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Modelling of Seepage and Slope Stability Analysis of Ribb Embankment Dam, Ethiopia

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Abstract

Safety against seepage is one in all the primary important steps for checking the possibility of failure of embankment dam and the stability of an embankment dam depends on its geometry, its components, materials, properties of every component, and therefore the forces to which it's subjected. This paper presented seepage and slope stability analysis against Ribb dam safety using finite element-based PLAXIS software, and so the result was compared with different standards. PLAXIS is alternative software that will be used for evaluating the protection of embankment dams due to seepage conditions. The simulated results showed the common rate of flow of seepage through the body of the dam at normal pool level was equal to $5.05 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}$ and through the foundation of the dam was $3.00 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}$. According to Look (2014) recommendation, the seepage results within the tolerable limit. The results of the factor of safety were considered too different loading conditions. The factor of safety results during the end of construction for both static and dynamic stability analysis were 1.3063 and 1.2226, respectively. For steady-state conditions, the factor of safety obtained for static stability analysis was 1.2604, and also the dynamic analysis 1.1803. The rapid drawdown condition is analyzed with a normal pool level of 1940 m lowered to 1900 m or rapidly reduced 57 % of the reservoir water. The analysis results showed that the factor of safety for the static, and dynamic analyses were 1.2021 and 1.0662, respectively. Using different recommended design standards: United States Army Corps of Engineers (USACE), British dam society (BDS), and Canadian dam association (CDA) the slope stability analysis of the Ribb embankment dam at all critical loading conditions is safe.

Keywords: - *Finite element method, Seepage, Stability analysis, PLAXIS.*

1. INTRODUCTION

1.1. Background

Dam failures are of particular concern because the failure of a huge dam has the potential to cause more death and destruction than the failure of the other synthetic structure (Al-Ansari et al., 2015). Once the project is commissioned, the operation, management, and periodic maintenance are equally important for attaining the intended purpose and a sustainable project (Asawa, 2010).

Embankment dam's failure is particularly caused by an absence of thorough investigations, improper design, seepage piping, slope instability, deformation, deterioration, and poor maintenance. Many failure modes are identified as causes of dam failure. According to Garg (1991), 40% of failures are attributed to hydraulic failures, 30% to seepage while the remaining 30% to structural failure.

Many seepage problems and failures of earth dams have occurred due to inadequate seepage control measures or poor/incomplete cleanup and preparation of the foundations and abutments. Seepage may result in piping and embankment sloughing or sliding, both of which could lead to dam failure (Ghazaleh et al., 2020). To stop dam failure, it's essential to manage the seepage within the dam. Seepage in dams caused water waste and also the decline of dam stability.

The stability of slopes has great strategic importance because the failure of the slope may cause human, economic, and environmental disasters, especially in large infrastructure projects. Therefore, the slopes should be carefully investigated to decrease the possibility of failure and to provide adequate safety against failure (Salmasi *et al.*, 2020). However, the safety and performance of embankment dams must be controlled during construction, first impoundment, and long-term operation. It's generally accepted that safety doesn't depend only on proper design and construction, but also on monitoring actual behaviors during the service life of the structure (Felder & Chanson, 2016).

Ensuring the analysis of the dam against seepage and slope failure may be a necessary component for the design of an earth-fill dam to perform the intended function throughout the service life. Therefore, this study aims to assess the seepage and slope stability analysis of the Ribb dam using finite element-based PLAXIS 2D software.

2. MATERIAL AND METHODS

2.1. Description of the study area

2.1.1. Geographical location

The Ribb dam is an earthen zoned type dam that's found within the Ribb River, on the eastern side of the lake basin, within the south Gondar zone of Amhara national regional state. The actual geographic grid reference location of the dam site is 120 02' 30" N and 370 59' 45" E. It's found around 33 km far from Addis Zemen and about 700 km from Addis Ababa, the capital city of Ethiopia (McCartney *et al.*, 2010). Figure 2-1 shows the location map of the Ribb dam site.

Figure 2-1 Location map of Ribb dam site

2.1.2. Topography

The dam site is characterized by broad and flat flood plains, old bench forming terraces, and low to high relief basaltic hills with steep to moderately steep slopes. The right and left abutments of the dam are characterized by steeper slopes with a slope angle of 35° to 46°. There are developments of relatively few shallow seated gullies at the reservoir catchments attributed to rill and gully erosion. The height's topography within the area is marked by Shikra Hill, which is at an altitude of 1973 m. The Upper Ribb watershed is characterized as a mountainous, wedge-shaped, and steep-sloped (3.6%) watershed. The highest elevation of the watershed is about 4,100 m in its southeastern part. The lowest topography land is at the dam site, which is at an altitude of 1873 m (McCartney *et al.*, 2010).

2.2. Main features of Ribb dam and reservoir

Table 2-1 Main features of the Ribb dam

Ribb main dam		Saddle dam	
Dam type	Earth rockfill dam	Saddle dam A	
Crest elevation	1945 amsl.	Crest length	629 m
Riverbed elevation	1870 amsl.	Maximum height	17 m
Length of an earth dam	800 m	Crest width	10 m
Max height	75 m	Crest elevation	1945 m
Crest width	10 m	Saddle dam B	
Spillway		Crest length	295 m
Type	Side-channel	Maximum height	2.20 m
Spillway crest elevation	1940 amsl.	Crest elevation	1945 m
Spillway crest length	107 m	Saddle dam C	
Design discharge	1060 m ³ /s	Crest length	203 m
Maximum flood level	1943 amsl.	Crest width	10 m

(MFL)			
Normal water level (NWL)	1940 amsl.		
Reservoir capacity	234 Mm ³		
Water surface area at full reservoir level	100 ha		

84 The Ribb dam is a zoned embankment dam, consisting of the permeable zone (shell),
85 impermeable zone (core), and a filter zone. Ribb dam itself is a rock fill dam zonal type
86 with clay core. Figure 3-1 shows a cross-section of the Ribb dam on the utmost cross-
87 section which is modeled using PLAXIS.

89 Figure 3-1 Ribb main dam geometry model

90 Where:

91	1- Compacted core material fill	96	6- Rip rap material
92	2- Fine filter material (F1)	97	7- Silty clay foundation
93	3- Course filter material (F2)	98	8- Rock foundation
94	4- Compacted shell material	99	9- Compacted alluvium /colluvium
95	5- Compacted rock fill material		

100 2.3. Data collection

101 The first assignment of the study was getting relevant information and data on the study
102 area. This study mainly requires two kinds of necessary data that were collected using
103 different data gathering techniques.

104

105

1. Primary data collection

The primary data collected from the ground are used for further analysis, interpretation, and comparison. Additionally, the prime data was collected from the ground was used to cross-checking secondary data. Observation and practical field were essential for; dam site visiting and visual inspection of the present condition of the dam, measuring reservoir water level and drawdown recorded data from the dam site and interviewing engineers, hydro geologists, and beneficiaries of the command area corresponding to the building of the dam.

2. Secondary data collection

Secondary data was collected from the Ethiopian waterworks construction and supervision enterprise (EWWCSE) and the Ministry of Water, Irrigation and Energy (MoWIE). The geometrical design of the dam, geotechnical parameters of the embankment, design document, seismic data, and foundation materials from the laboratory were collected from the Ethiopian waterworks construction and supervision enterprise (EWWCSE). Geological reports, project completion reports, and maps of the dam site and reservoir interfaces are collected from the Ministry of Water, Irrigation, and Energy (MoWIE). Reservoir under operation drawdown record and Study area background from ECDSWC and Ministry of Water, Irrigation, and Electricity (MoWIE).

To achieve the objective of this study, the main data was taken from the project document are the dam profile and property of construction materials and foundation. Engineering properties of soils are vital components of any geotechnical analysis.

Table 2-2 Geotechnical summarized data sets used

Material Type	γ_{un-sat} $(\frac{kn}{m^3})$	γ_{sat} $(\frac{kn}{m^3})$	$k_x = k_y$ $(\frac{m}{s})$	E (Mpa)	ν	c $(\frac{KN}{m^2})$	ϕ (°)	ψ (°)
Clay	16	18	$3.6 \cdot 10^{-8}$	20	0.32 2	3	15	0
Fine filter (F ₁)	18	21	$4 \cdot 10^{-6}$	45	0.24	0	34	4
Coarse filter (F ₂)	18	22	$7.29 \cdot 10^{-4}$	60	0.24	0	34	4
Shell fill	18	22.6	$1 \cdot 10^{-3}$	24	0.29	0	32	2

Rockfill	22	23	0.3025	38	0.3	0	40	10
Rip Rap	22	23	18.49	44	0.3	0	40	10
Foundation soil / Alluvium foundation	17	18.3	2.8×10^{-9}	19	0.31	20	13	0
Granular Colluvium/Alluvi um	18	22	1×10^{-3}	24	0.29	0	32	2
Rock foundation	22	23	1×10^{-7}	44	0.3	1000	38	8

2.4. Model simulation and analysis

In addition to PLAXIS software, Arc GIS 10.3 was used for study area delineation. To supplement this research, work physical tools/equipment and materials such as geographical position system (GPS), theodolite, tape, calibrated seepage measurement chamber, digital elevation model (DEM), camera, topographic map, Microsoft excel, and word are utilized.

This behavior of embankment dam could be a basic distinctive characteristic as compared with other type dams. Considering soil behavior in interaction with water is a very strong relationship between water, soil and other failures force is incredibly important for dam design. According to these factors and consequences of dam break which cause many troubles downstream, static and dynamic analysis is incredibly important which are studied during this research.

Many years ago, numerical methods are used as theory, but today, when computer science was very fast established, many numerical methods, like finite element are very widely used. During this study, it's been tried dam analysis carefully using PLAXIS software and output compared to project documents and standards.

2.4.1. Seepage analysis

Seepage, through an embankment and foundation of a dam, can, if not properly controlled, cause failure of the dam. Direct observation of unsatisfactory performance such as excessive piezometric levels, sand boils, turbidity in seepage discharge, increases in seepage discharge over time, or changes within the piezometric head for similar past

pool elevations is all indicators of potentially serious seepage conditions. These conditions could also be indicative of detrimental effects of seepage leading to piping and eventual breaching of an embankment dam or the foundation of a dam.

The flow of water through the soil is one of the basic issues in geotechnical and geo-environmental engineering. A numerical model is a mathematical simulation of a real physical process. Numerical modeling is mathematical and during this sense is incredibly different from scaled physical modeling within the laboratory or full-scaled field modeling. The finite element method is a useful analysis method in science engineering due to this process, some software has been developed in recent years. For instance, PLAXIS could be a very useful software that's grounded on finite element methods.

Flow in a very medium will be described by Darcy's law in PLAXIS 2D. Considering flow in a vertical x - y plane the next equations:

$$q_x = k_x \frac{\partial \phi}{\partial x} \dots\dots\dots 2.1$$

$$q_y = k_y \frac{\partial \phi}{\partial y} \dots\dots\dots 2.2$$

The equations express that the specific discharge, q, follows from the permeability, k in (x, y) direction, and the gradient of the groundwater head. The head (ϕ) is defined as follows:

$$\phi = y + \frac{p}{\gamma_w} \dots\dots\dots 2.3$$

where y is the vertical position, p is the stress in the pore fluid and γ_w is the unit weight of the pore fluid. For steady flow the continuity condition applies:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \dots\dots\dots 2.4$$

The groundwater head in any position within an element in PLAXIS 2D can be expressed in the values at the nodes of that element:

$$\phi(\xi, \eta) = N \phi^e \dots\dots\dots 2.5$$

where N is the vector with interpolation functions and ξ and η are the local coordinates within the element.

According to Equation (2-1), the specific discharge is based on the gradient of the groundwater head. This gradient can be determined using the B-matrix, which contains the spatial derivatives of the interpolation functions. To describe flow for saturated soil (underneath the phreatic line) as well as non-saturated soil (above the phreatic line), a reduction function K^r is introduced in Darcy's law (Brinkgreve *et al.*, 2011).

$$q_x = K^r k_x \frac{\partial \phi}{\partial x} \dots\dots\dots 2.6$$

$$q_y = K^r k_y \frac{\partial \phi}{\partial y} \dots\dots\dots 2.7$$

The reduction function has a value of 1 below the phreatic line (compressive pore pressures) and has lower values above the phreatic line (tensile pore pressures). In the transition zone above the phreatic line, the function value decreases to the minimum of 10^{-4} .

In the numerical formulation, the specific discharge, q , is written as:

$$q = K^r R B \phi^e \dots\dots\dots 2.8$$

where, q is the specific discharge, $q = \begin{bmatrix} q_x \\ q_y \end{bmatrix}$

$$R \text{ is the permeability matrix, } R = \begin{bmatrix} K_x & 0 \\ 0 & K_y \end{bmatrix}$$

$$\text{Gradient interpolation matrix, } B = \begin{bmatrix} \frac{\partial N}{\partial X} & 0 \\ 0 & \frac{\partial N}{\partial Y} \end{bmatrix}$$

ϕ^e is the gradient of the groundwater head and K^r is permeability reduction function.

In the case that the phreatic line is unknown (unconfined problems), a Picard scheme is used to solve the system of equations iteratively. The linear set is solved in incremental form and the iteration process can be formulated as:

$$K^{j-1} \delta \phi^j = Q - K^{j-1} \phi^{j-1}, \phi^j = \phi^{j-1} + \delta \phi^j \dots\dots\dots 2.9$$

where j is that the iteration number. In each iteration increments of the groundwater, the head is calculated from the unbalance within the nodal discharges and added to the active head.

From the new distribution of the groundwater head, the new specific discharges are calculated according to Equation (2-8), which may again be integrated into nodal discharges. This process is sustained until the norm of the unbalanced vector, i.e., the error in the nodal discharges is smaller than the tolerated error.

2.4.2. Slope stability analysis

The slice and numerical methods are the common methods of the slope stability analysis which mainly be contingent on the limit of equilibrium and elastic-plastic theories, respectively (Cheng, 2005). In between those two methods, the limit equilibrium method is a more traditional and mature method for slope stability analysis. This mainly includes the (Spencer, Fellenius, the Bishop, the Janhu method, and the sliding wedge, etc.) methods (Wei *et al.*, 2009).

Nowadays with the expansion of computer technology and calculating methods, the finite element method is widely adopted within the slope stability calculation among other numerical methods (He & Zhang, 2012).

In this study, two dimensions (2D) slope stability model was analyzed. The elastic-plastic large deformation finite element method (FEM) was adopted. Moreover, the strength reduction technology combined with convergence criterion, and plastic zone penetrability criterion was used.

The PLAXIS software is used to get slope stability analysis for the upstream and downstream slopes for various loading conditions (Zewdu, 2020). The analysis is performed in terms of effective stresses. Pore pressures are estimated as subsequently described. The section at which the dam height becomes maximum is particular for stability analysis because this is often the critical section for stability as compared to others and can give the minimum factor of safety.

Phi-c reduction (safety analysis)

A safety analysis in PLAXIS can be executed by reducing the strength parameters of the soil. The factor of safety analysis can be performed after each calculation phase and thus for the individual construction stage. However, note that a phi-c reduction phase can't be used as a starting condition for one more calculation phase because it ends in a state of failure.

230 When performing a factor of safety analysis, no loads will be increased simultaneously.
 231 The phi-c reduction could be a special kind of plastic calculation. Within the Phi-c
 232 reduction approach, the strength parameters ϕ and c of the soil are successively reduced
 233 until failure of the structure occurs. The factor of safety is given by:

234
$$FOS = \frac{c + \sigma_n \tan \phi}{c_r + \sigma_n \tan \phi_r} \dots\dots\dots 3.22$$

235 where c and ϕ are the input strength parameter and σ_n is the actual normal stress
 236 component. The parameter c_r and ϕ_r are reduced strength parameters that are just large
 237 enough to maintain equilibrium.

238 The summarized loading conditions and a corresponding minimum factor of safety, FOS
 239 requirements proposed by USACE are given in the table below.

240 Table 2-3 Minimum required factors of safety (USACE, 2003).

Case	Loading condition	Critical slope	FOS
I	End of construction	Upstream	1.3
		Downstream	1.3
II	Sudden drawdown	Upstream	1.3
III	Steady-state seepage	Upstream	1.5
		Downstream	1.5
IV	Steady-state seepage with earthquake	Upstream	1.1
		Downstream	1.1

241 Table 2-3 Minimum required factors for settlement (Fell *et.al.*, 2003).

Factor	Loading condition	Influence on Likelihood		
		Less Likely	Neutral	More Likely
Settlement as percentage of embankment height	During construction	1% or less	1 - 3%	3 - 5%
	post-construction	0.25% or less	0.25 - 1%	1 - 2%

The final step should result in a fully developed failure mechanism, if not the calculation will be repeated with a larger number of additional steps until failure. Ribb dam which is high at the deepest section of the dam (75 m) was divided into six stages of construction sections because those plastic materials need proportional time for loading. The stages of calculation and the type of analysis have summarized in the table as follows.

Table 2-4 Stages of construction of the analysis

No	Height of construction stage (m)	Time (Days)	Description
1	-42.5 - 13.2	150	1 st stage including boundary
2	13.2 - 25.70	90	2 nd stage above OGL
3	25.7 - 38.2	90	3 rd stage above OGL
4	38.2 - 50.7	90	4 th stage above OGL
5	50.7 - 63.2	90	5 th stage above OGL
6	63.2 - 75	90	6 th stage above OGL

Table 2-5 Calculation stages and types of analysis

No	Calculation stage	Type of analysis
1	End of construction	Static analysis
2	Steady-state	Static analysis
3	Rapid drawdown	Static analysis
4	End of construction	Dynamic analysis
5	Steady-state	Dynamic analysis
6	Rapid drawdown	Dynamic analysis

2.5. Overall procedure in the schematic diagram (conceptual framework)

The overall schematic procedures for this research work can be described by the following flow chart.

Figure 2-2 Conceptual framework showing the methodology followed in this study.

3. RESULTS AND DISCUSSIONS

3.1. Model of the Ribb earth rockfill dam

The Ribb dam is modeled using FEM as a real-world application within the present study. The water flowing through the earthen structure is simulated under steady-state and transient conditions. The finite element model employed during this study consists of seven different materials including the boundary material.

This study is conducted using modeling Mohr-Coulomb on PLAXIS, which is applying the finite element method by dividing the dam structure into small dots related to nodal (meshing). The PLAXIS finite element model for most section of the dam and profile, including bedrock is given in Figure 3-1. The model consisted of 4209 node points, 6096 stress points, and 508 plane-strain elements. Standard fixity elements were together with the bottom and vertical sides of the model.

Figure 3-1 Finite element model of the embankment

As shown in Figure 3-2 below, the outputs of the Mohr-Coulomb plastic stress points shows that the boundary used for the analyses was sufficient enough due to the plastic points reaches a mesh boundary.

Figure 3-2 Plastic points

3.2. Seepage Analysis and Results

Discharge of seepage calculation by analyzing the resultant discharge of the dam cross-section modeling using PLAXIS, which is calculated from the unit discharge of seepage along the utmost cross-section of the dam. Based on the analysis performed, the results discharge of seepage using PLAXIS modeling in normal pool level was analyzed during this study shown within the subsequent figures.

The phreatic line as seen from Figures 3-3 below has emerged below the toe of the dam. This indicates that the dam is safe against sloughing problems, which is that the most reason behind the failure of most downstream faces of dams. In all Figures, the horizontal and vertical axes are plotted in a coordinate system.

Figure 3-4 shows the phreatic lines within the steady-state condition. As seen within the figure, the phreatic line suddenly drops inside the core, because the low permeability of the core reduces the water flux flowing through the dam. Also, the clay layer beneath the core base improves the efficiency of the core in reducing the water flux by also preventing the flux from flowing beneath the core. However, the core raises the phreatic line on the upstream side, which successively increases the saturated area of the soil mass. The phreatic line at the upstream side is seen as becoming almost horizontal.

Figure 3-3 Location of the phreatic line at normal pool level

The seepage quantity through the body of the dam was studied and shown in Figure 3-4. The quantity of seepage through the most body of the dam is $5.05 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}$ and extreme velocity is $83.36 \times 10^{-9} \text{ m/s}$. The quantity of seepage through the foundation of the dam is $3.00 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}$ and extreme velocity is $175.59 \times 10^{-9} \text{ m/s}$ as shown in Figure 3-5.

Figure 3-4 Seepage quantity through the main body of the dam

Figure 3-5 Seepage quantity through the foundation of the dam

According to the tolerable resulting discharge of seepage must not exceed 0.56 liters/minute/meter, for tall dams taller than 40 meters (Look, 2014). The Ribb main Dam which is analyzed during this study features a height of 75 meters. Meanwhile, the intense discharge using PLAXIS is within the normal pool level (1940 amsl) meters with a whole discharge through the dam body and foundation at the utmost deepest section is $8.05 \times 10^{-6} \text{ m}^3/\text{s}/\text{m}$ or equal to 0.483 liters/minute/meter. The discharge value is smaller than 0.56 liters/minute/meter, so it's still but the tolerable discharge requirements.

In this analysis, the pore water pressure distribution (Figure 3-6) was also simulated of course with a minimum at the upper and maximum at the lowest proportionally with the depth of water increment. It's particularly higher below the reservoir bed. The magnitudes of pore water pressure at normal pool level (1940 m) and bottom of boundary condition (1870 m) a.m.s.l are zero and $1430 \text{ KN}/\text{m}^2$ (Figure 3-7), respectively. Within the figures shown below the pore water pressure distribution.

Figure 3-6 Active Pore water pressure distribution during normal pool level

Figure 3-7 Pore water pressure distribution around the bottom of boundary condition

3.3. Static Stability Analysis (without Earthquake)

The stability of the Ribb dam was evaluated for construction and operating conditions utilizing the in-situ engineering properties of the foundation and embankment materials and pertinent geologic information. Stability analyses were performed via PLAXIS software grounded on the strength reduction finite element method with different loading conditions. Though considering the stability of the Ribb dam, there are three generally recognized critical stages created on pore pressure conditions such as the end of construction, steady-state seepage, and rapid drawdown. Construction pore pressures usually attain their maximum value when the complete height of the embankment has been constructed. The steady-state seepage condition is attained after the reservoir remains filled for an extended time and also the pore pressure may be estimated from a

flow net. Rapid lowering of the reservoir water level produces the third critical condition, particularly for slow draining soils. The results of analyses are compared with the different standards.

3.3.1. End of construction

This case represents undrained conditions for low-permeability embankment and/or foundation soils, where excess pore water pressure is present because the soil has not had time to empty since being loaded in compression and shear. At the end of construction, significant pore pressure development is predicted within the embankment body and foundation either from rainfall or compaction water. The slope stability of the Ribb embankment dam was assessed at this loading condition using FEM-based PLAXIS software and therefore the results are shown in Figure 3-8.

Figure 3-8 Total displacements during the end of construction

Stability results are expressed within the kind of the factor of safety (FOS) for all the cases. The FOS values are shown along the y-axis and also the displacement shown along the x-axis within the entire figure below.

Figure 3-9 Factor of safety chart for the end of construction

The FOS obtained at end of construction shows 1.3063.

3.3.2. Steady-state seepage

This was another critical condition analyzed the reservoir is full long enough for seepage water to percolate through the embankment; the analysis is critical just for the downstream slope of the embankment. It's assumed that the steady seepage condition is developed when the reservoir is full at maximum retention level the pressure within the pore water within the downstream portion reaches its highest values. The downstream slope may have its lowest factor of safety against sliding. To compute the slope stability analysis phreatic surface within the embankment has been established. So, the slope stability of the dam was assessed and therefore the results are shown in Figure 3-10.

Figure 3-10 Total displacements during steady-state seepage

Figure 3-11 Factor of safety chart for the steady-state

The results of the factor of safety under steady-state conditions were studied for reservoir levels in 1940 m a.m.s.l. After modeling the dam and performing the strength reduction method for slope stability analysis using PLAXIS, the factors of safety were found to be 1.2604.

The results display a difference within the factor of safety from the end of construction because of the change within the stipulation within the reservoir and therefore the stress condition within the upstream slope soil mass or because of the hydrostatic pressure on the upstream slope. The presence of a core above a minimum permeability foundation resulted in an increase of the saturated soil zone in the upstream region, which caused a decrease in the effective stress. This, in turn, significantly reduces the slope factor of safety. Besides, the hydrostatic pressure coming from the water reservoir provides additional support to the slope and resists sliding failure.

3.3.3. Rapid drawdown

This case represents the condition whereby a protected flood stage or maybe normal storage saturates much of the upstream portion of the embankment, and so flood load or the reservoir falls faster than the soil can drain. This may cause both higher pore pressure directly, and by causing excess pore water pressure to develop from undrained shear. This may cause both higher pore pressure directly, and by causing excess pore water pressure to develop from undrained shear. For analysis purposes, it was assumed that drawdown is extremely fast, and no drainage occurs in materials with low permeability, the water level at the upstream dam surface is above dead storage level elevation at 40 m below from normal pool level. The upstream slope stability of the dam was assessed and therefore results are shown in Figure 3-12 and Figure 3-13.

Under drawdown conditions, the water inside the dam needs an extended time to flee from the dam, which causes the event of excess pore water pressure within the soil and consequently, a decrease within the shear resistance of the soil. Also, the hydrostatic pressure on the slope is reduced leading to the lowering of the soil resistance against sliding. Figure 3-13 shows the critical sliding surface under a drawdown of 57% of the reservoir. The results show that a shallow sliding of the soil develops on the slope when the water level is suddenly dropped to the level of 1900 m (57% of the reservoir). These

slides take place immediately after the drawdown is completed and it might because of cracking on the slope face.

Figure 3-12 Total displacements during rapid drawdown

Figure 3-13 Factor of safety result for the rapid drawdown

Figure 3-13 presents the results of the factor of safety for rapid drawdown the result shows 1.2021. The impact of the drawdown conditions on the slope factor of safety is shown within the figure, the factor of safety reaches the lowest value immediately after the drawdown is completed.

Under drawdown conditions, the boundary neutral force within the type of water weight within the reservoir will decrease faster than the buoyancy force of the soil because of the low permeability of the soil. Also, excess pore water will develop toward the upstream face causing a rise within the buoyancy force. This mixture ends up in a decrease within the stability of the upstream slope.

3.4. Dynamic Stability Analysis (with Earthquake)

Embankments constructed of loose cohesionless materials or founded on loose cohesionless materials are particularly prone to failure because of liquefaction during earthquakes which will occur at any time and are evaluated using expected groundwater conditions. The analysis of slopes will be decreased because of the presence of a seismic load. The earthquake ground motions are capable of destabilizing internal forces in soil matrices and also initiate the surplus pore water pressures. When the shear strength decreases, the analysis of the slope is affected. Post-earthquake stability analysis has been done after the earthquake shaking.

3.4.1. End of construction with earthquake

In PLAXIS analysis, additional displacements are generated during a safety calculation. The total displacements in each stage (at failure) indicate a likely failure mechanism. The shading of the total displacements indicating the most applicable failure mechanism of the embankment in the final stage.

In the present study, stability analysis of the Ribb embankment dam immediately after the end of construction against the design earthquake was conducted using the FEM-based PLAXIS software and the results are shown below.

Figure 3-14 Total displacements during the end of construction

Figure 3-15 Dynamic times Vs Horizontal acceleration

Figure 3-16 FOS during the end of construction

The FOS obtained at this calculation and modeling stage is 1.2226

3.4.2. Steady-state seepage with earthquake

Figure 3-17 Total displacements during steady-state seepage

Figure 3-18 Dynamic time Vs Horizontal acceleration

Figure 3-19 Plot of FOS during steady-state seepage shows 1.1803

3.4.3. Rapid drawdown with earthquake

Figure 3-20 Total displacements during rapid drawdown

Figure 3-21 Dynamic time Vs Horizontal acceleration

Figure 3-22 FOS during rapid drawdown

The FOS obtained at this calculation and modeling stage is 1.0662.

Table 3-1 Summary result of static and dynamic slope stability analysis

Loading condition		FOS (USACE)	FOS (BDS)	FOS (CDA)	FOS	Status
Static analysis	End of construction	1.3	1.3 – 1.5	1.3	1.3063	OK
	Steady-state	1.5	1.3 – 1.5	1.5	1.2604	OK
	Rapid drawdown	1.2	1.2 – 1.3	1.2 – 1.3	1.2021	OK
Dynamic analysis	End of construction	N/A	N/A	1	1.2226	OK
	Steady-state	N/A	N/A	1	1.1803	OK
	Rapid drawdown	N/A	N/A	1	1.0662	OK

From the results of the performed analysis for three critical loading conditions, it can be concluded that the dam satisfies all the requirements of United States Army Corps of Engineers (USACE), British dam society (BDS), and Canadian dam association (CDA) recommendations as shown in Table 3-1 above.

4. CONCLUSIONS

Finite element modeling was employed during this study to investigate the combined seepage and slope stability analysis of the Ribb embankment dam. Three different loading conditions were considered. The seepage result showed that the seepage rate of the Ribb dam at the normal pool level is 0.483 liters/minute/meter. The discharge value is smaller than 0.56 liters/minute/meter, so it's still less than the tolerable discharge requirements. The dam safety checked based on the minimum required FoS stated in USACE, BDS, and CDA. The results showed that the geometric design of the dam is appropriate consistent with BDS criteria and the seepage through the dam is within the code recommendations. The rapid drawdown case is that the most important compared to other operating cases. It can be concluded that the Ribb embankment dam is safe against seepage failure and slope failure under the various cases of operation and also the factor of safety result clearly showed that the slope stability decreases when applying seismic load at section.

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Conflict of interest

We here submitted the manuscript entitled “**Modelling of Seepage and Slope Stability Analysis of Ribb Embankment Dam, Ethiopia**” to be considered for publication. We declare that this is our original research work. There is no conflict of interest between authors.

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