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FINITE ELEMENT METHOD OF SEEPAGE AND STABILITY ANALYSIS OF SAURA-KEFFI EARTH DAM

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Abstract

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Finite element method (FEM) based analysis using the SEEP/W and SLOPE/W sub-programme options of a GEOSTUDIO software was used to analyze Saura-Keffi earth dam in Nasarawa State, Nigeria with the view to analyze the dam seepage and its stability. The created dam geometry was assigned material properties and boundary conditions at reservoir water levels of: minimum (3 m), normal (6 m) and maximum (7 m). The analysis was conducted under the cases that the dam was without and with seepage measures (SCM). The results of the analyzed semi-permeable homogenous dam revealed a percentage reduction inseepage flux to 28.3% when the dam was considered with a central core and complete cut-off trench along the dam crest axis. see figure 7. The pore-water (PWP) revealed a decrease in value from (12 to 11.2) kPa at minimum water head with SCM. The PWP further increased by 18.9% as water rises from 6 m to 7m with SCM. The exit gradient showed an insignificant increase in value of 1.2% with the construction of SCM which indicates less flow at the exit end of the dam leading to increase in stability. The horizontal filter drain at the downstream lower and kept the phreatic line within the dam body to allow for adequate embankment and foundation drainage as shown in figure (5&6). The F.S at the maximum water level revealed an increase in value from 1.27 to 1.52 when a horizontal filter was considered. The Morgenstern-priced method of slope stability was used to estimate an acceptable minimum F.S of 1.52 at 0.5 lambda value with the introduction of horizontal filter.

Keywords: Finite Element Method, SCM (Seepage Control Measures), SEEP/W, SLOPE/W, GEOSTUDIO Software

1.0 INTRODUCTION

The investigation of seepage in earth dams is one of the essential analysis in the design of dam to inspect the amount of losses from the reservoir, check the approximate distribution of the pore water pressure, determining the position of the free surface which is used in the analysis of the dam stability against shear failure. Studying the hydraulic gradient gives a general idea about the potential piping through dams. To this regard, seepage becomes a problem only if proper study and analysis of materials used are not investigated and checked for suitability. Seepage must be controlled to prevent the erosion of embankment or its foundation (Nada and Maysam 2020).

Earth dams generally constructed of earth or rock-fill materials are known as embankment dams or sometimes called fill-type of dams. It is a simple kind of structure which uses its self-weight to avoid sliding and overturning. This kind of dam can also be zoned with the introduction of an impermeable central core material that is enclosed with permeable shell material. Hence the three vertical zones include a low permeable core material at the center and two semi- permeable materials (i.e. shells) on either side of the core. The earth dam failure is categorized into hydraulic, seepage and structural failure (Shivakumar, 2015).

Dams are classified in different ways however they are classified mostly based on their function as storage dams, diversion dams, detention dams, debris dams and coffer dams or based on their design structure, they can be classified as follows: gravity, buttress, arch, rock-fill and earth dams (Shivakumar, 2015). This research will focus on earth dams as the prevalent type of dam all over the world. Therefore, their stability is of major concern in dam engineering.

Very recently, computer based analysis can be used to check the stability of an earth dam by simulating the effects of all the material properties that contribute to its strength using numerical models. The materials used in constructing an earth dam are very important to the stability and its safety. Hence, they are considered as important in this study (Thair, 2018).

The investigation of seepage in earth dams is one of the essential analysis in the design of dam to inspect the amount of losses from the reservoir, check the approximate distribution of the pore water pressure, determining the free surface position used in the analysis of the stability for the dam against shear failure. Perusing the hydraulic gradient helps to obtain a general idea about the dam's potential piping. To this regard, seepage becomes a problem only if proper study and analysis of materials used are not investigated and checked for suitability. The control of Seepage must be done to prevent the erosion of foundation or its embankment. (Nada and Maysam 2020).

The main purpose of a dam is flood control, irrigation and for hydro-electric power generation. This multi-dimensional function of dams shows an enduring importance in maintain growth and development for both ancient and modern human transformations. Therefore, Nigeria as a country relaying on dams and reservoirs as source of water resources ; mainly for agricultural and domestic purposes, must as a matter of importance prioritized the provision and management of dams for optimum benefit and intended purposes (Ahmed et al, 2022).

Finite Element Method (FEM) based on Geo-Studio is a computer aided software programming for the theoretical analysis of various failure modes through an earth dam. The software uses SEEP/W and SLOPE/W sub-program option for seepage and stability analysis of an embankment dam. The SLOPE/W option in the software, uses different methods to assess the factor of safety (FOS) against the failure of the slope given different soil conditions and water elevations (Nada and Maysam, 2020). Seepage through earth dams is generally one of the main reasons that causes failure in an earth dam structure. The resultant failure mode arising from seepage usually lead to the collapse of the dam and the effect can ultimately result to the loss of lives and the destruction of infrastructures such as: bridges, power line and access road that may be located downstream.

Griffiths (as cited in Usama, 2018) in His work, conducted studies associated with the problems of finite element (FE) slope stability analysis in comparison with other solution method such as the stress-strain method, with the inclusion of the effect of free surface having on slope and dam stability. This method studied had proven that the FE method has shown to be more dependable and rich method for evaluating the factor of safety of slopes. The approach by the finite element method FEM, in determining the factor of safety of slopes has met the measure for efficient computer-aided analysis. Hence, it is an accepted fact that the finite element method of slope stability analysis is more powerful compared to the traditional limit equilibrium methods.

The study of seepage and stability analysis of earth dam utilizes numerical method as a very powerful weapon to achieving exact knowledge of embankment dam behavior under stimulation. Many years ago numerical methods were used as theory but today with the advent of computer programs very fast development is achieved with the use of finite element methods in analysis (Kamanbedast, 2012).

Computer based numerical models are used to check dam stability by simulating the effects of all the parameters that play a role in its safety. The material property used in constructing an earth dam are vital in determining the stability of an earth dam (Nada and Maysam, 2020). Mishal and Khayyun 2018 used 2D finite element analyses to simulate pore-water pressure development by Geo-Studio software for saturated and unsaturated conditions. Its result demonstrated that the presence of a chimney drains is significant in dissipating of pore-water pressure.

The failure or dam break can cause potential risk to property and lives of people who live downstream of the dam and also other life activities. Therefore, it is essential to study the behavior of material properties of an earth dam. Numerical approach based on finite element method (FEM) will be used to estimate seepage and check the stability of the dam against sudden failure. The functionality and stability of the earth dam can be checked using computer aided program. This study therefore would provide the requisite knowledge into understanding the causes of seepage and instability in earth dam in the view to mitigating any failure or potential hazard to people and the environment. Therefore, Saura-Keffi earth dam, Nasarawa State Nigeria was considered for this research and the aim is; To Analyze the Seepage and Stability of an earth dam using Finite Element Method and the following objectives were studied:

a) To conduct finite element method numerical analysis of the earth dam
b) To analyze the amount of seepage and compare its percentage reduction for the dam cases.
c) To analyze the pore-water pressure and exit gradient through the earth dam.
d) To study the phreatic line and stability mechanism at the downstream.
e) To locate the critical slip surface and determine the minimum factor of safety.

2.0 STUDY AREA

The present study was carried out using the Saura-Keffi earth dam located in a valley in Saura village North west of Keffi town, Nasarawa State, Nigeria. The dam coordinate location is (972571.05 Nm, 379090.98 Em.) with two river courses flowing from upstream of the dam and several other tributaries into the catchment as shown in figure 1 below. The main river flowing into the dam location is called the "Fadaman Bubula" and the major occupation of the "Saura locals" is farming and cattle rearing, hence the need for the provision of an earth dam.

Figure 1: Google Earth Map project location delineating dam catchment Area.

3.0 METHODOLOGY

3.1 Materials

GEO-STUDIO software tool utilized both the SEEP/W and SLOPE/W sub-program in the product to analyse the dam and its stability mechanism. Also to study the phreatic line positions as a result of seepage through the body of the dam. (Salama, 2018). Numerical model was a powerful tool used to simulate a real physical process mathematically.

The material composition of the earth dam consists of a brownish-red lateritic soil for the shell, dark-ash silty clay for the central core, crushed rock for the upstream stone pitching and downstream horizontal filter drainage respectively. These materials were locally sourced and their physical properties tested in the laboratory in accordance B.S 1377: part 2 1990. Figure 2 below describes the typical cross-section of the earth dam with the upstream and downstream slope kept at 1:3 and 1:2.5 respectively (Zedan, 2017).

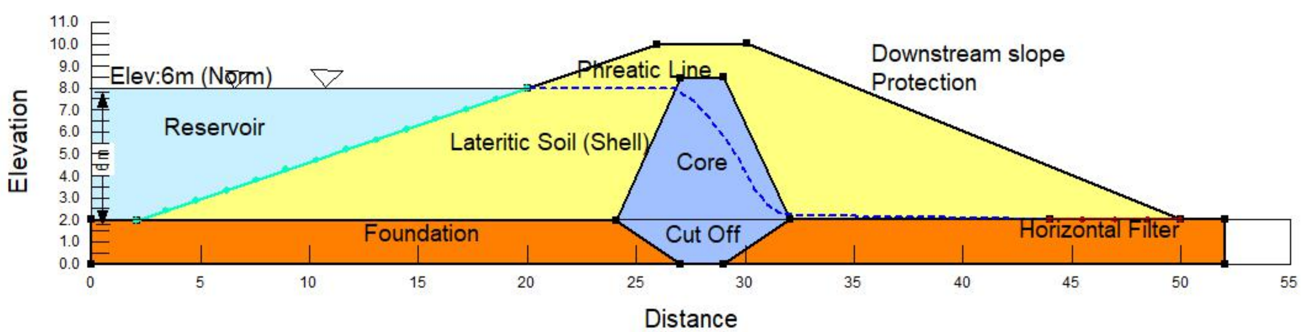

Figure 2: Typical Cross-section of Saura-Keffi Earth Dam, Nasarawa State

3.2 Modelling Case Scenarios For Analysis

The following case scenarios were considered as listed below:
Case 1. The earth dam was considered homogenous at different reservoir water levels of 3 m, 6 m and 7 m.

Case 2. The earth dam was zoned with a low permeable central core and horizontal filter blanket at downstream toe of the dam.

Case 3. The zoned earth dam with central core material compacted into the cut-off trench section along the dam crest axis..

3.3 Formed mesh and Boundary Conditions

The generated mesh and boundary conditions of the dam using a Geo-Studio software tool is shown in figure 3. The finite element model (FEM) comprised four forms of elements: triangular, square, rectangular and trapezoidal type of different sizes composed of 264 nodes and 236 elements. (Salama, 2018).

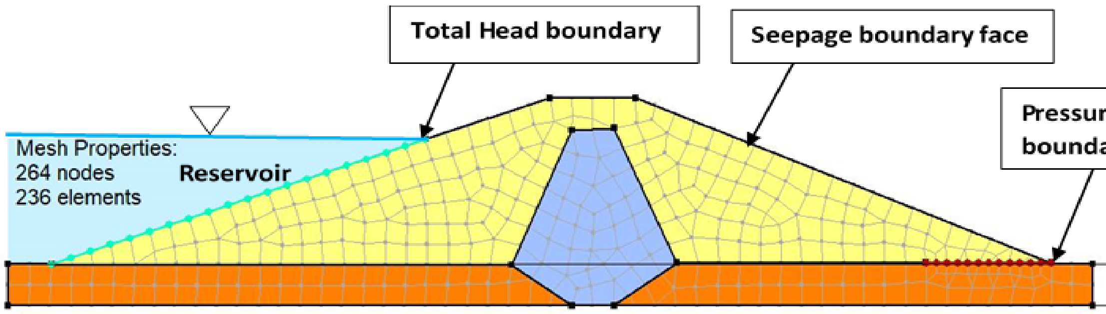

Figure 3: Generated Mesh and Boundary conditions.

The following assigned boundary conditions enabled the finite element mesh analysis conducted as listed below:

I. The upstream boundary condition was considered to have a reservoir water head of minimum (3 m), normal (6 m) and at maximum (7 m) in accordance with the findings of (Al-Nedawi, 2020).

II. The downstream toe of the embankment face was assigned a zero pore water pressure.

III. The potential seepage face boundary at the downstream along the slope face predicts the seepage at any location along the downstream face of the dam.

4.0 RESULTS AND DISCUSSION

The material properties of the earth dam components obtained from the laboratory tests conducted are shown in Table 1. Other inputted material property for the different soils used in the SEEP/W programme is the volumetric water content function.

Table 1: Results from experimental Laboratory test for Lateritic soil (Shell)

Type of tests	Results		Soil Classification
	Lateritic soil (shell)	Silty-clay soil (central core)	(AASHTO)
Sieve Analysis	Soil: 54% silt & 44% sand	Soil: 33% silt & 67% clay	A-2-4 (Brownish-red Lateritic soil (shell) And A-2-6 for silty clay soil (central core)
Compaction	MDD=1.78g/cm^3;OMC=12.1%	MDD=1.82g/cm^3;OMC=12.1%	
Liquid limit	25.6%	28.0%	
Plastic limit	16.5%	20.6%	
Plasticity index	(25.6-16.5)% =9.1%	(28.0-20.6)% =7.4%	
Specific gravity	2.65 (@ 20^{o}C)	2.66 (@ 20^{o}C)	
Permeability	1.95x10^{-3} cm/s (@ 20^{o}C)	2.70x10^{-6} cm/s (@ 20^{o}C)	

4.1 Output of Computer Simulation Using Geo-Studio Software

The generated flow net from the CAD software included: phreatic lines, stream lines, equipotential lines and flow vectors concentrated at the downstream toe of the earth dam (Haseeb, 2017). The steady-state analysis option of the SEEP/W program option estimated the pore-water pressure, seepage flux and exit gradient at different water levels of minimum (3 m), normal (6 m) and maximum (7 m) with and without SCM. This step is necessary for determining the direction of flow within dam body (Salama, 2018). The optimized output results of the analysis for the different reservoir levels are as shown in Table 2.

Table 2: Comparison between pore pressure, seepage flux and exit gradient for different reservoir Elevations with and without seepage control measures.

Type of Experiments	**Reservoir Elevations**					
	With **seepage control Measures**			Without **seepage control MM Measures**		
	3 m	**6 m**	**7 m**	**3 m**	**6m**	**7m**
Pore pressure (kPa)	11.2	12.0	14.8	12.0	10.0	9.8
Seepage Flux (m³/s)	3.76E-07	7.56E-06	9.88E-05	1.30E-04	6.32E-04	9.59E-04
Exit gradient	0.510	0.810	0.820	0.051	0.120	0.159

Figures 4, 5 and 6 represents the analysis results of the dam under the following case scenarios considered:

I. A homogeneous earth dam without core.
II. An earth dam with central core.
III. An earth dam with a core and a complete cut-off (Al-Labban, 2018).

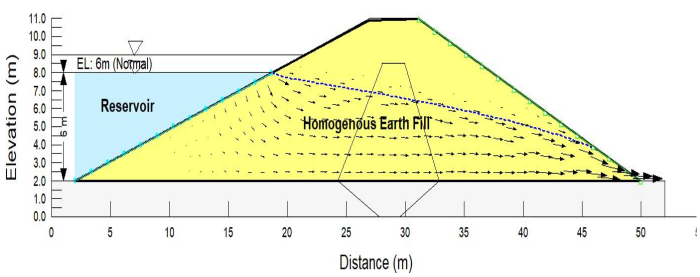

Figure 4: Homogenous earth dam without Core (case1)

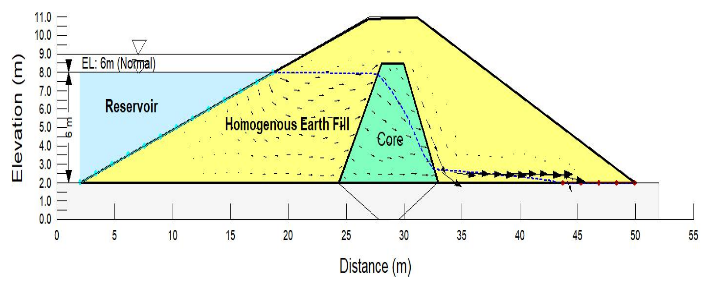

Figure 5: Earth dam with central Core (case2)

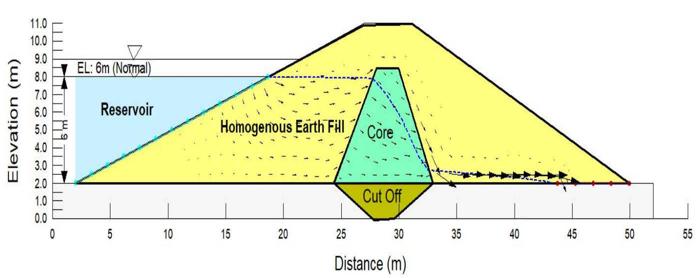

Figure 6: Earth dam with central Core & cut-off (case3)

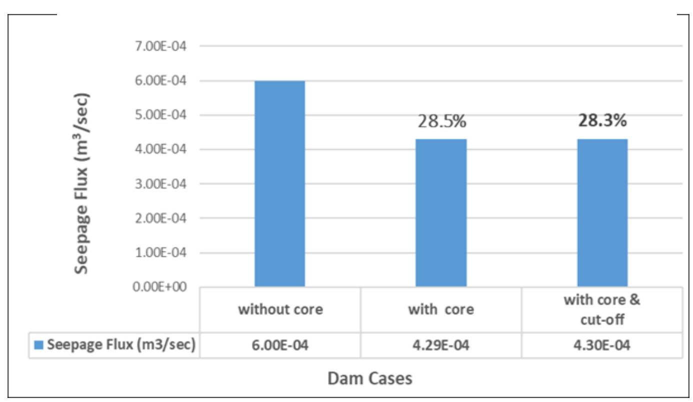

Figure 7: Comparison of percentage reduction in Seepage Flux for Dam Cases considering Reservoir level at 6 m in Steady State Analysis.

Figure 7 shows a percentage reduction in seepage flux to 28.5% when the earth was considered with a central core. Also further reduction to 28.3% was observed when the dam was constructed with a complete cut-off along the axis of the dam crest.

The graphical output result in figures 8 showed a decrease in seepage flux from (3.76×10^{-7} m^3/s to 1.30×10^{-4} m^3/s) at the reservoir water level of 3m with seepage control measures (SCM). This trend is the same for water head at 6m and 7m. Figure 9 showed a decrease in pore-water pressure from 12.0 kPa to 11.2kPa at reservoir water level of 3m with (SCM). Further increases from (12 kPa to 14.8 kPa) was observed as water rises from 6 m to 7 m with SCM.

Figure 10 showed an increased in exit gradient from (0.510 to 0.810) with increase in water level from 3 m to 6 m. However, at maximum water level of 7 m, a slight increase in the exit gradient from (0.810 to 0.820) was observed.

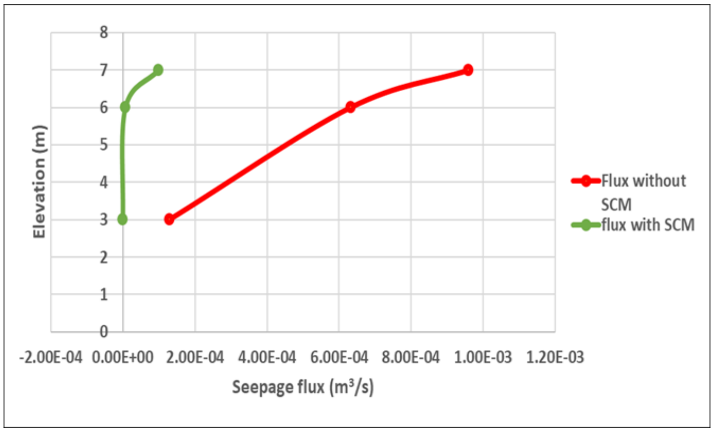

Figure 8: Comparison between seepage flux Vs Elevation(m) without & with SCM.

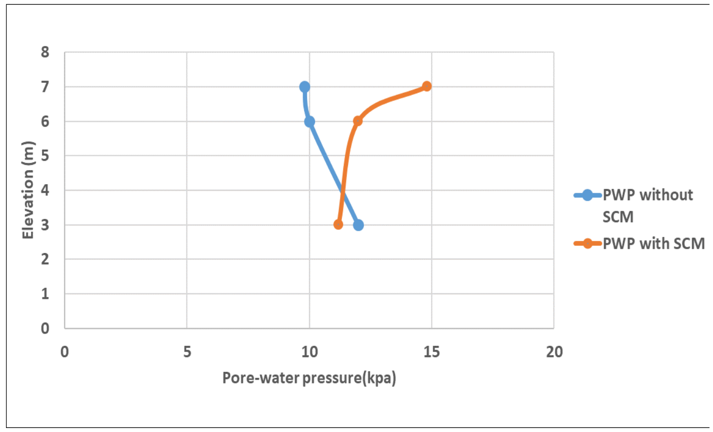

Figure 9: Comparison between pore-water pressure Vs Elevation(m) without & with SCM.

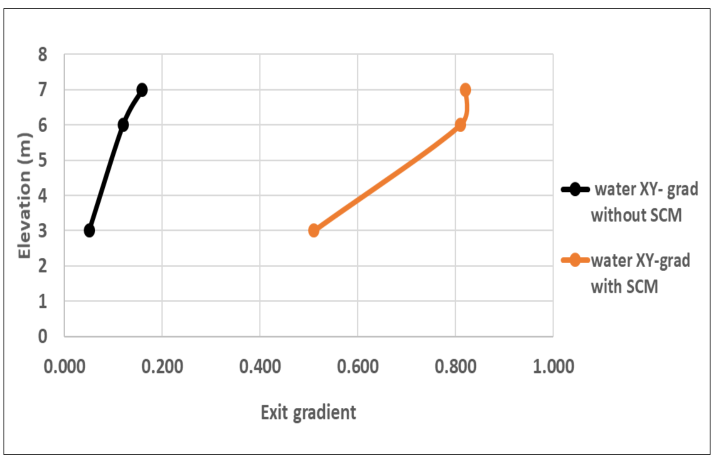

Figure 10: Comparison between exit gradient Vs Elevation(m) without & with SCM.

4.2 Output Result of Slope Stability

Table 3 below shows the properties of materials used for slope stability analysis using SLOPE/W CAD program.

Table 3: Experimental Material Properties of the Earth Dam.

Material Properties	**Silty Clay (CORE)**			**Lateritic soil (Shell)**		
	Y (kN/m^3)	**ϕ (Degrees)**	**c (kPa)**	**Y (kN/m^3)**	**ϕ (Degrees)**	**c (kPa)**
	20.14	25	12	17.80	30	12

The output result in Figure 11 to 12 showed the slope stability analysis at maximum water level of 7m yielding the critical minimum factors of safety using the SEEP/W programme option.

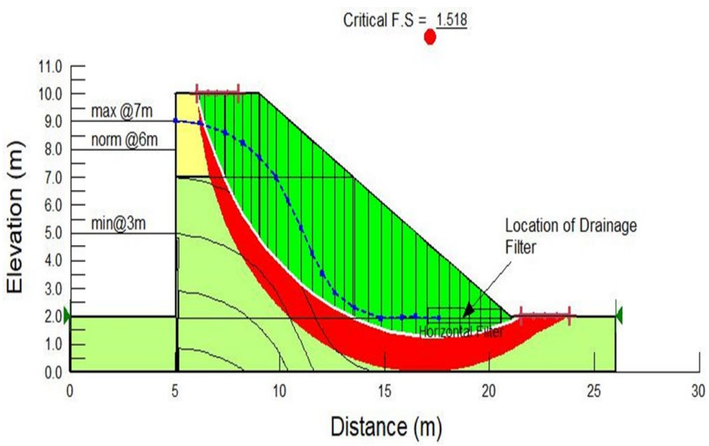

Figure 11: Slip surface for critical safety factor at reservoir water level 7 m with filter blanket.

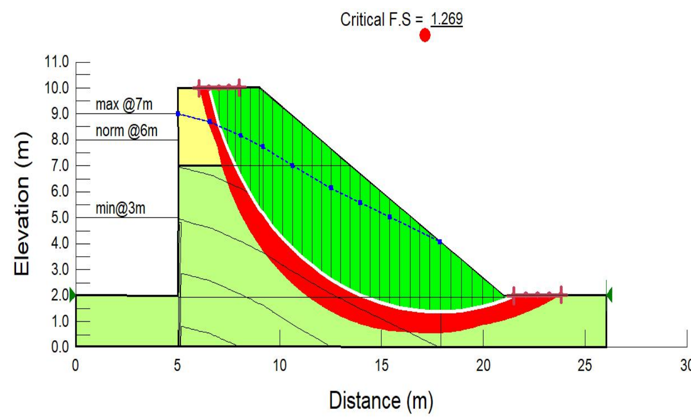

Figure 12: Slip surface for critical safety factor at reservoir water level of 7 m without filter blanket

4.3 ***Determination of Factor of Safety***

Table 4 showed the various factor of safety obtained at different water levels of 3 m, 6 m and 7 m considering the dam with and without horizontal filter. The table revealed a reduction in the factor of safety progressively with increase in water levels in the reservoir without and with horizontal filter (Al-Labban,2018).

Table 4 SLOPE/W Results for Factor of Safety for different reservoir water levels without and with horizontal filter.

Perimeter	**Reservoir Elevations**		
	Minimum (3 m)	**Normal (6 m)**	**Maximum (7 m)**
Safety Factor without HFHF	1.52	1.38	1.27
Safety factor with HF	1.63	1.53	1.52

Figure 13 below shows the relationship between actual factor of safety at different water heads when the dam was constructed with and without a horizontal filter. From the SLOPE/W analysis, an acceptable minimum factor of safety of 1.52 was achieved with the construction of a downstream horizontal filter at maximum water level of 7 m. The GLE plot (i.e. Graphics layout engine) showed an increase in safety factor from 1.27 to 1.52 at lambda values of 0.4 and 0.5 with the introduction of a horizontal filter at the downstream face of the dam. The maximum water level of 7 m was considered critical for determining the minimum safety factor for the overall stability of the dam because any further rise in water level beyond 7 m can lead to overtopping of the embankment for the dam which can cause its instability. (Al-Nedawi, 2020).

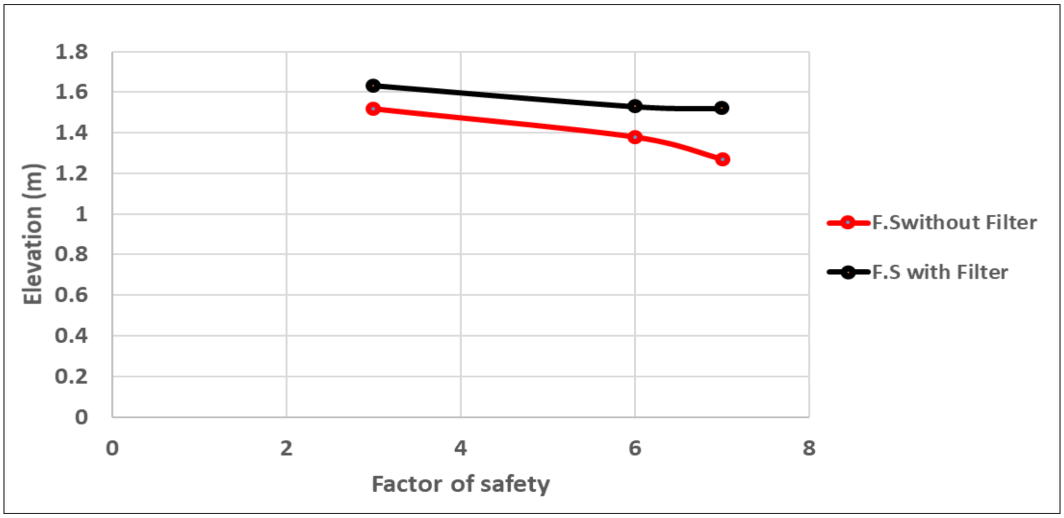

Figure 13: Comparison between Factor of Safety Versus Elevation without and with horizontal Filter.

The Morgenstern-Price and Spencer method of stability analysis in the Geo-studio software programme was used to determine the actual factor of safety to be the equilibrium point where the factor of safety (FOS) with regards to moment and force intersect (i.e. Fm=Ff) (GEO-SLOPE International Ltd, 2004-2021).

5.0 CONCLUSION

The results obtained from the study revealed an increased in seepage flux with rise in water level in the reservoir without SCM. However, in figure 7 the bar chart revealed a percentage decrease in value of 28.5% of seepage flux with the construction of seepage control measures line with the findings of (Al-Labban, 2018).

The pore water pressure (PWP) at minimum reservoir level of 3m decreased from 12 kPa to 11.2 kPa with the introduction of SCM. However, the PWP increased progressive by 18.9% from (12 kPa to 14.8 kPa) at rise in water levels from 6 m to 7 m with SCM. This indicated decrease in PWP upstream of the dam and increased in pore pressure downstream.

The exit gradient increases in value from 0.81 to 0.820 as water rises from 6 m to 7 m accounting for just 1.2% and this insignificant percentage increase was as a result of the SCM incorporated downstream of the dam see figure 17. Further findings revealed also that at the exit end of the dam, the gradient reduced in value from 0.308 to 0.175, when a downstream filter was introduced and this account for 43% reduction in the value of the exit gradient. The significant of this is that the stability at the downstream face of the dam was achieved by the drastic reduction in flow concentration at the downstream due to the present of horizontal drainage filters.

The pattern or position of the phreatic line after analysis influences the general stability of the earth dam as shown in figures (11 to 13). The presence of a horizontal drainage filter at the downstream toe of the dam direct flow away from potential seepage face into the drainage filter as depicted by the phreatic line to mitigate the effect of erosion downstream face of the dam that may arise due to piping.

The SLOPE/W sub program was utilized in analyzing slope stability at downstream face of the dam for the various case scenarios at different water levels. The Morgenstern-price method of analysis was used to evaluate the minimum factor of safety of the dam over the other simpler methods like Fellenius, Bishop and Janbu because it satisfied the equilibrium conditions and attempts to be more realistic in estimating the interslice forces resulting in higher factor of safety FOS. Table 8 showed an acceptable minimum factor of safety of 1.52 for an earth dam with the introduction of a horizontal drainage filter at critical maximum water level of 7 m. This concur with the findings of (Schnaid et al., 2020).

Recommendation

To avoid any form of failure or dam break resulting from the instability of a dam structure, this research recommended that an impervious material be provided and place at the upstream slope face of the dam section to reduce excessive seepage through the dam body. Furthermore, a shore line protection of boulders be provided and positioned at the upstream dam's toe to improve the stability of the soil grain and by extension the overall dam structure. The minimum acceptable factor of safety for an earth dam can also be achieved by placing of horizontal drainage filter at the downstream along the pressure head boundary during the construction of an earth dam.

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