at 636 m, 615 m and 595 m (Figure 3). For each reservoir level, five (5) coefficients of permeability and ten (10) sets of coefficient of permeability values of the core and earthfill materials are used for Categories 1 and 2, respectively. All flux sections for Categories 1 and 2 were fixed at identical locations (see Figure 4).

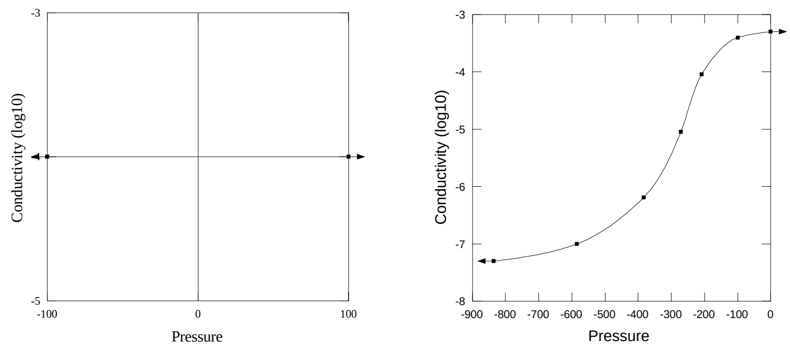


(a) Category 1



(b) Category 2

Figure 1 The cross section of the dam for the parametric studies using (a) homogeneous earthfill and (b) zoned earthfill.



(a) (b)

Figure 2 Coefficient of permeability functions; (a) straight line – constant with pore-water pressure for Categories 1 and 2, (b) curve – varies with negative pore-water pressure for the case study.

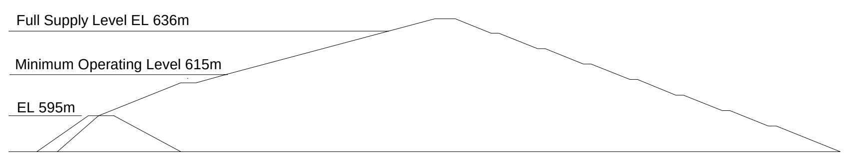


Figure 3 Reservoir water levels at upstream face at; 636 m, 615 m and 595 m (in elevation).

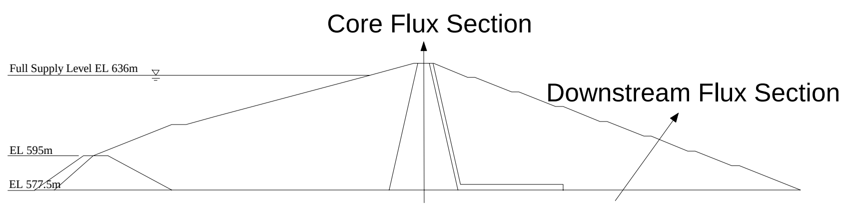


Figure 4 Determination of flux or seepage quantity at core and downstream section.

Two types of interpretation of results for Category 1 and 2 were presented. The results of seepage or flux quantity were interpreted with respect to different coefficient of permeability values for both Category 1 and Category 2. The maximum seepage velocity from each category was analysed with reference to the seepage or flux quantity. The maximum seepage velocity represents the largest value determined within the finite element of the embankment dam used in the simulations.

Case Study

The Kuala Yong Dam configuration was used for the analysis of steady state for the case study. The dam consists of three zones; the core zone, filter zone and the inner and outer shell zone (Figure 5). Each zone was assigned a specific coefficient of permeability function (Figure 6). The coefficient of permeability function can be defined as the ability of a soil to transport or conduct water under both saturated and unsaturated conditions. The coefficient of permeability function used in case study varies with negative pore-water pressure or matric suction.

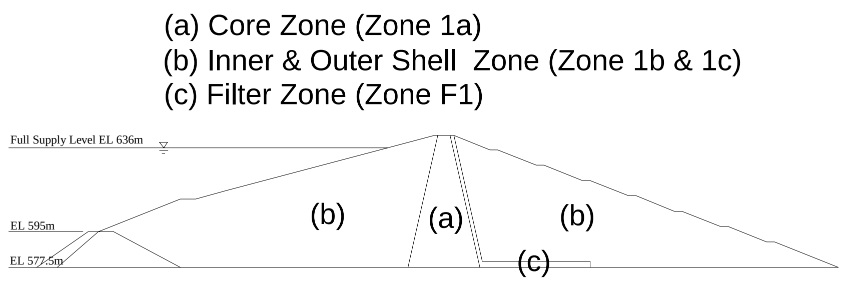


Figure 5 General cross section of Kuala Yong Dam. Outer and inner shells have the same material properties.

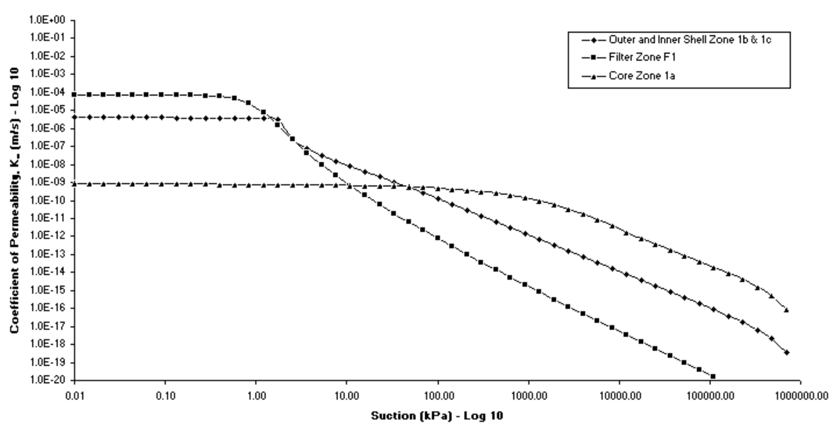


Figure 6 Coefficient of permeability functions or curves for multiple zones of

Kuala Yong Dam based on particle size distribution database.

The coefficient of permeability functions or curves are determined using the SoilVision, a knowledge-based software. In order to obtain the coefficient of permeability functions with this prediction method, few basic properties are required, namely, the particle size distribution, dry density, water content and specific gravity of the soil. The soil properties are obtained from the site investigation report of Pergau Hydroelectric Project. Before the coefficient of permeability function for each zone can be determined using the SoilVision software, the volumetric water content function or soil-water characteristic curve needs to be obtained as well. The soil-water characteristic curves are determined based on the particle size distribution curve and volume-mass properties for each zone. All these were determined using the SoilVision software.

For the third set of simulation modeling or case study, three different levels of reservoir storage were investigated (i.e., at 636 m, 615 m and 595 m). Flux quantities with respect to different reservoir level at core and downstream were analysed. Maximum seepage velocities for three reservoir levels were compared between the analysis using the coefficient of permeability function and the one with constant coefficient of permeability.

Parametric Study

The flux or seepage quantities, q at the core section and the downstream section were determined using the SEEP/W software. The results of the seepage modelling for Category 1 are shown in Table 3. The table shows the values of flux quantity, q for different values of reservoir level and coefficient of permeability, k. The maximum seepage velocity, v_s, was obtained for each *Run*. The maximum seepage velocity is the highest value selected from overall nodal in the finite element analysis. The results in Table 3 are presented based on the reservoir water level. Each *Run* consists of three sub categories for different reservoir levels (i.e., 636 m, 615 m and 595 m).

The results from the seepage modelling for Category 2 are shown in Table 4. There are two sets of coefficient of permeability, k values of between core and upstream and downstream section respectively. Due to the difference of coefficient of permeability, k for the core and upstream/downstream section, the flux quantity for downstream section was expected to be less than the results of Category 1.

The results of seepage modelling from Categories 1 and 2 were combined together owing to some similarities. It can be seen that there is a transitional from homogenous earth dam to the zoned earth dam in term of hydraulic conductivities and vice versa. As the coefficient of permeability for both core and upstream/downstream in Category 2 approaches to unity (i.e., coefficient of permeability, k for core and upstream/downstream are equivalent), it can be considered that the dam is homogeneous, which is represented in Category 1.

The flux quantities at downstream from Categories 1 and 2 are compared with respect to the ratio of coefficient of permeability of the core to that of the downstream or upstream. It can be seen that there is a *coupling* effect of the hydraulic conductivities of core and of the upstream which produce a single downstream flux quantity. This can be represented in three-dimensional graph that depicts the flux quantity, the core coefficient of permeability and upstream coefficient of permeability on *z*-, *x*- and *y*-axis respectively. However, the three-dimensional graph is difficult to interpret and identify with. In order to simplify the presentation of the results, the coefficient of permeability for both the core and downstream can be represented as a single entity which is shown in the following equation:

$$K_{ratio} = \frac{k_{core}}{k_{upstream}} \quad \text{(Equation 1)}$$

Results from Tables 3 and 4 were then combined and K_{ratio} was introduced (see Table 5). The downstream flux quantity, *q* for all *Run*s (as in Table 5) are plotted against the K_{ratio} and are shown in Figure 8, 9 and 10 for different reservoir level of 636 m, 615 m and 595 m, respectively. Each bold curve in the plot graphs (i.e., in Figures 8, 9 and 10) was drawn to represent flux results for simulations using the same coefficient of permeability for the core. The rectangular box with numeric label (e.g., 1.0E-08) indicates the value of coefficient of permeability for both downstream and upstream sections.

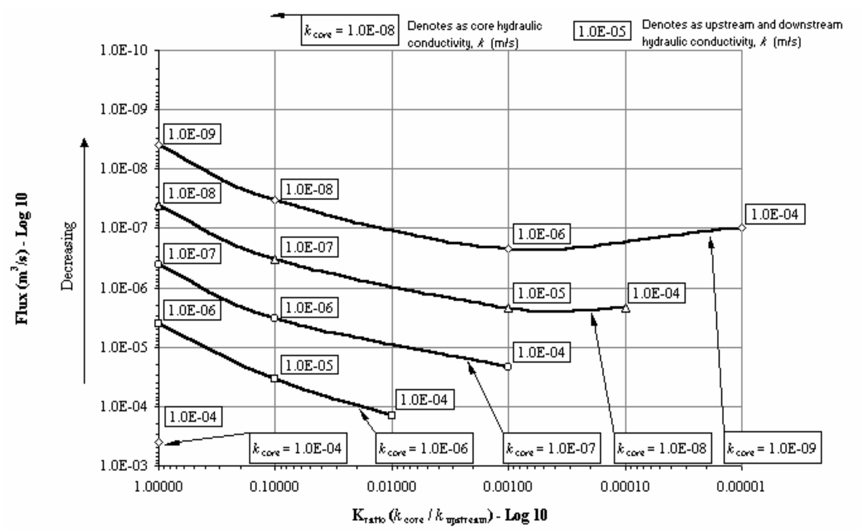


Figure 8 Downstream flux quantity versus K_{ratio} for Reservoir Level at 636 m.

From Figures 8 to 10, it can be observed that there is a similar trend. It depicts a concave type of curve. As the K_{ratio} decreases from 1.0 to 0.001, the quantity of flux increases with increasing $k_{upstream}$ values. It is also can be interpreted that the seepage flow is continuous at the interphase of the upstream earthfill zone and the core of the dam. However, for a K_{ratio} smaller than 0.001, the flux quantity at downstream is decreasing with increasing $k_{upstream}$ because of the big difference of the hydraulic conductivities at upstream and core. In other words, the seepage flow was impeded at the interphase of the upstream earth and the core of the dam. However, this is only visible in Figure 8 and 9 at the two lowest coefficient of permeability value at core zones (i.e., k_{core} = 1.0E-09 m/s and k_{core} = 1.0E-08 m/s). Due to limited data, it is not significant enough to say that it will be the same for other core coefficient of permeability values, i.e., k_{core} = 1.0E-07 m/s and k_{core} = 1.0E-06 m/s.

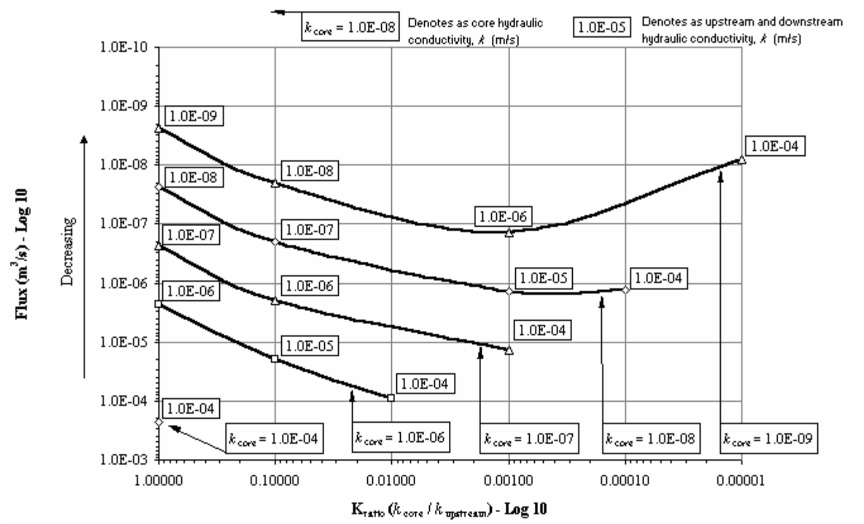


Figure 9 Downstream flux quantity versus K_{ratio} for reservoir level at 615 m.

To view the problem in different perspectives, the downstream flux quantity, *q* is plotted against the maximum seepage velocity, v_s for each *Run* using the results from Table 6. This graph, which considers various reservoir levels at 636 m, 615 m and 595 m, is shown in Figure 11. The linear relationship between the downstream flux quantity, *q* and maximum seepage velocity, v_s can be seen in this graph (i.e., Figure 11). As the seepage velocity decreases, the downstream flux quantity decreases as well. However, it must be noted that the maximum seepage velocity for each *Run* are based on the largest value of the overall seepage velocities within the cross section of the dam. This interpretation is unique for this dam configuration only. Other dam configurations may present other type of trend.

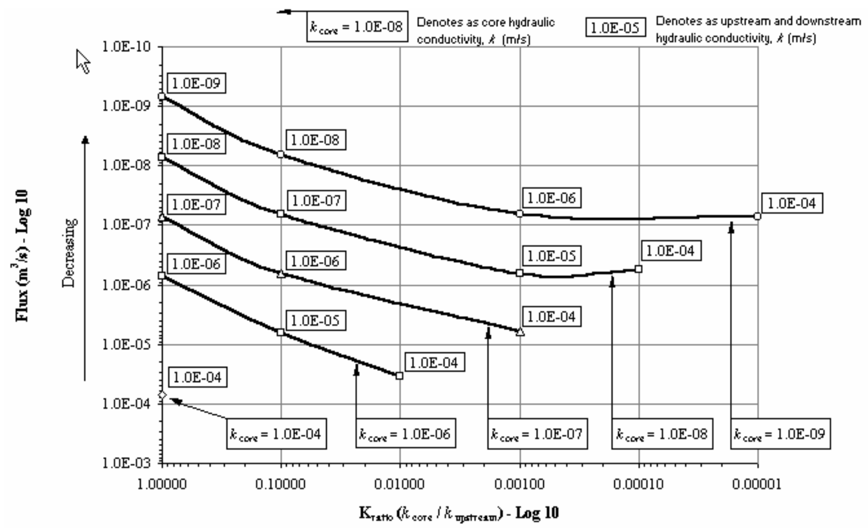


Figure 10 Downstream flux quantity vs. K_{ratio} for reservoir level at 595 m.

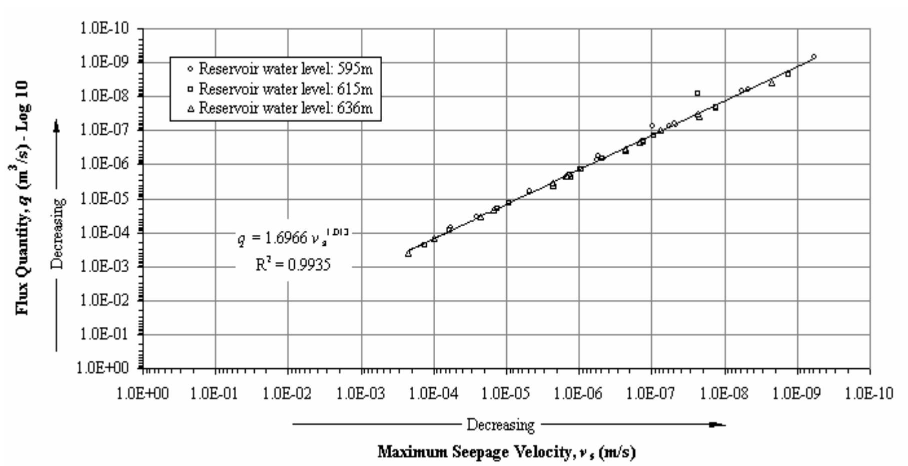


Figure 11 Downstream flux quantity versus maximum seepage velocity for Category 1 and Category 2.

Case Study (or Set 3)

For this paper, the simulations for steady state seepage are presented. The numbers of reservoir level for the simulations for the case study are same as of the parametric study of Categories 1 and 2, where three different reservoir levels were investigated (i.e., at 636 m, 615 m and 595 m). For the case study, the effect of coefficient of permeability function was investigated, followed by comparison of results between the one with coefficient of permeability function or *k-Fn* (*Run 1*) and the one with constant *k* (*Run 2*). Two *Run*s were investigated as explained earlier. The results of seepage simulations for case study are shown in Table 6. The reservoir levels are plotted against the flux quantity for both core and downstream sections as shown in Figure 12. While the reservoir level at 636 m, 615 m, and 595 m are plotted against the maximum seepage velocity for each *Run* (see Figure 13).

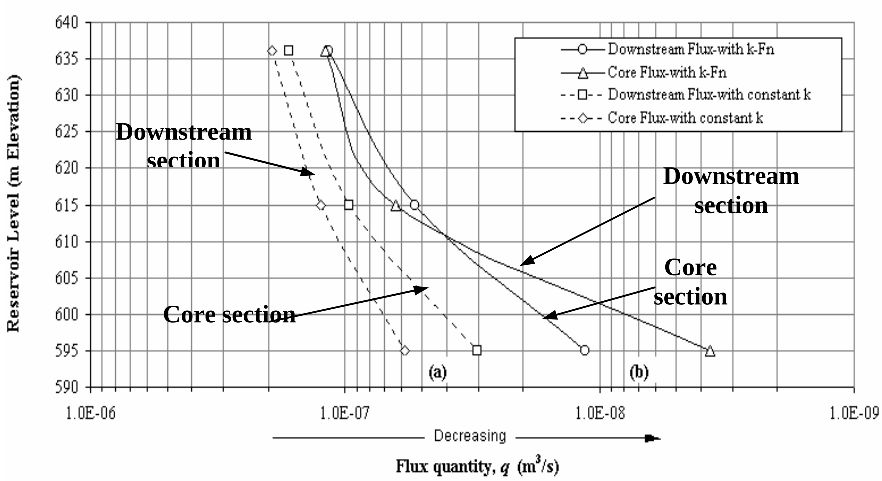


Figure 12 Reservoir water levels vs. flux quantity at downstream and core section for the case study; (a) with constant *k*, (b) with *k-Fn.*

In Figure 12, the broken lines as denoted by **(a)** represent the curves where coefficient of permeability, *k*, is constant with pore-water pressure, while **(b)** denotes simulation results using coefficient of permeability function. It can be seen that the changes of flux quantity between core and downstream sections varies almost constantly for the one with constant *k*. While the one with coefficient of permeability function, flux quantity at core and downstream section varies differently, compare to **(a)**. There are some similarities for downstream flux quantity, for both the *k-Fn* and constant *k*. However, difference was observed for core flux quantity, for one with *k-Fn* versus one with constant *k*. As the reservoir level reaches to 595 m, the core flux quantity reduces more drastically.

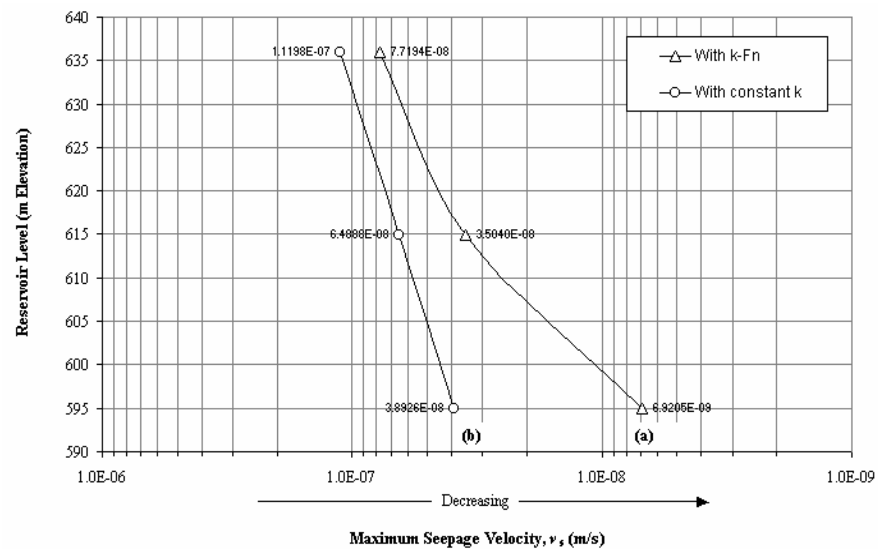


Figure 13 Reservoir water levels vs. maximum seepage velocity for the case study; (a) with *k-Fn*, (b) with constant *k.*

It can be seen that there are some reduction of seepage quantity for the ones with coefficient of permeability function or *k-Fn* compared with the one with constant *k* (see Figure 12). The difference of changes ranges from 40 to 60 percent. This shows that calculation or seepage modelling using constant *k* would produce inaccurate results.

The difference of maximum seepage velocity for both the *k-Fn* and constant *k* can be seen as shown in Figure 13. The changes of maximum seepage velocity with reference to the reservoir level for the case study of constant coefficient of permeability is almost linear (see Figure 13, **(a)**). While for the one using coefficient of permeability function (see Figure 13, **(b)**), the changes do not depict linear relationship. This shows that coefficient of permeability function has some significant effects on the seepage velocity for various reservoir levels in the dam. There is some reduction of maximum seepage velocity for each reservoir level (i.e., at 636 m, 615 m and 595 m) by comparing lines **(a)** and **(b)** in Figure 13. The percentage of difference ranges from 31 to 82 percent. It shows that a large percentage of error occurs if constant *k* is used in the seepage analysis.

DISCUSSIONS OF THE NUMERICAL SIMULATION RESULTS

Parametric Study

From the preceding interpretations given above, it can be concluded that for Categories 1and 2:

- Downstream flux quantity, q is controlled by the K_{ratio} or the combinations of core and upstream coefficient of permeability.
- There is a linear relationship between the downstream flux quantity and maximum seepage velocity within the cross section of the dam for Category 1 and Category 2. As the flux quantity at downstream decreases, the maximum seepage velocity in the earth dam will decrease as well. In other words, seepage velocity decreases with decreasing fluxes.
- For a core with a constant k_{core} value (Category 2), the flux or seepage flow behaviour increases with increasing $k_{upstream}$ until a threshold K_{ratio} of 0.001 is reached. Beyond the threshold value, however, the flux or seepage flow behaviour decreases with increasing $k_{upstream}$. A large difference between k values of adjacent materials impedes seepage flow, which may cause occurrence of internal erosion or piping of a dam.

Case Study

For the case study, based on preceding interpretation of results, it can be summarised that:

- Seepage modelling considering constant coefficient of permeability versus that of using *k*-function (*k*-*Fn*) can results in significant difference of flux quantity for both the in core and in the downstream section.
- Maximum seepage velocity in the dam for cases using constant coefficient of permeability shows linear relationship with reservoir levels. While for analysis with *k*-*Fn*, maximum seepage velocity varies with reservoir levels in non-linear form. The downstream flux for steady state simulation using constant k decreasing with the core flux values. While for the steady state simulation with *k*-function (*k*-*Fn*), the downstream flux values are influenced by combination of reservoir levels and seepage flow above the phreatic surface.
- There is a significant difference in both the flux quantity and maximum seepage velocity for between cases of seepage modeling using constant k and the one using *k*-function (*k*-*Fn*).

CONCLUSIONS OF THE STUDY

The parametric simulations for steady state flow show that the total flux at downstream changes with coefficient of permeability. The upstream portions control the flux quantity at downstream of the dam. The maximum seepage velocity changes linearly with flux quantity. The interpretation for parametric simulations is unique for the dam configuration only. Other dam configurations may present other type of trend.

The disparity of coefficient of permeability values of between two adjacent materials influences the rate and continuity of the seepage flow at the interphase of adjacent materials.

Significant differences can be observed in the case study, i.e., between results for analysis using coefficient of permeability function (varies with matric suction) and constant coefficient of permeability. Relationship between flux quantity at downstream and maximum seepage velocity is non-linear when coefficient of permeability function is introduced in seepage analysis.

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Table 1 Input Data – Hydraulic Conductivity for Category 1 (Homogeneous Dam)

Run #	Hydraulic Conductivity, *k* (m/s)
1	1.00×10^{-4}
2	1.00×10^{-6}
3	1.00×10^{-7}
4	1.00×10^{-8}
5	1.00×10^{-9}

Table 2 Input Data – Hydraulic Conductivity – Category 2 (Zoned Dam)

Run #	Hydraulic Conductivity, *k* (m/s)	
	Core	Upstream / Downstream
1	1.00×10^{-6}	1.00×10^{-4}
2	1.00×10^{-6}	1.00×10^{-5}
3	1.00×10^{-7}	1.00×10^{-4}
4	1.00×10^{-7}	1.00×10^{-6}
5	1.00×10^{-8}	1.00×10^{-4}
6	1.00×10^{-8}	1.00×10^{-5}
7	1.00×10^{-8}	1.00×10^{-7}

8	1.00 x 10^{-9}	1.00 x 10^{-4}
9	1.00 x 10^{-9}	1.00 x 10^{-6}
10	1.00 x 10^{-9}	1.00 x 10^{-8}

Table 3 Results of Seepage Modelling for Category 1

Run #	Reservoir Water Level (m)	Flux Quantity, q (m^3/s)		Hydraulic Conductivity, k (m/s)		Max. Seepage Velocity, v_s (m/s)
		Core	Downstream	Core	Upstream	
1	636	4.0172E-04	4.0160E-04	1.00E-04	1.00E-04	2.2634E-04
2	636	4.0143E-07	4.0171E-07	1.00E-07	1.00E-07	2.2636E-07
3	636	4.0164E-09	4.0167E-09	1.00E-09	1.00E-09	2.2633E-09
4	636	4.0168E-06	4.0168E-06	1.00E-06	1.00E-06	2.2631E-06
5	636	4.0161E-08	4.0143E-08	1.00E-08	1.00E-08	2.2635E-08
1	615	2.3130E-04	2.3119E-04	1.00E-04	1.00E-04	1.3031E-04
2	615	2.3106E-07	2.3130E-07	1.00E-07	1.00E-07	1.3036E-07
3	615	2.3126E-09	2.3129E-09	1.00E-09	1.00E-09	1.3031E-09
4	615	2.3126E-06	2.3125E-06	1.00E-06	1.00E-06	1.3029E-06
5	615	2.3107E-08	2.3123E-08	1.00E-08	1.00E-08	1.3035E-08
1	595	7.1022E-05	7.0906E-05	1.00E-04	1.00E-04	5.7611E-05
2	595	7.0921E-08	7.1180E-08	1.00E-07	1.00E-07	5.7417E-08
3	595	7.0966E-10	7.1004E-10	1.00E-09	1.00E-09	5.7610E-10
4	595	7.0963E-07	7.0958E-07	1.00E-06	1.00E-06	5.7634E-07
5	595	7.0883E-09	7.1018E-09	1.00E-08	1.00E-08	5.7488E-09

Table 4 Results of Seepage Modelling for Category 2
(Zoned Dam – with constant hydraulic conductivity)

Run #	Reservoir Water Level (m)	Flux Quantity, q (m^3/s)		Hydraulic Conductivity k (m/s)		Max Seepage Velocity, v_s (m/s)
		Core	Downstream	Core	Upstream	
1	636	1.4658E-04	1.4644E-04	1.00E-06	1.00E-04	9.8679E-05
2	636	3.3847E-05	3.3863E-05	1.00E-06	1.00E-05	2.2811E-05
3	636	2.2041E-05	2.1899E-05	1.00E-07	1.00E-04	1.4769E-05
4	636	3.3853E-06	3.3856E-06	1.00E-07	1.00E-06	2.2811E-06
5	636	2.3211E-06	2.1698E-06	1.00E-08	1.00E-04	1.4827E-06
6	636	2.2030E-06	2.2149E-06	1.00E-08	1.00E-05	1.4889E-06
7	636	3.3831E-07	3.3866E-07	1.00E-08	1.00E-07	2.2815E-07
8	636	2.3335E-07	1.0025E-07	1.00E-09	1.00E-04	7.6590E-08
9	636	2.2033E-07	2.2048E-07	1.00E-09	1.00E-06	1.4860E-07
10	636	3.3855E-08	3.3851E-08	1.00E-09	1.00E-08	2.2810E-08
1	615	8.9872E-05	8.9721E-05	1.00E-06	1.00E-04	6.0471E-05
2	615	1.9666E-05	1.9680E-05	1.00E-06	1.00E-05	1.3255E-05
3	615	1.4034E-05	1.3889E-05	1.00E-07	1.00E-04	9.3744E-06
4	615	1.9670E-06	1.9670E-06	1.00E-07	1.00E-06	1.3254E-06
5	615	1.4870E-06	1.3465E-06	1.00E-08	1.00E-04	9.2098E-07

6	615	1.4023E-06	1.4162E-06	1.00E-08	1.00E-05	9.4938E-07
7	615	1.9652E-07	1.9687E-07	1.00E-08	1.00E-07	1.3261E-07
8	615	1.4959E-07	8.1756E-09	1.00E-09	1.00E-04	2.3283E-08
9	615	1.4025E-07	1.4043E-07	1.00E-09	1.00E-06	9.4645E-08
10	615	1.9672E-08	1.9668E-08	1.00E-09	1.00E-08	1.3255E-08
1	595	3.5058E-05	3.4911E-05	1.00E-06	1.00E-04	2.5715E-05
2	595	6.4109E-06	6.4243E-06	1.00E-06	1.00E-05	4.7023E-06
3	595	6.3548E-06	6.2077E-06	1.00E-07	1.00E-04	4.7002E-06
4	595	6.4116E-07	6.4128E-07	1.00E-07	1.00E-06	4.7072E-07
5	595	6.9175E-07	5.5551E-07	1.00E-08	1.00E-04	5.5368E-07
6	595	6.3433E-07	6.4742E-07	1.00E-08	1.00E-05	4.7294E-07
7	595	6.4049E-08	6.4389E-08	1.00E-08	1.00E-07	4.6884E-08
8	595	6.9792E-08	7.2689E-08	1.00E-09	1.00E-04	9.8663E-08
9	595	6.3437E-08	6.3503E-08	1.00E-09	1.00E-06	4.7751E-08
10	595	6.4133E-09	6.4104E-09	1.00E-09	1.00E-08	4.7085E-09

Table 5 Results of Seepage Modelling for Categories 1 and 2
(Combined from Table 3 and 4)

Case	Run#	Reservoir Water Level (m)	Flux Quantity, q (m^3/s)		K ratio ($k_{core}/k_{upstream}$)	Max. Seepage Velocity, v_s (m/s)
			Core	**Downstream**		
1	1	595	7.1022E-05	7.0906E-05	1	5.7611E-05
1	4	595	7.0963E-07	7.0958E-07	1	5.7634E-07
2	2	595	6.4109E-06	6.4243E-06	0.1	4.7023E-06
2	1	595	3.5058E-05	3.4911E-05	0.01	2.5715E-05
1	2	595	7.0921E-08	7.1180E-08	1	5.7417E-08
2	4	595	6.4116E-07	6.4128E-07	0.1	4.7072E-07
2	3	595	6.3548E-06	6.2077E-06	0.001	4.7002E-06
1	5	595	7.0883E-09	7.1018E-09	1	5.7488E-09
2	7	595	6.4049E-08	6.4389E-08	0.1	4.6884E-08
2	6	595	6.3433E-07	6.4742E-07	0.001	4.7294E-07
2	5	595	6.9175E-07	5.5551E-07	0.0001	5.5368E-07
1	3	595	7.0966E-10	7.1004E-10	1	5.7610E-10
2	10	595	6.4133E-09	6.4104E-09	0.1	4.7085E-09
2	9	595	6.3437E-08	6.3503E-08	0.001	4.7751E-08
2	8	595	6.9792E-08	7.2689E-08	0.00001	9.8663E-08
1	1	615	2.3130E-04	2.3119E-04	1	1.3031E-04
1	4	615	2.3126E-06	2.3125E-06	1	1.3029E-06
2	2	615	1.9666E-05	1.9680E-05	0.1	1.3255E-05
2	1	615	8.9872E-05	8.9721E-05	0.01	6.0471E-05
1	2	615	2.3106E-07	2.3130E-07	1	1.3036E-07
2	4	615	1.9670E-06	1.9670E-06	0.1	1.3254E-06
2	3	615	1.4034E-05	1.3889E-05	0.001	9.3744E-06
1	5	615	2.3107E-08	2.3123E-08	1	1.3035E-08

2	7	615	1.9652E-07	1.9687E-07	0.1	1.3261E-07
2	6	615	1.4023E-06	1.4162E-06	0.001	9.4938E-07
2	5	615	1.4870E-06	1.3465E-06	0.0001	9.2098E-07
1	3	615	2.3126E-09	2.3129E-09	1	1.3031E-09
2	10	615	1.9672E-08	1.9668E-08	0.1	1.3255E-08
2	9	615	1.4025E-07	1.4043E-07	0.001	9.4645E-08
2	8	615	1.4959E-07	8.1756E-09	0.00001	2.3283E-08
1	1	636	4.0172E-04	4.0160E-04	1	2.2634E-04
1	4	636	4.0168E-06	4.0168E-06	1	2.2631E-06
2	2	636	3.3847E-05	3.3863E-05	0.1	2.2811E-05
2	1	636	1.4658E-04	1.4644E-04	0.01	9.8679E-05
1	2	636	4.0143E-07	4.0171E-07	1	2.2636E-07
2	4	636	3.3853E-06	3.3856E-06	0.1	2.2811E-06
2	3	636	2.2041-05	2.1899E-05	0.001	1.4769E-05

Table 5 Results of Seepage Modelling for Categories 1 and 2 (Combined from Table 3 and 4) - continued

1	5	636	4.0161E-08	4.0143E-08	1	2.2635E-08
2	7	636	3.3831E-07	3.3866E-07	0.1	2.2815E-07
2	6	636	2.2030E-06	2.2149E-06	0.001	1.4889E-06
2	5	636	2.3211E-06	2.1698E-06	0.0001	1.4827E-06
1	3	636	4.0164E-09	4.0167E-09	1	2.2633E-09
2	10	636	3.3855E-08	3.3851E-08	0.1	2.2810E-08
2	9	636	2.2033E-07	2.2048E-07	0.001	1.4860E-07
2	8	636	2.3335E-07	1.0025E-07	0.00001	7.6590E-08

Table 6 Results of Seepage Modelling for Case Study (Kuala Yong Dam)

Case	Run#	Reservoir Water Level (m)	Flux Quantity, q (m^2/s)		Max Seepage Velocity v_s (m/s)
			Core	Downstream	
3	1	636	1.2005E-07	1.1544E-07	7.7194E-08
3	1	615	6.3321E-08	5.2850E-08	3.5040E-08
3	1	595	3.6682E-09	1.1403E-08	6.9205E-09
3	2	636	1.9448E-07	1.6577E-07	1.1198E-07
3	2	615	1.2460E-07	9.6398E-08	6.4888E-08
3	2	595	5.7955E-08	3.0229E-08	3.8926E-08

Notes:
Run1 – the hydraulic conductivity function included (see *Figure 2b*)
Run2 – hydraulic conductivity constant with all range of pore-water pressure (see *Figure 2a*)