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STUDY THE SLOPE STABILITY OF EARTHEN DAM USING DIMENSIONAL ANALYSIS TECHNIQUES

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ABSTRACT: Slope stability is calculated using several methods. All these methods produce estimated results based on inaccurate assumptions, and their results were particularly acceptable. Furthermore, these methods rely on supposing and segmenting the surface of failure as well as performing complex calculations. This paper introduces the "Dimensional Analysis Technique" as a new approach for dealing with earthen slopes. Four dimensionless groups ($\frac{c}{\gamma H}, \frac{K}{\sqrt{gH}}, i, \frac{\emptyset}{\alpha}$) were driven to calculate the slope stability of a homogeneous filtered at the downstream earth dam. Geo-Slope and Geo-Seep software are used to compute Factor of Safety by Spencer's method. The derived formula shows that estimated upstream water levels match the calculated results and reasonably fit with coefficient of determination (R^2) greater than to .97. Results suggest that the "Dimensional Analysis Technique" is a safe and new direct method to track the stability of the natural earth slope.

Keywords: Slope Stability, Dimensional Analysis, Spencer, Earth Dam, Limit Equilibrium

1. INTRODUCTION

An analysis of the failure of the dams with associated accidents based on statistical approach was published by the International Large Dams Commission [1]. The study showed that structural failure was common for both the dam body and its foundation under different conditions. For any slope stability, a potential line of failure and discretization into slices of sliding mass over that line is the common method of analyzing and obtaining the factor of safety (FS) during the last century [2]. Thus, depending on the discretization, several methods tended to simplify the system of complex forces affecting each slice and to obtain convergence results [2-5].

The line of failure (potential collapse surface) may be plane, circular, or irregular shape [3], [6]. The frequently taken shape is circular during the last dedicates as shown in (Fig.1) [2]. The major challenge of analyses is the number of determinacies (DOD, degree of determinacy). LEM (liquid equilibrium method) have been usually used to reach equilibrium for forces and moments [4], [7]. There are several methods for determining FS depending on the approach of the slices, such as Ordinary (Fellenius), Bishop, Junbu, Morgenstern-Price, and Spencer [7]. Computer software, such as Low-Karafiath and Corps of Engineers is used for other methods [2]. The ordinary method is considered the first and the simplest method, while Spencer is the most popular and accurate method. [8]. The difference between methods can be delineated by the number and location with their slope of interslice forces affecting each slice and which ignored according to assumptions.

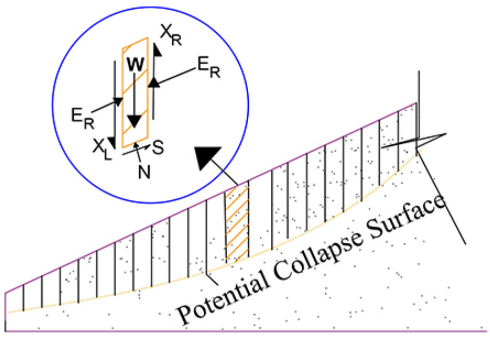

Fig.1 Basic of slice forces (Redrawing from [2], [5])

As shown in (Fig.1) the forces are lateral (Earth forces Right and Left, E_R and E_L), shear forces (X_R and X_L), the weight of the slice (W), and the resistance shear (S) or friction forces between two slices, and normal (N) forces. The Ordinary method assumed the lateral earth forces (E_R and E_L) are parallel to the potential collapse surface and equal in magnitude and then they can be ignored or no effects. In the same way the lateral shear forces(X_R and X_L) [6]. Bishop method assumed that the lateral forces are horizontal in direction and no friction between two slices (i.e., no X_R and X_L) [3]. Then he took the moment of the lateral forces into account. Junbu put as Bishop assumption but included the friction forces between slices [3]. Mogenstern and Spencer included all interslice forces and moment [2].

Generally, the FS is determined either by dividing the resisting forces against driving forces or by dividing the resisting moments against driving moments and sometimes both of them as Spencer method. [2]. All methods assumed that the FS is constant along the potential collapse surface (slip or failure surface) then it is the same for each slice. While these assumptions are not optimal according to the results of the experiment, they yield appropriate values, which is why they are widely used.

As has been shown, all methods assume a failure surface, then find FS based on their hypotheses, and repeat for other surfaces until they reach the critical surface [5]. The FS is obtained by the critical slip surface. As a result, they need a lot of work and analyses. The designers practically need a convenient way to evaluate their slope options. Because of this, this article will present a simple equation for determining slope stability and FS.

Any physical Item may be scalar quantity or vector quantity and either constant or variables[9]. Any physical quantity means can be dimensional or dimensionless. To construct a dimensional system, it should be assembled some fundamental entries (dimensions) which define any group of physical quantities and this group must be dimensionless[9]. The major purpose of this method is to get some relations in a general way that can use for any similar case regardless of units [10]. In 1916, Buckingham presented a homogeneity function which refers to the equation where all components can be re-writed to get dimensionless groups [10].

The dimensional analysis approach is used for analyzing a phenomenon by assembling the related quantities to get dimensionless groups[10], [11]. This is the approach that will be used in this paper.

2. RESEARCH SIGNIFICANCE

This article will be the first step in presenting a theoretical equation that can describe the slope stability of the natural or man-made earth slope. This is a new method for checking the stability of slopes without having to do complicated calculations. Previous slope stability approaches focused on the method of slices, but analytical methods are rarely used. Researchers would be able to use this approach to obtain results and build relationships.

3. METHODOLOGY

The interslice forces of each slice, can be seen in seven forces (E_R, E_L, X_R, X_L, W, N, and S). So, to determine the fundamental parameter that can be later assembled into dimensionless groups, it must be known which of these forces depends on.

3-1 Fundamental parameters of Dam stability

By (Fig. 2) the envelope of Mohr-Coulomb failure shows that the effective and total resisting

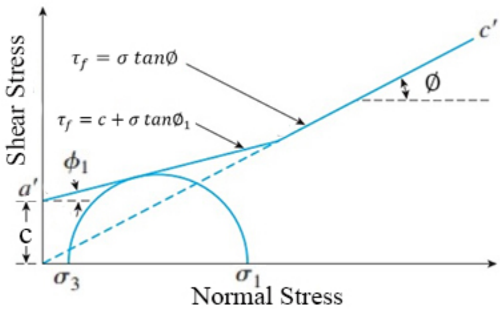

Fig. 2 Envelop of Mohr-Coulomb failure[3]

stress (strength shear stress s) as referred by "Eq. (1-2)'' [4] :

$$\boldsymbol{S = C + \sigma \tan \emptyset} \quad (1)$$

$$\boldsymbol{S = C' + \sigma' \tan \emptyset'} \quad (2)$$

Where σ' and σ effective and total normal stresses, and similarly for shear stresses S and soil cohesion stresses c. While $\emptyset'$ and $\emptyset$ effective and normal repose angle (internal friction angle).

The water content of soil voids varies, allowing the soil to be partially or fully saturated. The water contact will affect by upward force and downward forces and the result of the driving force called effective force. The upward water force called pore water pressure (u) or force (U)[4].

Bishop put a relationship between normal and effective stresses including the effect of Volumetric Water Content (VWC) by a fraction (0-1) expressing the ratio of the area having water titled ℵ and expressed [2]as referred by "Eq. 3":

$$\boldsymbol{\sigma' = \sigma - u_a + \aleph\,(u_a - u_w)} \quad (3)$$

Where a and w refer to air and water respectively. u refers to pore pressure.

As known, normal stresses, either total or effective, depend on variables; the first one is the depth of the calculated position according to the surface of the slope; the second is the specific weight γ ($\gamma = \rho g$, mass density ρ, and g gravity acceleration) of the soil.

Spencer's method. The equations "Eq. (4-6)" as expressed by [2], [5], [7]:

For $\sum momment = 0$:

$$FS = \frac{\sum[c'\beta\, R + (N - u\, \beta) R \tan \emptyset']}{\sum wx - \sum N f \;\; \pm D\, d} \tag{4}$$

For $\sum forces = 0$:

$$FS = \frac{\sum[c'\beta \cos\alpha + (N - u\, \beta) R \tan\emptyset' \cos\alpha]}{\sum N \sin\alpha - D\cos\omega} \tag{5}$$

$$N = \frac{W + (X_R - X_L) - \frac{c'\beta \sin\alpha + u\,\beta \sin\alpha \tan\emptyset'}{FS}}{\cos\alpha + \frac{\sin\alpha \,\tan\emptyset'}{FS}} \tag{6}$$

In which c/ and c are effective and total cohesion stresses of the soil, $\emptyset$'and $\emptyset$ effective and total repose or internal friction angle, u pore water pressure, and the others $\beta, \alpha, \omega, D, d, and\ x$ are geometrical variables.

The lateral earth force can be considered as an active lateral force. Two common scientists, Rankine and Coulomb, tried to determine the magnitude of such force X_R. Here can be taken Rankine active lateral equation because of moving soil downward when the failure occurs. Rankine expressed this force by P_a as shown in "Eq. 7-8" expressed by [3]:

$$P_a = \tfrac{1}{2}\gamma H^2 k_a - 2cH\sqrt{k_a} \tag{7}$$
$$k_a = tan^2\left(45 - \frac{\emptyset}{2}\right) \tag{8}$$

At the start of moving, on the left side of the chosen slice shown in Fig 1, the soil starts to compress. So, the passive lateral earth force will be active. In this case, the Coulomb's relationship will be used. The relationship equation is similar to the Rankine equation but passively, i.e., it depends on the same fundamental parameters.

The height of dam (H) is an important variable for slope stability[12]. There is a common classification of the dam height (low dams < 10m , 10m < medium dams < 30m , High dams > 30 m) [6]. The angle of inclination α of the slope is found a significant variable of stability of earthen slope[6].

Hydraulic conductivity K is an important parameter for the seepage as Darcy law. The effects of K depend on the pore water or volumetric water content (VWC) [13]. In similar, the length of the seepage line l.

The height of water h_w at the upstream of the dam and its changing (Rapidly or Slowly) is also a very important parameter that affects directly on the slope stability [14]. So, and in general, it is noted there are 9 fundamental parameters (ρ , g , α , C , $\emptyset$, k, H, h_w, l) that can be taken into dimensional analysis.

3-2 FS Calculation by Dimensional Analysis

By dimensional analysis, the general relationship will be ten variables as in "Eq. 9":

$$\varphi\ (FS,\ h_w\ , l, \emptyset, \alpha, C, k\ , \rho\ , g\ , H\ ) = 0 \tag{9}$$

The dimensions of each above variables are: $[FS] = [M^0L^0T^0]$; $[\alpha] = [M^0L^0T^0]$; $[\emptyset] = [M^0L^0T^0]$; $[H] = [L]$; $[l] = [L]$; $[h_w] = [L]$; $[\rho] = [ML^{-3}]$; $[g] = [LT^{-2}]$; $[k] = [LT^{-1}]$; $[c] = [ML^{-1}T^{-2}]$.

In general, some variables affect other collected groups repeatedly [10]. So, such variables are put with all those groups. By this paper, it will be taken ρ , g , H as repeated ones. To get dimensionless groups, it will be equal to 7 as follows in "Eq. (10 - 16)":

$$\boldsymbol{\pi_1} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_1}\ [\boldsymbol{g}]^{b_1}\ [\boldsymbol{H}]^{c_1}\ [\boldsymbol{C}] \tag{10}$$

$$\boldsymbol{\pi_2} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_2}\ [\boldsymbol{g}]^{b_2}\ [\boldsymbol{H}]^{c_2}\ [\boldsymbol{k}] \tag{11}$$

$$\boldsymbol{\pi_3} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_3}\ [\boldsymbol{g}]^{b_3}\ [\boldsymbol{H}]^{c_3}\ [\boldsymbol{FS}] \tag{12}$$

$$\boldsymbol{\pi_4} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_4}\ [\boldsymbol{g}]^{b_4}\ [\boldsymbol{H}]^{c_4}\ [\emptyset] \tag{13}$$

$$\boldsymbol{\pi_5} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_5}\ [\boldsymbol{g}]^{b_5}\ [\boldsymbol{H}]^{c_5}\ [\boldsymbol{\alpha}] \tag{14}$$

$$\boldsymbol{\pi_6} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_6}\ [\boldsymbol{g}]^{b_6}\ [\boldsymbol{H}]^{c_6}\ [\boldsymbol{h_w}] \tag{15}$$

$$\boldsymbol{\pi_7} = [\boldsymbol{M^0L^0T^0}] = [\boldsymbol{\rho}]^{a_7}\ [\boldsymbol{g}]^{b_7}\ [\boldsymbol{H}]^{c_7}\ [\boldsymbol{l}] \tag{16}$$

After finding and evaluating $a, b, and\ c$ and using the rules and properties of dimensional analysis theorem, the FS will appear as a function of four groups as shown in "Eq. 17":

$$\boldsymbol{FS = \varphi\left(\frac{c}{\gamma H}, \frac{K}{\sqrt{gH}}, i, \frac{\emptyset}{\alpha}\right)} \tag{17}$$

As known, the hydraulic gradient $\boldsymbol{i}$ equals ($\frac{h_w}{l}$).

4. THE GENERAL SHAPE OF A DAM

4-1 Geometrical Dimensions of the Dam

As mentioned, the dam may be low, medium, and high dam according to it is height H. In this study Medium dam (10-30) is used as it's the homogeneous body of the dam. The top crest width b is a function of the height as expressed below by [6]:

a- $b = 0.2\, H + 3$ for a low dam.
b- $b = 0.55\sqrt{H} + 0.2\, H$ for a medium dam.
c- $b = 1.65\sqrt{1.5 + H}$ for a high dam.

The inclination slope angle $\boldsymbol{\alpha}$ is in between (2.5:1 to 3:1), horizontal: vertical, for the upstream slope and from (2:1 to 2.5:1) for downstream[4], [6].

Usually, the safer is the less sharp angle so it will be taken the safe values of up and downstream slope i.e., 3:1 and 2.5:1 respectively.

4-2 Properties of the Soil Dam

Usually, the type of soil's used in constructing the body of the dam depends on the location of the site, i.e. clay, silty clay, silt, silty sand, sand, and gravel [2], However, it cannot be organic soils [15]. Any homogenous dam is often used the fine-grained soils[15].

According to the Unified Soil Classification System (USCS), the fine soils either silt or clay. It is not recommend to build a dam from clay soil only [16]. In this paper the silty clay will be used as the main soil in constructing the dam body. The range of the specific weight of the silty clay can be found by [17]. For silty clay, it can be used 16-20 KN/m^3 [18].

The cohesion stress value used with such soil has a big range (10-20) kPa as expressed by [19]. So, it will be used that range by (10, 13, 16, 18, and 20) kPa.

The internal friction angle has also a wide range from (18-32)^0 [20], but the undrained or drained condition is determined to the exact value of $\emptyset$ [3]. The undrained condition leads to zero $\emptyset$ while drained give large values of $\emptyset$. Because of homogeneity and the soil is silty clay, it will be taken (10, 13, 16, 18, and 20)^0 as the values of $\emptyset$.

4-3 Kinematic Parameters

The range of hydraulic conductivity K show in [21] for silty, clay, or silty clay in between $5 \times 10^{-6} - 5 \times 10^{-10}$ m/s. Some studies indicated that the hydraulic conductivity through body dam is anisotropic especially for the rainfall case on the dam shells [22]. The speed of drawdown of water content at the upstream influence directly on the stability and seepage (indirect to K) through the body dam [23], [24]. As known, K affects by VWC which is a function of the porosity of soil [2]. In 1991, Franzmeir published a table showing the range of porosity and water content for different types of soils, and silty clay was (0.45-0.46) for total porosity and water content was (0.35-0.34)[25].

The water content affects the pore water pressure u as shown in (Fig. 3A) the body dam will be neither fully saturated nor dry during the steady-state case. Some of it will be in suction pressure over the phreatic line (the line where the saturated soil is under it) [6]. Therefore, in the current study, the hydraulic conductivity (K) value will be considered as a constant for saturated zone and a faction of VWC for unsaturated zone, as shown in the relation between pore-water pressure and hydraulic conductivity in (Fig. 3B).

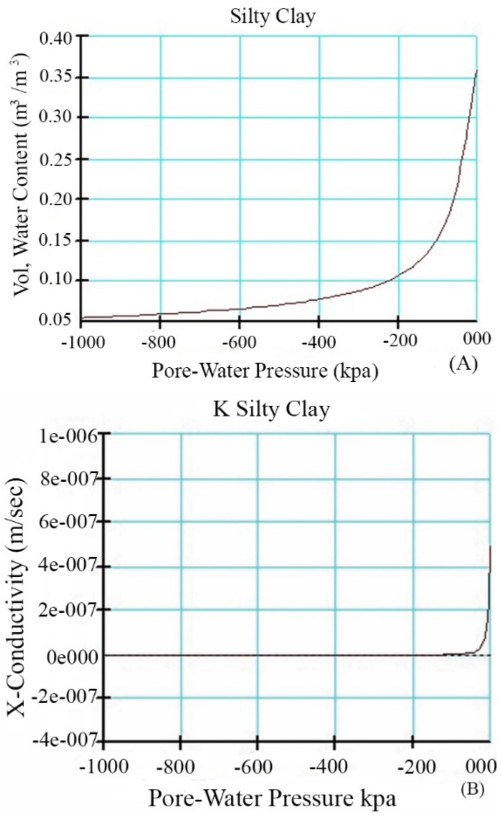

Fig.3 Relation between Pore-Water Pressure (A) with water content and (B) with Hydraulic Conductivity

The other parameters, the water level at the upstream, will be used three steady levels (0.2 H, 0.4 H, and 0.8H) which represents the intermediate values of common levels. So, all values will be used for evaluating the formula using dimensional analysis[26,27,28], shown in (Table 1) and the initially designed dam is plotted in (Fig. 4).

Table 1 The parameters of the initially designed dam

Saturated Hydraulic Conductivity (m/s)	Cohesion C (kPa)	Unit weight (kN/m^3)	Friction angle (degree)
5.0×10^{-7}	10	16	10
	13	17	13
	16	18	16
	18	19	18
	20	20	20

5. RESULTS AND DISCUSSION

The geometrical dimensions of the studied dam (initially designed dam) can be seen in (Fig. 4). For different soil properties, there are three cases of water level (the level of water at 0.2, 0.5 and 0.8 m for the three upstream water level a, b, and c respectively) as shown in (Fig.5). For each case, there are different ranges of soil properties as mentioned before.

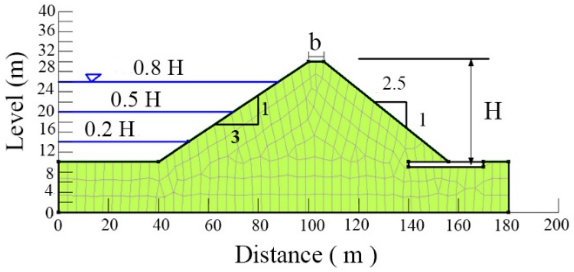

Fig. 4 Geometrical dimensions of studied dam

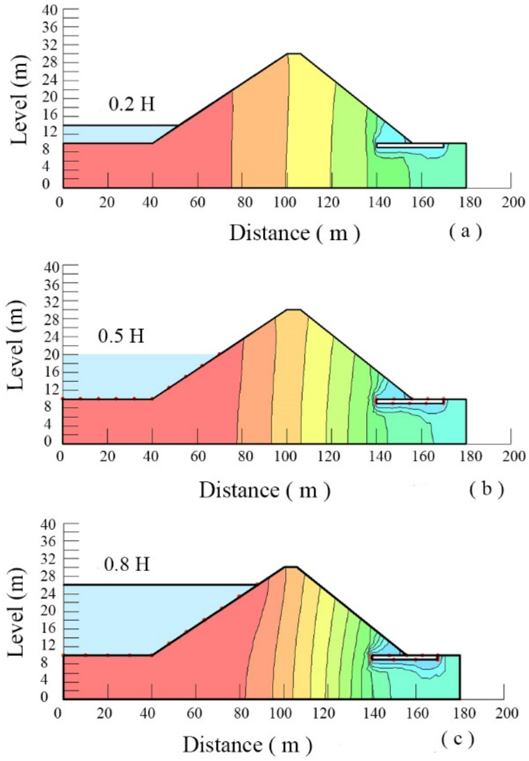

Fig. 5 Three different upstream water level

(a) 0.2 H (b) 0.5 H (c) o.8 H

For each water level ((a) 0.2 H, (b) 0.5 H and (c) o.8 H), 125 probable value properties were calculated, and each result in a critical slip surface with a deferent value of the factor safety. Consequently, this will result in 375 values of FS, in (Fig. 6) the samples of a range of soil properties with the same upstream water level with different FS was shown.

Four dimensionless groups were found for each case by Geo-Slope under Geo-Seep files and their related value of factor safety found by Spencer's method. The relation between the pore water pressure with the distance of the collapse surface plotted as shown in (fig. 7), the figure shows that the pore water pressure decreases with the distance. While the shape of distance conductivity relates to matric suction shown in Fig. 8. The value of FS increases when the value of $\frac{c}{\gamma H}$ increases for different upstream water levels as shown in (Fig.9).

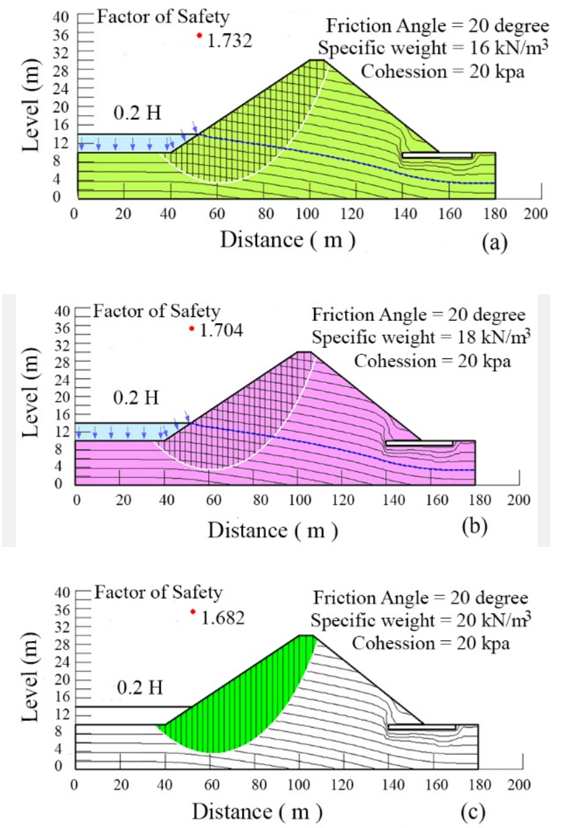

Fig. 6 Samples of different soil properties with the same upstream water level with different FS

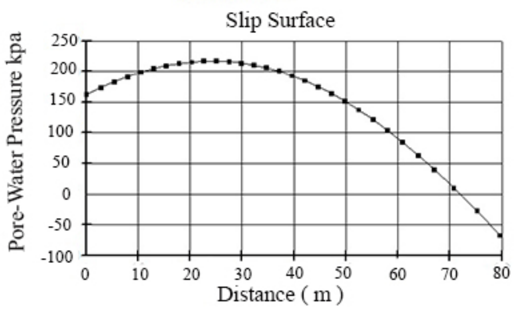

Fig. 7 Pore Water pressure related distance

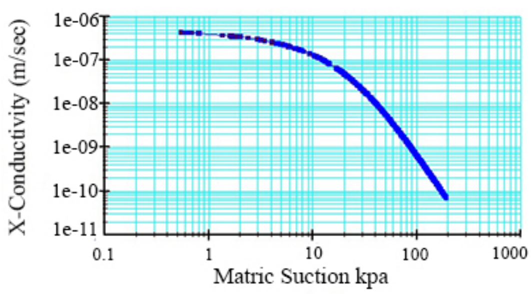

Fig.8 Conductivity Vs Matric suction

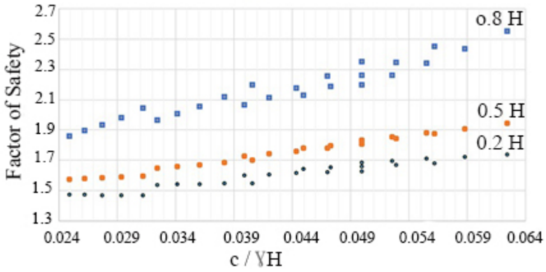

Fig.9 Factor of Safety VS $\frac{c}{\gamma H}$

This means that the bigger cohesion gives more safety for homogeneous fine earthen dam while the bigger value of specific weight for the same cohesion the smaller of safety.

It is noted that, for the steady-state case, when the value of i increases the FS will rise for different properties of body dam soil as shown in Fig.10. This means that the specific weight will be lower (submerged) and then bigger FS.

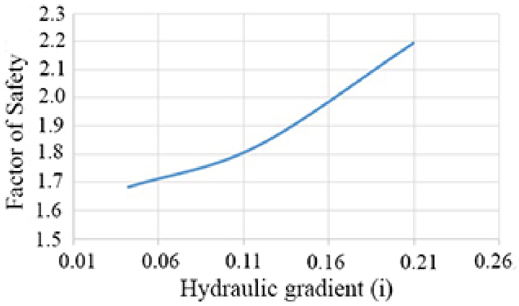

Fig.10 Factor of Safety VS i

The $\frac{\emptyset}{\alpha}$ is noted that takes a linear relationship with FS and for bigger values of $\frac{\emptyset}{\alpha}$ better range of FS, as shown in (Fig. 11).

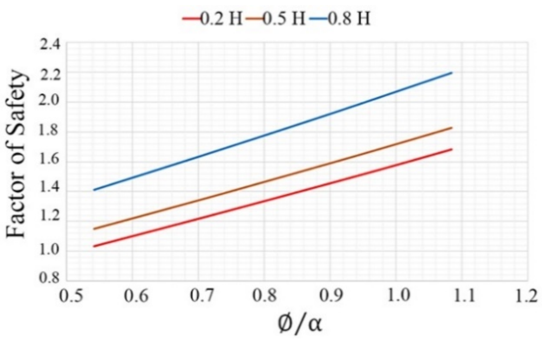

Fig.11 Factor of Safety VS $\frac{\emptyset}{\alpha}$

5.1 Formula for Calibration and Validation

The suggested shape of a formula having all four dimensionless groups is referred to in "Eq. 18":

$$FS = A1(\frac{\emptyset}{\alpha})^{A2} + A3(\frac{c}{\gamma H})^{A4} + A5(\frac{K}{\sqrt{gH}})^{A6} + A7(i)^{A8} + A9 \quad (18)$$

Where A1 to A9 are arbitrary constant. This formula "Eq.19" established on two bases, the first base includes the shape of relationships that appeared in (Fig. 8-11); and the second was the results of analyses that were done for sets of plots for sets of dimensionless groups versus FS.

For calibration purpose, it has taken 65% of the results. After evaluating these constants, it is noted that A1=1.276; A2=1; A3=11.667; A4=1; A5=-7965080.7; A6=1; A7=14.301; A8=2; and A9=0, so the suggested formula will be "Eq. 19":

$$FS = 1.276\left(\frac{\emptyset}{\alpha}\right) + 11.667\left(\frac{c}{\gamma H}\right) - 7965080.7\left(\frac{K}{\sqrt{g\,H}}\right) + 14.301(i)^2 \quad (19)$$

Recalculating all the data of the designed dam properties and cases using the formula in "Eq. 19" and plotted the relationship between the calculated FS by Spencer's Method with that obtained by "Eq. 19", it can be noted the closed values and relation between of them with coefficient of determination (R^2) near to one as shown in (Fig. 12). The first line with R^2=0.9861 represents 0.2 H upstream water level, R^2=0.9987 and R^2=0.9741 for 0.5H and 0.8 H respectively.

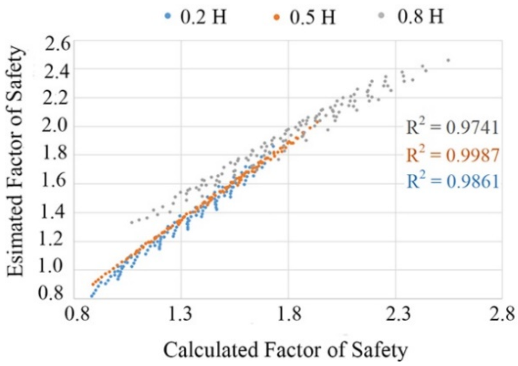

Fig.12 Estimated Fs versus Calculated FS

5-2 Limitation of the Derived Formula

The scope of the derived formula has the following values:

- Homogeneous dam
- Medium dam (10m <H<30 m)
- The ranges of ($c, \emptyset$, and γ) are as shown table 1.
- Saturated hydraulic conductivity (5-8) x10^{-7} m/s.
- Steady-state condition
-

6. CONCLUSIONS

To conclude, Dimensional Analysis Techniques can be used to define and evaluate the factor of safety in a rapid way for both natural and man-made earthen dam. The estimated and calculated FS are negligible. The derived formula is still a theoretical equation compared to Spencer's method, which yield accurate FS results. However, it is recommended to conduct experimental analysis to validate the equation and to consider non-homogeneous earthen dam in future research.

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