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Numerical and experimental modelling of slope stability and seepage water of earthfill dam

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Abstract

In this paper, finite element modelling is employed for simulating and analysing seepage and slope stability of earthfill dam via GeoStudio software. Two products are employed, which are SLOPE/W for slope stability and SEEP/W for seepage analysis. The behaviour of earthfill dam with four different types of sandy soils having different values of hydraulic conductivity (K) has been studied. Different upstream (US) slopes of 1:2, 1:2.5, 1:3 and 1:3.5 for the earthfill dam are simulated. The downstream (DS) slope is constant at 1:2.

The results showed for all the four types of soils that when the US slope is increased, the amount of seepage from the dam increases and the factor of safety (F) decreases. For each US slope, when K (type of soil) increases, both seepage and F increase. Fine sand soil is associated with less seepage and less F. Sixteen equations are obtained to predict both seepage and F with respect to US slope for each type of soil and K of the soil for US slope.

An experimental model for earthfill dam is constructed in the laboratory of hydraulics, Benha University to investigate the seepage of water through earthfill dams. It is concluded that seepage decreased when K decreased, and when the US slope for each type of soil decreased. The seepage increased when K increased for each US slope. Seven equations are obtained to predict seepage with respect to US slope for each type of soil, and K for each US slope.

Key words: *earthfill dam, finite element modelling, GeoStudio, seepage, slope stability*

INTRODUCTION

Dams have been used to store water for different purposes especially irrigation [ADJIM, DJEDID 2018]. The earthfill dams are the most common economic type of dams [EL-HAZEK 2013; 2014]. That is mainly because its construction involves using materials in their natural state with little processing. A homogeneous type of earthfill dams is composed entirely of a single type of material. Since the action of seepage is not favourable in such a purely homogeneous section, the upstream (US) slope has to be relatively flat for safety in rapid draw down when embankment is relatively impervious [OMOFUNMI 2017]. Also when the downstream (DS) slope is flat, it will provide a sufficiently stable slope to resist the forces resulting from a high saturation level. The effectiveness of earthen structures is summed up in stability, durability, cost-effectiveness, sediment storage, flood plating and water storage for a significant length of time and had a positive impact on reducing erosion and the silting rate of the dam [ZOBIRI *et al.* 2018].

Dams have to be designed and maintained to control seepage safely. Excessive seepage may lead to a problem with the safety of a dam if not treated properly. It is important to understand how seepage is affecting a particular dam and to define the measures, if any, that must be adapted to ensure that the seepage does not affect the safety of the dam. According to ABDEL-GAWAD and SHAMAA [2004] boundary element method (BEM) for Laplace's equation was applied to solve the problem of seepage through earth dams underlined by a horizontal filter. According to KOKANEH *et al.* [2013] the determination of seepage induced flow under and through an earth dam based on the Group Method of Data Handling (GMDH) type neural network was studied. According to KANCHANA and PRASANNA [2015] the usage of various materials with different combinations to zone type earthen dams with a central impervious vertical core was studied and analyzed. Phreatic seepage surface, pore water pressure distribution and total hydraulic head variation of earth dams for three cases of operation under steady state conditions were obtained and analyzed [ZEIDAN *et al.* 2017]. According to PHAM *et al.* [2018b] a study for the influence of hydraulic characteristics on the stability of unsaturated slope under transient seepage conditions for different types of soil-water characteristic curve (SWCC) models was conducted. The kinematic limit analysis method was adopted to estimate the stability of slopes subjected to vertical unsaturated steady flow in the context of a 3D rotational failure mechanism [LI, YANG 2018]. According to PHAM *et al.* [2018a] experimental results were utilized to identify the suitable soil-water characteristic curve model for each soil type based on the fitting criterion.

GeoStudio software is used for the analysis of deformation and stability of earthfill dams. This software is a finite element based code. The basic concept of the finite element method is to divide the problem region into finite elements connected at their common nodal points and the unknown function of the field variable is defined approximately within each element [ZEIDAN 1993]. GeoStudio software includes eight products, which are SLOPE/W for slope stability, SEEP/W for groundwater seepage, SIGMA/W for stress-deformation, QUAKE/W for dynamic earthquake, TEMP/W for geothermal, CTRAN/W for contaminant transport, AIR/W for air flow, VADOSE/W for vadose zone and covers. SEEP/W is a comprehensive computer tool for seepage analysis, which is capable of modelling both the saturated and unsaturated soils. It calculates the seepage using partial differential equations that make the water flow. The slope stability of earthen dams was discussed using GeoStudio software [DURGA NAGA LAXMI DEVI, ANBALAGAN 2017]. The slope stability problems could be analysed using two-dimensional software such as GeoStudio by assuming soil under plane strain or plane stress condition [LI *et al.* 2018]. The quantity of seepage through homogenous earth dam without filter resting on an impervious base using SEEP/W was studied by JAMEL [2016]. Results showed that less than 2% error with SEEP/W results, while Dupuit's solution had more than 20% error and Casagrande's solution had more than 15% error.

According to KAMANBEDAST and DELVARI [2012] the behaviour of rockfill dam with different effective parameters had been studied using both Ansys and GeoStudio Software with Maroon dam in Iran as case study. The seepage of water through the earthen portion of Ujjani dam, which is an earthfill masonry dam in India, was investigated [KULKARNI, HANGARGEKAR 2017a, b]. The phreatic line was simulated for single change and the observed actual field results of seepage were compared with results obtained by GeoStudio software sub product SEEP/W. A research study was conducted on Hub dam, which is a small earthen dam in Pakistan [ARSHAD, BABAR 2014]. The SEEP/W software was used to study seepage problems. A study of the influence of both elasticity and pore water pressure on the seismic response of earthen dams to artificial earthquake records using finite element software QUAKE/W in GeoStudio was presented [PAVAN *et al.* 2016]. Seepage analysis and slope stability in Ilam earthfill dam in Iran had been done employing SEEP/W and SLOPE/W software [HASANI *et al.* 2013]. According to KIRRA *et al.* [2015] the results confirmed the safety of Mandali dam in Iraq against combined seepage and slope stability under all cases of operation. The case of rapid drawdown was the most critical operating case compared to other cases of operation.

There are several methods to evaluate the stability of earth dam such as limit equilibrium methods [ABBAS *et al.* 2017]. One of these methods is the ordinary or Fellenius method that was developed to satisfy the moment equilibrium for a circular slip surface but neglects both the inter slice normal and shear forces [FELLENIUS 2006]. The advantage of this method is its simplicity in obtaining the factor of safety (*F*) since it does not require an iteration process. Bishop simplified method is another method that advanced the last ordinary method for circular shear surface (SS) [BISHOP 1955]. This method considers the inter slice normal forces but neglects the inter slice shear forces. This method satisfies moment equilibrium for *F*. Janbu's simplified method is a method based on a composite shear surface (non-circular) and *F* is determined by horizontal force equilibrium [JANBU 1954]. The Morgenstern–Price method satisfies both force and moment equilibriums and assumes the inter slice force function [BISHOP, MORGENSTERN 1960]. Spencer's method is the same as Morgenstern–Price method except the assumption made for inter slice forces [SPENCER 1967]. For earth core rockfill dams, four analysis methods of dynamic stability against the sliding of the dam slope were compared, where multiple methods were suggested to be used to carry out a comprehensive analysis and assessment [MA, CHI 2016]. A laboratory model was constructed and analysed with an intention to keep the stability of the zone type earth dam against seepage of water with different pool level in smooth bed [MANDAL *et al.* 2018].

METHODS

In this paper, the 2-D finite element model is employed for simulating slope stability analysis of earth dam problems via GeoStudio software. The stability of the dam side slopes is assessed using analytical methods. Under steady state conditions, phreatic seepage surface, pore water pressure distribution and total hydraulic head variation of earthfill dams are obtained and analysed. The factor of safety is calculated as the ratio of resisting forces to driving forces according to the Bishop method. The forces acting in the vertical direction of a slice are integrated and the resulting vertical forces are considered along with the Mohr–Coulomb criterion to determine the shear forces acting on the base of slices. Then, moments about the centre of the circular slip surface are summed.

The boundary conditions for the numerical model are defined after assigning hydraulic conductivity (K) values. Four types of sandy soils are employed. The effective size of grains is deduced employing maximum sieve sizes of 1.5, 1.0, 0.5 and 0.25 mm. Both the coefficient of gradient and coefficient of uniformity were calculated using D_{10}, D_{30}, and D_{60}. Then, the values of K were obtained, where Hazen empirical formula for uniformly graded soil is followed [HUSSAIN, NABI 2016].

SLOPE/W provides 14 strength models for simulating the shear strength characteristics of soil or rock. Shear strength is computed based on the Mohr-Coulomb equations. Basic parameters include unit weight, the cohesion component of the shear strength, and the friction angle of the soil. However, the friction angles of the soils were taken to be in the range of 26–32 for the four studied types of soils.

As commonly used for sandy soils, four upstream (US) slopes 1:2, 1:2.5, 1:3 and 1:3.5 are studied, with constant downstream (DS) slope of 1:2. Values for the height of the dam, water elevation, and crest width are 25 cm, 20 cm and 10 cm respectively.

In order to investigate the seepage of water through an earthfill dam, an experimental model for earthfill dam was constructed in the laboratory of hydraulics located in the Faculty of Engineering at Shoubra, Benha University. Seepage is observed and studied by both numerical model (GeoStudio Software) and laboratory experiments.

RESULTS

NUMERICAL ANALYSES BY GEOSTUDIO SOFTWARE

The numerical results of seepage (Q) and factor of safety (F) are obtained by the SEEP/W and SLOPE/W software, as presented in Table 1.

For soil 1, the resulted seepage and factor of safety for the case of US slope 1:3.5 is shown in Figure 1. For soil 2, the resulted seepage and factor of safety for the case of US slope 1:3 is illustrated in Figure 2. For soil 3, the resulted seepage and factor of safety for the case of US slope 1:2.5 is shown in Figure 3. For soil 4, the resulted seepage and factor of safety for the case of US slope 1:2 is illustrated in Figure 4.

Table 1. The results obtained from the GeoStudio software

Sieve size (mm)	Type of soil	Hydraulic conductivity K ($cm \cdot s^{-1}$)	Upstream slope	Seepage Q ($cm^3 \cdot s^{-1}$)	Factor of safety F
1.5	soil 1	0.0484	1:2	2.88	1.00
			1:2.5	2.81	1.04
			1:3	2.76	1.06
			1:3.5	2.69	1.08
1.0	soil 2	0.0361	1:2	2.56	0.86
			1:2.5	2.49	0.89
			1:3	2.44	0.91
			1:3.5	2.39	0.94
0.5	soil 3	0.0289	1:2	2.16	0.78
			1:2.5	2.10	0.81
			1:3	2.06	0.83
			1:3.5	2.01	0.85
0.25	soil 4	0.0272	1:2	1.95	0.70
			1:2.5	1.90	0.73
			1:3	1.86	0.75
			1:3.5	1.81	0.77

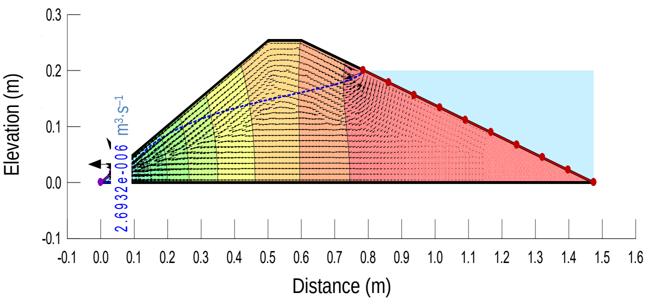
Source: own study.

EXPERIMENTAL ANALYSES

An experimental model for an earthfill dam is constructed in the laboratory of hydraulics, Faculty of Engineering at Shoubra, Benha University. The model is composed of a transparent glass basin with dimensions of 200 cm length, 100 cm width, 100 cm depth and 10 mm thickness of the glass, as illustrated in Figure 5.

Three types of sandy soils are used for the model dam, which are soils 1, 2 and 3 as illustrated in Table 1. The downstream (DS) slope of the model is constant at 1:2, while the upstream (US) slopes are variable. The values of US slopes are taken to be 1:2, 1:2.5, 1:3, and 1:3.5. The model is compacted in three layers using a wooden piece until reaching an acceptable degree of compaction. Height of sandy soil is 25 cm. The water is added in four stages (5 cm in each stage) to maintain the saturated degree of soil. Thereafter, the seepage water is collected, as shown in Figure 6. The crest width (B) is 10 cm.

The obtained results for seepage employing the experimental model of the earthfill model dam are presented in Table 2.



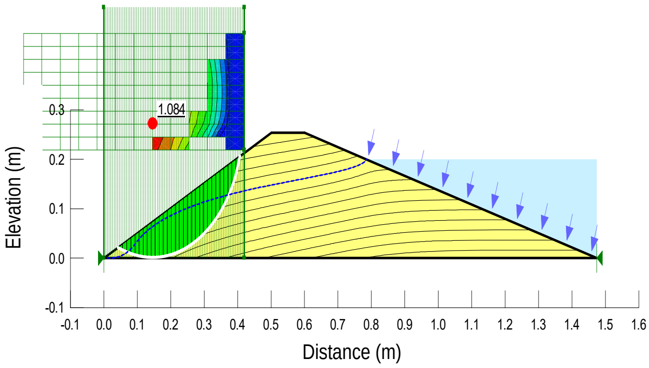


Fig. 1. Numerical analyses by GeoStudio software for soil 1 and upstream slope 1:3.5: a) seepage, b) factor of safety; source: own study

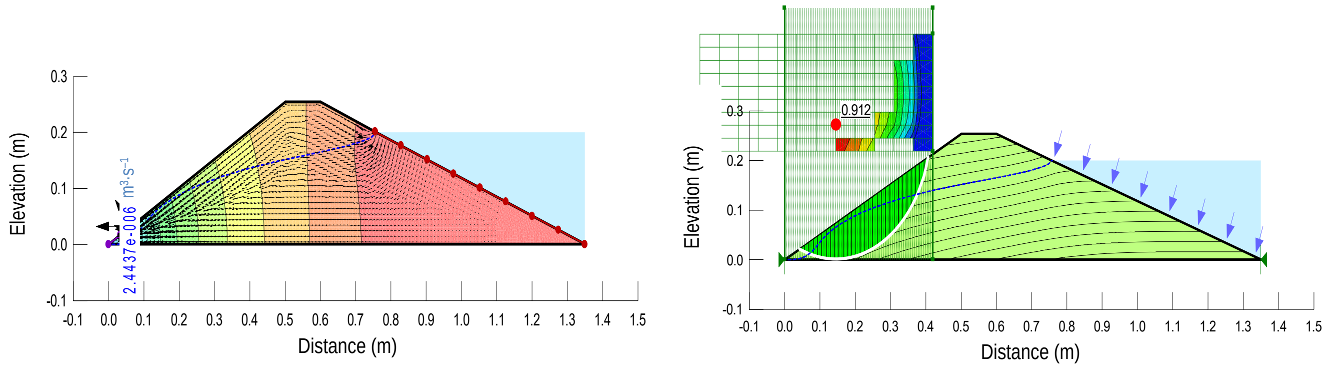


Fig. 2. Numerical analyses by GeoStudio software for soil 2 and upstream slope 1:3: a) seepage, b) factor of safety; source: own study

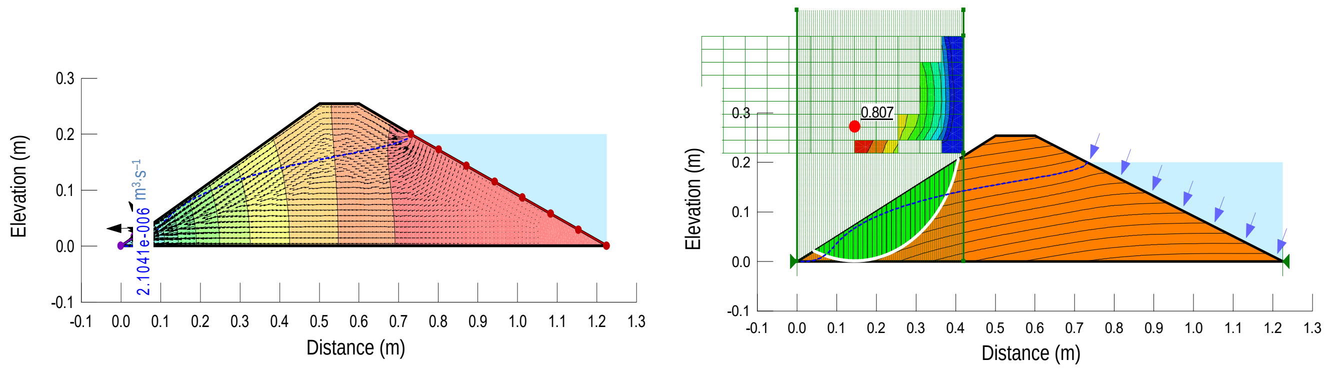


Fig. 3. Numerical analyses by GeoStudio software for soil 3 and upstream slope 1:2.5: a) seepage, b) factor of safety; source: own study

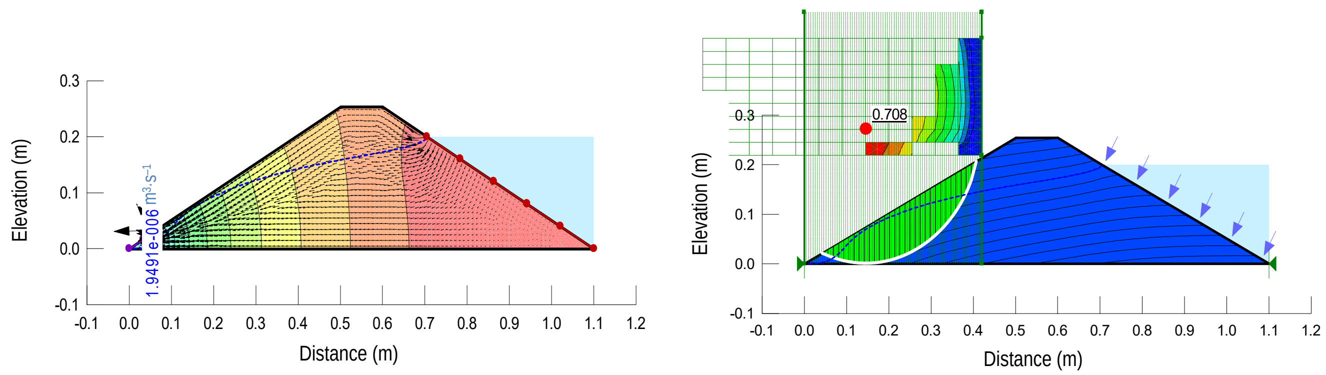


Fig. 4. Numerical analyses by GeoStudio software for soil 4 and upstream slope 1:2: a) seepage, b) factor of safety; source: own study

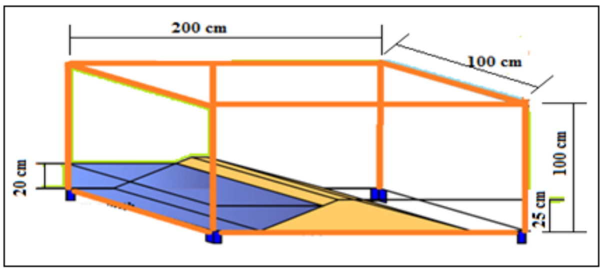


Fig. 5. Schematic diagram of the experimental model for earthfill dam; source: own study

Fig. 6. Seepage water of the experimental model dam; source: own study

Table 2. The obtained results for the experimental model dam

Sieve size (mm)	Type of soil	Hydraulic conductivity K (cm·s^{-1})	Upstream slope	Seepage Q (cm^3·s^{-1})
1.5	soil 1	0.0484	1:2	3.305
			1:2.5	3.158
			1:3	3.015
			1:3.5	2.759
1.0	soil 2	0.0361	1:2	2.819
			1:2.5	2.738
			1:3	2.679
			1:3.5	2.518
0.5	soil 3	0.0289	1:2	2.321
			1:2.5	2.250
			1:3	2.194
			1:3.5	2.114

Source: own study.

DISCUSSION

RESULTS FOR NUMERICAL ANALYSES BY GEOSTUDIO SOFTWARE

The results show that for each specific type of soil when the US slope increases seepage increases, while the factor of safety decreases. For a specific US slope, when hydraulic conductivity increases both seepage and factor of safety increase. The relationships between these parameters will be studied in the following sections.

Relation between seepage and the upstream slope (GeoStudio software)

The relationship between seepage and the US slope obtained from the GeoStudio software is illustrated in Figure 7 for all types of soils. From this figure, it is found for all types of soils that the amount of seepage decreases with the decrease of US slope. Also, soil 1 with higher K is associated with higher values of seepage than the other types of soils with lower K.

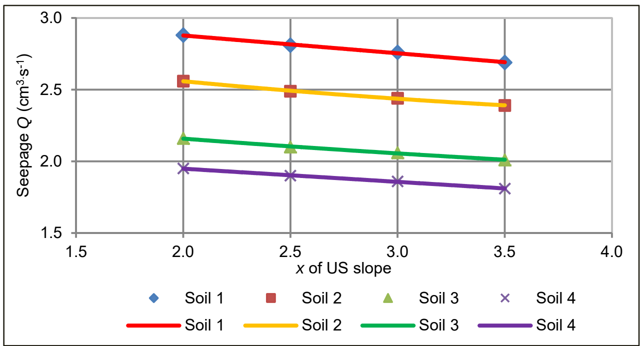


Fig. 7. Seepage and upstream (US) slope relationship for different types of soils; source: own study

For the soil 1, the seepage decreases from 2.88 cm^3·s^{-1} at the upstream slope 1:2 till 2.69 cm^3·s^{-1} at the upstream slope 1:3.5. For the soil 2, the seepage decreases from 2.56 cm^3·s^{-1} at the upstream slope 1:2 till 2.39 cm^3·s^{-1} at the upstream slope 1:3.5. For the soil 3, the seepage decreases from 2.16 cm^3·s^{-1} at the upstream slope 1:2 till 2.01 cm^3·s^{-1} at the upstream slope 1:3.5. For the soil 4, the seepage decreases from 1.95 cm^3·s^{-1} at the upstream slope 1:2 till 1.81 cm^3·s^{-1} at the upstream slope 1:3.5.

Regression analyses are done to investigate the relation between the seepage and the upstream slope for each sieve size. Equations are obtained to predict the seepage with respect to the upstream slope for each type of soil. These equations are:

$$Q_{\mathrm{Soil1}} = 1E^{-14}\, x^2 - 0.124x + 3.126 \tag{1}$$

$$Q_{\mathrm{Soil2}} = 0.02x^2 - 0.222x + 2.923 \tag{2}$$

$$Q_{\mathrm{Soil3}} = 0.01x^2 - 0.153x + 2.4245 \tag{3}$$

$$Q_{\mathrm{Soil4}} = -4E^{-15}\, x^2 - 0.092x + 2.133 \tag{4}$$

Where: Q is the seepage discharge, cm^3·s^{-1}; x is the value associated with the upstream (US) slope.

The values of coefficient of determination (R^2) for these obtained equations are 0.9959, 0.9987, 0.9963, and 0.9981 respectively.

Relation between seepage and hydraulic conductivity (GeoStudio software)

The relationship between seepage and hydraulic conductivity (representing the type of soil) obtained from the GeoStudio software is shown in Figure 8. From the figure, for all US slopes, it is found that the amount of seepage increases with the increase of hydraulic conductivity that represents the type of soil. Also, 1:2 US slope is associated with higher values of seepage than the other US slopes.

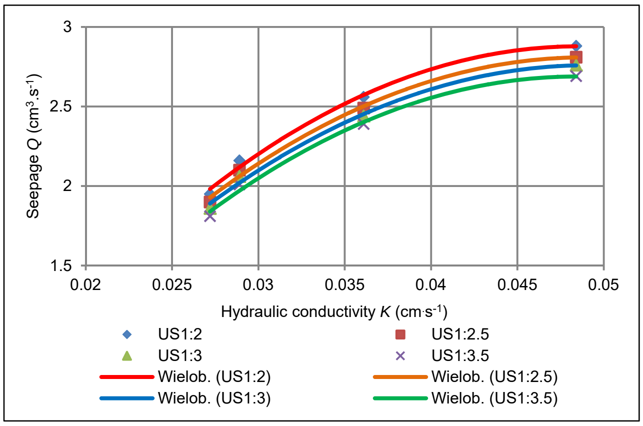


Fig. 8. Seepage and hydraulic conductivity relationship for different US slopes; source: own study

As discussed early in Table 1, hydraulic conductivity values are 0.0484, 0.0361, 0.0289 and 0.0272 cm·s^{-1} for the soil types 1, 2, 3 and 4. For 1:2 US slope, the seepage increases from 1.95 till 2.88 cm^3·s^{-1}. For 1:2.5 US slope, the seepage increases from 1.90 till 2.81 cm^3·s^{-1}. For 1:3 US slope, the seepage increases from 1.86 till 2.76 cm^3·s^{-1}. For 1:3.5 US slope, the seepage increases from 1.81 till 2.69 cm^3·s^{-1}.

Regression analyses are done to investigate the relation between the seepage and hydraulic conductivity (the type of soil) for each upstream slope. Equations are obtained to predict the seepage with respect to the hydraulic conductivity of the soil for each US slope. These equations are:

$$Q_{\mathrm{US1;2}} = -1964.1K^2 + 190.79K - 1.7553 \quad (5)$$

$$Q_{\mathrm{US1;2.5}} = -1861K^2 + 182.17K - 1.6492 \quad (6)$$

$$Q_{\mathrm{US1;3}} = -1806.5K^2 + 177.51K - 1.6018 \quad (7)$$

$$Q_{\mathrm{US1;3.5}} = -1883.7K^2 + 182.43K - 1.7289 \quad (8)$$

Where: Q is the seepage discharge, $\mathrm{cm^3 \cdot s^{-1}}$, K is hydraulic conductivity, $\mathrm{cm \cdot s^{-1}}$.

The values of coefficient of determination (R^2) for these obtained equations are 0.9944, 0.995, 0.9944, and 0.9943 respectively.

Relation between factor of safety and the upstream slope (GeoStudio software)

The relationship between the factor of safety (F) and the upstream slope obtained from the GeoStudio software is illustrated in Figure 9 for all types of soils. From this figure, it is found for all types of soils that factor of safety increases with the decrease of US slope. Also, soil 1 with higher K is associated with higher values of F than the other types of soils with lower K.

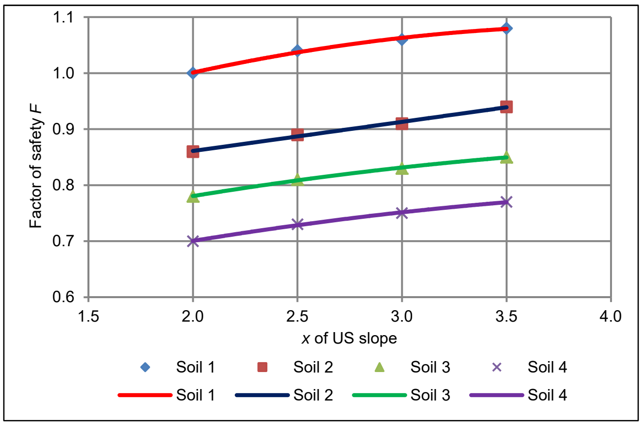


Fig. 9. The factor of safety and upperstream (US) slope relationship for different types of soils; source: own study

For the soil 1, F increases from 1.00 at the upstream slope 1:2 to 1.08 at the upstream slope 1:3.5. For the soil 2, F increases from 0.86 at the upstream slope 1:2 to 0.94 at the upstream slope 1:3.5. For the soil 3, F increases from 0.78 at the upstream slope 1:2 to 0.85 at the upstream slope 1:3.5. For the soil 4, F increases from 0.70 at the upstream slope 1:2 to 0.77 at the upstream slope 1:3.5.

Regression analyses are done to investigate the relation between factor of safety (F) and the upstream slope for each type of soil. Equations are obtained to predict F with respect to US slope for each type of the soil. These equations are:

$$F_{\mathrm{Soil1}} = -0.02\,x^2 + 0.162\,x + 0.757 \quad (9)$$

$$F_{\mathrm{Soil2}} = 0.052\,x + 0.757 \quad (10)$$

$$F_{\mathrm{Soil3}} = -0.01\,x^2 + 0.101\,x + 0.6185 \quad (11)$$

$$F_{\mathrm{Soil4}} = -0.01\,x^2 + 0.101\,x + 0.5385 \quad (12)$$

Where: F is factor of safety, x is the value associated with the upstream (US) slope.

The values of coefficient of determination (R^2) for these obtained equations are 0.9943, 0.9941, 0.9981, and 0.9981 respectively.

Relation between factor of safety and hydraulic conductivity (GeoStudio Software)

The relationship between the factor of safety (F) and hydraulic conductivity (representing the type of soil) obtained from the GeoStudio software is illustrated in Figure 10 for all US slopes. From this figure, for all US slopes, it is found that F increases with the increase of hydraulic conductivity. Also, 1:2 US slope is associated with lower values of seepage than the other US slopes.

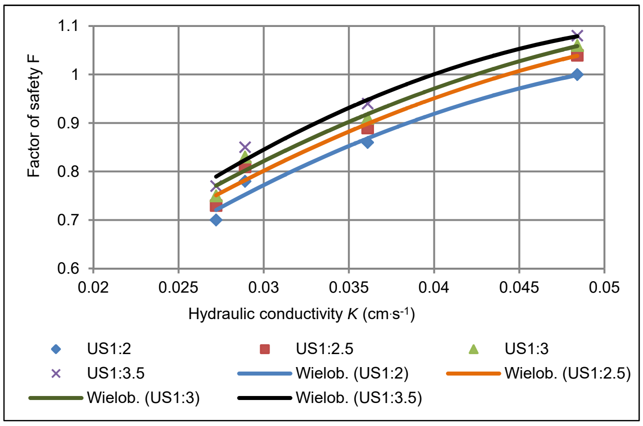


Fig. 10. The factor of safety and hydraulic conductivity relationship for different US slopes; source: own study

As discussed early in Table 1, hydraulic conductivity values are 0.0484, 0.0361, 0.0289 and 0.0272 $\mathrm{cm \cdot s^{-1}}$ for the soil types 1, 2, 3 and 4. At US slope 1:2, F increases from 0.70 till 1.00. At US slope 1:2.5, F increases from 0.73 till 1.04. At US slope 1:3, F increases from 0.75 till 1.06. At US slope 1:3.5, F increases from 0.77 till 1.08.

Regression analyses are done to investigate the relation between factor of safety (F) and the hydraulic conductivity (type of soil) for each upstream slope. Equations are obtained to predict F with respect to hydraulic conductivity of the soil for each US slope. These equations are:

$$F_{\mathrm{US1;2}} = -283.48K^2 + 34.548K - 0.0094 \quad (13)$$

$$F_{\mathrm{US1;2.5}} = -244.84K^2 + 32.089K + 0.0591 \quad (14)$$

$$F_{\mathrm{US1;3}} = -244.84K^2 + 32.089K + 0.0791 \quad (15)$$

$$F_{\mathrm{US1;3.5}} = -338.03K^2 + 39.202K - 0.0268 \quad (16)$$

Where: F is factor of safety, K is hydraulic conductivity ($\mathrm{cm \cdot s^{-1}}$).

The values of coefficient of determination (R^2) for these obtained equations are 0.9743, 0.9754, 0.9754, and 0.9788 respectively.

RESULTS FOR EXPERIMENTAL ANALYSES

Relation between seepage and the upstream slope (experimental model)

The results obtained from the experimental model include seepage discharge quantity with varying US slopes. For each type of soil, the relationship between seepage and the US slope obtained from the experimental model is illustrated in Figure 11.

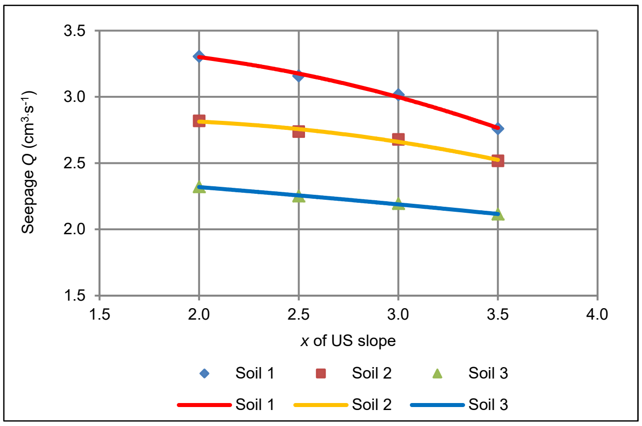


Fig. 11. Seepage and US slope relationship for different types of soils; source: own study

For soil 1 (K = 0.0484 cm·s^{-1}), it is found that the amount of seepage was 3.31 cm^3·s^{-1} at the US slope 1:2 and decreased gradually with decreased US slope till 2.76 cm^3·s^{-1} at US slope 1:3.5. For soil 2 (K = 0.0361 cm·s^{-1}), it is found that the amount of seepage was 2.82 cm^3·s^{-1} at the US slope 1:2, decreased gradually with decreased US slope till 2.52 cm^3·s^{-1} at US slope 1:3.5. For soil 3 (K = 0.0289 cm·s^{-1}), it is found that the amount of discharge was 2.32 cm^3·s^{-1} at the US slope 1:2, decreased gradually with decreased US slope till 2.11 cm^3·s^{-1} at US slope 1:3.5.

It is concluded that seepage decreased when hydraulic conductivity decreased. Also, seepage decreased when the US slope decreased for each type of soil (or hydraulic conductivity). Soil 1 with higher K is associated with higher values of seepage than the other types of soils with lower K.

Regression analyses are done to investigate the relation between the seepage discharge and the US slope for each type of soil (or hydraulic conductivity). Equations are obtained to predict the seepage discharge with respect to the US slope for each type of soil. These equations are:

$$Q_{\mathrm{Soil1}} = -0.1084x^2 + 0.24x + 3.2529 \tag{17}$$

$$Q_{\mathrm{Soil2}} = -0.0797x^2 + 0.2456x + 2.6405 \tag{18}$$

$$Q_{\mathrm{Soil3}} = -0.0096x^2 - 0.0825x + 2.5221 \tag{19}$$

Where: Q is the seepage discharge, cm^3·s^{-1}, x is the value associated with the upstream (US) slope.

The values of coefficient of determination (R^2) for these obtained equations are 0.9957, 0.9841, and 0.9971 respectively.

Relation between seepage and hydraulic conductivity (experimental model)

The results obtained from the experimental model include seepage discharge quantity with varying hydraulic conductivity (representing the type of soil). For each US slope, the relationship between seepage and hydraulic conductivity obtained from the experimental model is illustrated in Figure 12.

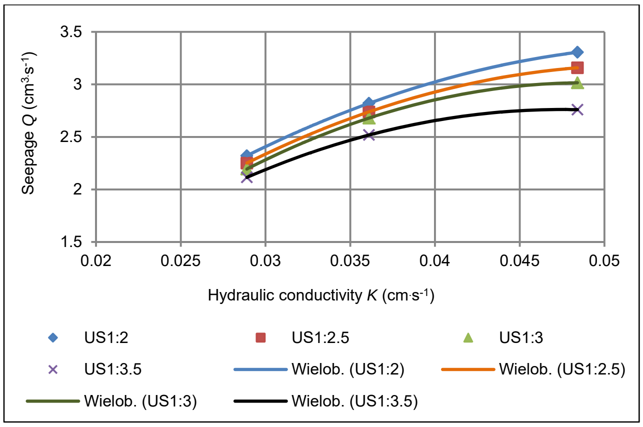


Fig. 12. Seepage and hydraulic conductivity relationship for different US slopes; source: own study

At US slope 1:2, seepage from the earthfill dam was 2.32 cm^3·s^{-1} at K = 0.0289 cm·s^{-1}, increased gradually with increased hydraulic conductivity till 3.31 cm^3·s^{-1} at K = 0.0484 cm·s^{-1}. At US slope 1:2.5, seepage from the earthfill dam was 2.25 cm^3·s^{-1} at K = 0.0289 cm·s^{-1}, increased gradually with increased hydraulic conductivity till 3.16 cm^3·s^{-1} at K = 0.0484 cm·s^{-1}. At US slope 1:3, seepage from the earthfill dam was 2.19 cm^3·s^{-1} at K = 0.0289 cm·s^{-1}, increased gradually with increased hydraulic conductivity till 3.02 cm^3·s^{-1} at K = 0.0484 cm·s^{-1}. At US slope 1:3.5, seepage from the earthfill dam was 2.11 cm^3·s^{-1} at K = 0.029 cm·s^{-1}, increased gradually with increased hydraulic conductivity till 2.76 cm^3·s^{-1} at K = 0.0484 cm·s^{-1}. It is seen that seepage increased when hydraulic conductivity increased for each US slope. The 1:2 US slope is associated with higher values of seepage than the other US slopes.

Regression analyses are done to investigate the relation between the seepage discharge and hydraulic conductivity for each US slope. Equations are obtained to predict the seepage discharge with respect to hydraulic conductivity for each US slope. These equations are:

$$Q_{\mathrm{US1;2}} = -1524.6K^2 + 168.35K - 1.2713 \tag{20}$$

$$Q_{\mathrm{US1;2.5}} = -1720.8K^2 + 179.55K - 1.5013 \tag{21}$$

$$Q_{\mathrm{US1;3}} = -2051.9K^2 + 200.73K - 1.8936 \tag{22}$$

$$Q_{\mathrm{US1;3.5}} = -1868.5K^2 + 177.52K - 1.4558 \tag{23}$$

Where: Q is the seepage discharge, cm^3·s^{-1}, K is hydraulic conductivity, cm·s^{-1}.

It is noticed that the coefficient of determination (R^2) is equal to 1 for these last four equations. These are ideal results although obtained from only three points.

DISCUSSION

Comparative discussion for numerical and experimental analyses

Obtained results for seepage are compared with respect to the type of soil for both the numerical model (GeoStudio software) and the experimental model. Three types of soil and four US slopes are studied, as shown in Figure 13. For all types of soil, the experimental model has higher values for the seepage than the numerical model.

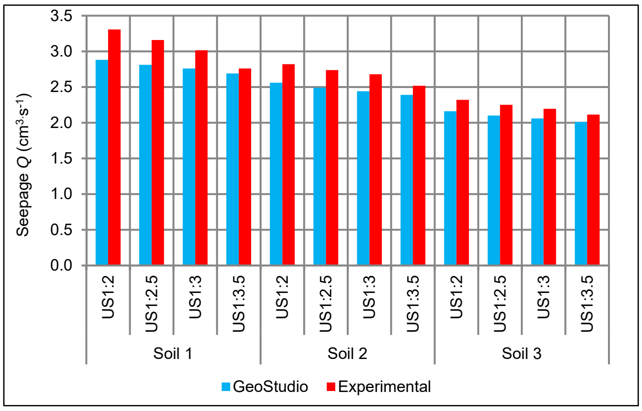


Fig. 13. Comparison of seepage for the numerical and experimental models; US = upstream slope; source: own study

The percentage differences between the experimental and numerical models are investigated and studied. According to the type of soil, the difference ranges between 7–14%, 7–12%, 6–9%, and 2–5% for US slopes of 1:2, 1:2.5, 1:3, and 1:3.5 respectively. It is found that for each type of soil, the difference decreases with the decrease of US slope. Also, the lowest difference between the experimental and numerical models is associated with the lowest US slope of 1:3.5.

3.2. Failure cases for experimental model

It has to be noted that some failure cases occurred for the experimental model when the crest width (B) of the dam model was less than 10 cm, as shown in Table 3. Figure 14 presents a failure case for B = 5 cm for the experimental model.

Table 3. Failure cases for experimental model dam, crest width – B = 5 cm

Type of soil	Hydraulic conductivity K (cm·s^{-1})	Upstream slope	Downstream slope	Seepage Q (cm^3·s^{-1})
1	0.0484	1:2	1:2	failure
2	0.0361			failure
3	0.0289			failure

Source: own study.

Fig. 14. Failure of the experimental model dam, crest width – B = 5 cm; source: own study

Employing GeoStudio software as a numerical model of an earthfill dam with 5 cm crest width is established, and the obtained results are presented in Table 4. It is probably that failure for the experimental model occurred due to the high amount of seepage as explained by GeoStudio software.

Table 4. The results obtained from the GeoStudio software; crest width – B = 5 cm; upstream slope – US = 1:2

Type of soil	Hydraulic conductivity K (cm·s^{-1})	Seepage Q (cm^3·s^{-1})	Factor of safety F
1	0.0484	2.99	0.96
2	0.0361	2.65	0.82
3	0.0289	2.23	0.74

Source: own study.

CONCLUSIONS

Finite element model is employed for simulating and analyzing seepage and slope stability of earthfill dam via GeoStudio software. The stability of the dam side slopes is assessed using analytical methods for steady state conditions and the factor of safety (F) is calculated according to the Bishop method. As components of GeoStudio software, SEEP/W is used for seepage analysis and SLOPE/W is used to analyse the slope stability. Four types of sandy soils are employed, four upstream (US) slopes are studied, and the downstream (DS) slope is constant.

The results show that for all the four studied types of soils, when the US slope is increased, the amount of seepage water from the dam increases and F decreases. For all US slopes, when hydraulic conductivity (representing the type of soil) increases both seepage and F increase. Soil 1 with higher K is associated with higher values of seepage and F than the other types of soils with lower K. The 1:2 US slope is associated with higher values of seepage and lower values of F than the other US slopes.

Regression analyses are conducted, where sixteen equations are developed to predict both seepage and factor of safety with respect to US slope and hydraulic conductivity. Four equations are obtained to predict the seepage with respect to the US slope for each type of soil, and other four equations are developed to predict the seepage with respect to hydraulic conductivity for each US slope. Also, four equations are obtained to predict F with respect to US slope for each type of soil, and the other four equations are developed to predict F with respect to hydraulic conductivity for each US slope.

An experimental model for an earthfill dam is constructed in the laboratory of hydraulics, Faculty of Engineering at Shoubra, Benha University in order to investigate the seepage of water through earthfill dams.

It is concluded that seepage decreased when hydraulic conductivity decreased. Also, seepage decreased when the US slope decreased for each type of soil (or hydraulic conductivity). It is seen that seepage increased when hydraulic conductivity increased for each US slope. Soil 1 with higher *K* is associated with higher values of seepage than the other types of soils with lower *K*. The 1:2 US slope is associated with higher values of seepage than the other US slopes.

Regression analyses are employed, where seven equations are developed to predict seepage with respect to both US slope and hydraulic conductivity. Three equations are obtained to predict the seepage with respect to the US slope for each type of soil, and other four equations are developed to predict the seepage with respect to hydraulic conductivity for each US slope.

Obtained results for seepage are compared with respect to three types of soil for both the numerical model (GeoStudio software) and the experimental model. For all types of soil, the experimental model has higher values for the seepage than the numerical model. It is found that for each type of soil, the difference decreases with the decrease of US slope.

It has to be noted that some failure cases occurred for the experimental model when the crest width (*B*) of the dam model was less than 10 cm. It is probably that failure for the experimental model occurred due to the high amount of seepage.

It can be concluded that the numerical models developed in this paper are accurate enough to be used for the analysis of earthfill dams. The materials in the area of the study are not suitable for construction of earthfill dams, where the values for *F* of the dam model are less than the proposed factor of safety for dams.

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