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Slope Stability Analysis in Embankment Dam Under Static Condition Using Numerical Model (Case Study: LegeamaraEarthen Dam)

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ABSTRACT

Slope stability is now the most important factor in determining the overall safety of earthen dams. The primary goal of this study was to assess the slope stability of the Legeamara earthen dam found in South Wollo, Ethiopia. The GeoStudio software was used to analyze the slope stability safety factors using SLOPE/W in various operational scenarios. In this study, the slope stability analysis for each state and each slope with American Crops Engineer #1 and #2, Ordinary, Bishop, Jambu, Morgenstern-Price, and Spencer methods, calculated that the minimum factor of safety in each of those methods, being considered as a safety factor of slope stability. The three different loading conditions were analyzed i.e., end of construction (upstream and downstream slope), steady-state (upstream and downstream slope) at EL 2449 m, and rapid drawdown (upstream and downstream slope) with a minimum factor of safety 2.09,1.93, 2.07, 1.35, 2.14 and 1.91 respectively from all methods of Limit Equilibrium slope stability analysis. Using the recommended dam design standards bythe United States Army Corps of Engineers (USACE) and the British Dam Association (BDS),the slope stability analysis of the Legeamara earthen dam is safe at all critical load conditions. And, it is found that Legeamara dam is able to withstand stresses at all load conditions as the minimum factor of safety lies between (2.098-2.246) and (1.93-2.003) in upstream and downstream, respectively.

Keywords: Slope Stability, Legeamara Earthen Dam, SLOPE/W, GeoStudio

1. INTRODUCTION

Embankment Dams are hydraulic structures that store, control, and divert water by impounding it behind the dam's upstream side in a reservoir for various purposes such as water supply, irrigation, navigation, and transportation [1],[2]. Even though dams have many advantages, the risk of failure still exists [3],[4]. Dams can endanger downstream communities and properties if they are not properly designed, operated, and maintained [5],[6]. During extreme events, all types of embankment dams, regardless of design or construction, are subjected to increased forces, increasing the potential for failure [7]-[9]. Once the embankment dam project is operational, observations, surveillance, inspections, and ongoing evaluation are required to ensure the dam's satisfactory performance [10],[11]. Thus, the primary and most important reason for determining the overall safety of earthen dams is subsequent monitoring of slope stability [12]. After the completion of the embankment Dam construction. The earth-fill dam must be stable at all times [13]. Because these dams are more prone to structural failures, the main causes, such as improper design, a lack of thorough investigations, insufficient care in operation, and poor maintenance, must be avoided [14]. The embankment must be capable of safely accommodating an appreciable degree of slope stability, the slopes of the embankment must be stable during construction and under all reservoir operation conditions, and the upstream slope must be protected against erosion by wave action, while the crest and downstream slope must be protected against erosion due to wind and rain [15],[16]. In general, ensuring the dam's stability against slope failure is an important component of the design. Aside from stability, the dam must also be able to demonstrate satisfactory serviceability, which means that the dam must be able to perform the intended function throughout its service life [17],[18]. Slope stability analysis has great importance because the failures of embankment dams to slope may affect humans, the economy, and environment. In order to reduce the possibility of failure and provide safety against failures of embankment dams, the slope should be carefully investigated [19],[20]. The safety of embankment dams must be controlled during the construction period, first Pondage, and operation period [21],[22]. The extreme storage volumes and downstream population and properties, it poses a higher risk potential in the project area [23]. The purpose of this study was to assess the slope stability of the Legeamara earthen dam using finite element-based GeoStudio software with different analysis methods i.e., American Crops Engineer #1 and #2, Ordinary, Bishop, Jambu, Morgenstern-Price, and Spencer methods and to find out the minimum factor of safety and to locate the critical slip surface location.

2. MATERIALS AND METHODS

2.1Description of the Study Area

The Legeamara earthen dam is located in, the Welaka subbasin of Abay basin at Borena Woreda, Ethiopia's north-central highlands, and the South Wollo Administration Zone of the Amhara Regional State as shown in Figure 1. The project location is 10043'21"N and 38043'47"E. It is located approximately 590kilometers north of Addis Ababa and southwest of Dessie town. The project site is approximately 5kilometers from Makenaselam, the capital city of Borena Woreda. It is a one-purpose dam that will irrigate 180 hectares of land. It was designed and built by the Amhara Water, Irrigation, and Energy Bureau and the Amhara Waterworks Contracting Enterprise, respectively.

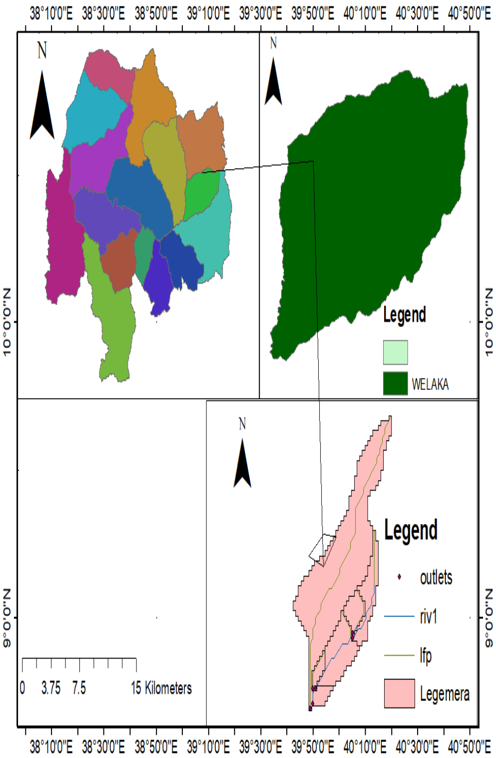

Fig.1 Location of the study area

2.1.1 Topography

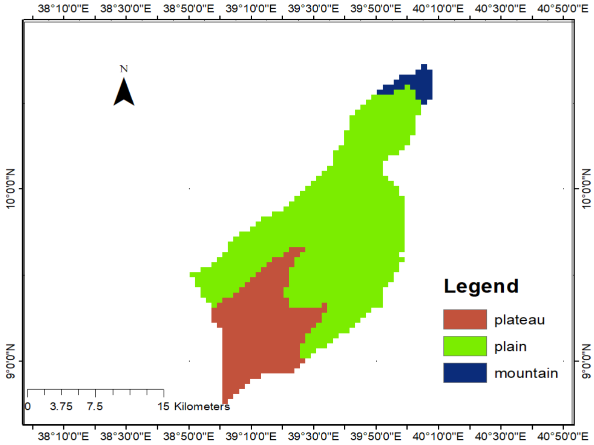

Fig. 2 Topography of Legeamara watershed

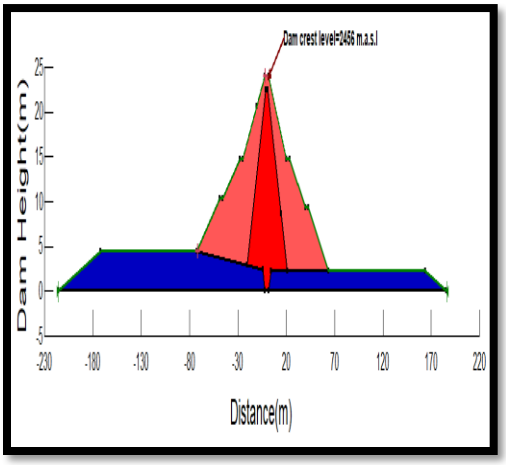

Fig.3 Legeamara main dam geometry model

The study's topography is composed of 65 percent plain, 25 percent plateau, and the remaining 10 percent mountains. The upper and middle parts of the catchment, on the other hand, are divided by a series of gullies. The upper catchments at the beginning of the stream have hilly and small mountainous landforms. In general, the catchment is characterized by an elongated shape with no significant sub-water sheds. The highest elevation of the Legeamara watershed is about 3184 m in its southeastern part. The lowest topography land is at the dam site, which is at an altitude of 2423m.

2.1.2 Main Features of Legeamara Earthen Dam and Reservoir

Table 1. Details of Legeamara dam

LegeamaraDam	
Dam type	Earth fill dam
Crest elevation	2456 m
River bed elevation	2432 m
Length of earthen dam	243 m
Maximum height of dam	21 m
Crest width of dam	4 m

The Legeamara dam is an earthen fill embankment dam, consisting of two the permeable zone (shell), one impermeable zone (core), and two a filter zone. Figure 2 shows a cross-section of the Legeamara dam which is modeled using GeoStudio software.

2.2 Data Collection

The first task of this study was gathering an important data and information related to the study area. Therefore, this study needs two basic pieces of data that were gathered using several data collection techniques.

2.2.1 Primary Data Collection

The primary data collected from the study area was used to cross- check the secondary data. Field observations were essential for; visiting the dam site, inspection of the present condition of the dam, interviewing site engineers, hydrogeologists, beneficiaries from the command area and contractors of the dam project.

2.2.2 Secondary Data Collection

The geotechnical parameter of the dam, the design document, the geometric parameter of the dam, the foundation material, and dam body material laboratory were collected from Amhara Water, Irrigation, and Energy Bureau (AWIE). The geological data, project completion report, and dam site map were collected from Amhara Water Works Construction Enterprise (AWWCE). To perform and achieve the objective of this study, the main important data were collected and taken from the design document are the profile of the dam, and the material properties of the dam body. The material engineering properties are the vital part of any geotechnical analysis about the slope stability of the dam.

The long periods, Numerical models were used as theory, due to the fast establishment of computer science most of the numerical models like Limit

Table 2.Geotechnical summarized data sets used for dam slope stability analysis

S.No	Material descriptions	Unit weight (tf/m^3)			kx = ky(m /s)	Cohesion, C (tF/m^2)	Ø (00)	OMC / FMC
		γ_b	γ_{sat}	γ_{sub}				
1	Foundation material	1.86	1.87	0.87	$8.9x 10^{-6}$	2.24	18	34
2	Core material	1.71	1.803	0.838	$1.52x10^{-7}$	1.83	20	33.88
3	Shell material	1.96	2.03	1.03	$1.06x10^{-5}$	0.61	33	19.02

2.3 Methods Used

Various analytical methods for slope stability analysis of the Legeamara earth dam under static loading conditions were developed in this study. Stability analysis, as the primary design criterion for stability calculation, can be evaluated using a variety of methods, including the Limit Equilibrium Method (LEM), which includes the Bishop Method, Force Equilibrium Method, Ordinary Method of Slices, Janbu Method, Morgenstern-Price Method, and Spencer Method. The analysis was performed in the program in SLOPE/W. The study area delineation was done using Arc-GIS software. To supplement this research, physical tools/equipment, and materials such as Geographical Position System (GPS), Digital Elevation Model (DEM), Residential documents (such as design, construction, and operational), and Geological and Soil maps, among others, will be used to assess the current performance of the Legeamara dam.

2.4 Model Simulation and Analysis

In-addition to the GeoStudio software, Arc-GIS 10.5 was used for delineation of the study area. To perform this study electronic physical equipment and like, global positioning system (GPS), digital elevation model(DEM), photo camera, topographic map of the study area, Microsoft excel, and word were used. Over Equilibrium and Finite Element model are used very widely in the world. For this study, the GeoStudio software extension slope/W were used carefully and the output of the software was compared with the project document and standards.

2.5 Slope Stability Analysis

The numerical methods are the more common methods of slope stability analysis in embankment dams depending on the elastic- plastic theories. In this study the numerical limit equilibrium methods such as American Crops Engineer #1 and #2, Ordinary, Bishop, Jambu, Morgenstern-Price, and Spencer methods were used. This was due to Considers both shear and normal inter-slice forces, satisfies both moment and force equilibrium, and Allows for a variety of user-selected inter-slice force function over other methods. Finally, minimum factor of safety was calculated on the basis simulated results obtained from the SLOPE/W software and discussed accordingly [25].

$$\text{FOS} = \frac{\text{C}+\sigma\text{n} \tan \emptyset}{\text{Cr}+\sigma\text{n} \tan \emptyset\text{r}} - - -(1)$$

where c and Φ are the input strength parameter and σn is the actual normal stress component. The parameter c_r and ϕ_r are reduced strength parameters that are just large enough to maintain equilibrium. The summarized loading conditions and a corresponding minimum factor of safety, FOS requirements proposed by USACE are presented in Table 3.

Table3.Minimum required factors of safety (USACE, 2003)

Case	Loading conditions	Critical slope	FOS
I	End of construction	Upstream	1.3
		Downstream	1.3
II	Sudden drawdown	Upstream	1.3
		Downstream	1.3
III	Steady state	Upstream	1.5
		Downstream	1.5

3. RESULTS AND DISCUSSIONS

The SLOPE/W software used to get the slope stability of the dam at the upstream and downstream slope and cheek by different slope stability methods in limit equilibrium modeling accordingly. In this study, the analysis was carried based on the effective stress. Pore pressures for various loading conditions were estimated as subsequently described. For each case analysis the critical slip surface yielding the minimum safety factor was found by rigorous search. The section at which the dam height becomes maximum is selected for stability analysis, because this is the critical section for stability as compared to others and will give the minimum factor of safety. From SLOPE/W simulations it may be noted that the minimum safety factors on all loading cases were having critical surface near outer faces only, and location of the critical slope surface along with the safety factors obtained by different methods (American Crops Engineer #1 and #2, Ordinary, Bishop, Jambu, Morgenstern-Price, and Spencer methods). The obtained factor of safety (FOS) from all the above methods are compared with the limit of United States Army Corps of Engineer (USACE) and British Dam Association (BDS).

3.1 Slope Stability Analysis at End of Construction

Both upstream and downstream slopes are analyzed for end of construction. The pore pressures which remain in the filling material of upstream and downstream shells at the end of construction depend on the placement moisture content, the pore pressure response to loading at the relevant stress and moisture content, the rate of dissipation and the rate of construction. Considering the free draining nature of filters blanket, it is assumed that no construction pore pressures will develop in these zones. It is also assumed that the foundations will not be saturated during construction and will therefore not develop pore pressure. Typical results for upstream slope and downstream slope after the construction of dam with minimum safety factor ranges from (2.098-2.246) and (1.93-2.003) respectively for all limit equilibrium slope stability analysis methods. From this result, the dam is stable for all methods of analysis because of its factor of safety result is within the range of United States Army Corps of Engineer (USACE) and British Dam Association (BDS) as shown in the Table 3 and in Figure 4.

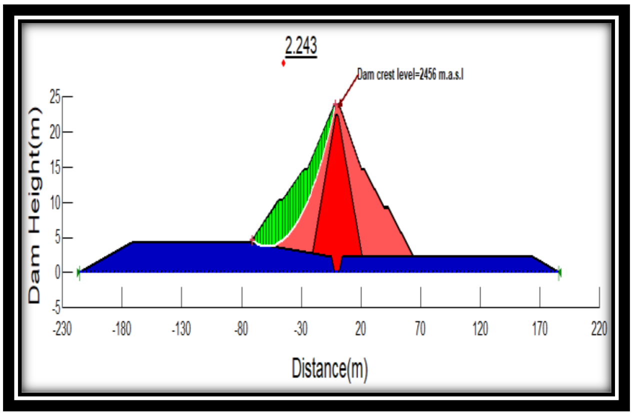

Fig.4 FOS for upstream slope by Morgenstern-price method (End of construction)

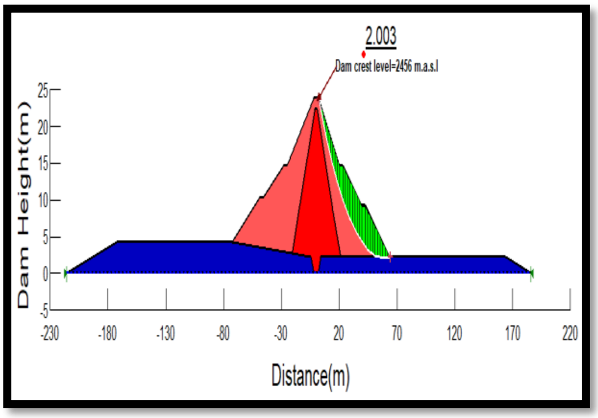

Fig.5 FOS for downstream slope by M-price method (End of construction)

3.2 Slope Stability Analysis under Steady-State Seepage

The reservoir is full long enough for seepage water to percolate through the embankment in this condition, and the pressure in the pore water in the downstream portion reaches its maximum value. A phreatic surface within the embankment has been established to compute the slope stability analysis. The steady-state seepage state is first established through seepage analysis. The drained (effective) stress strength parameter was calculated using the Mohr-Coulomb failure criterion by the standards of the various agencies.

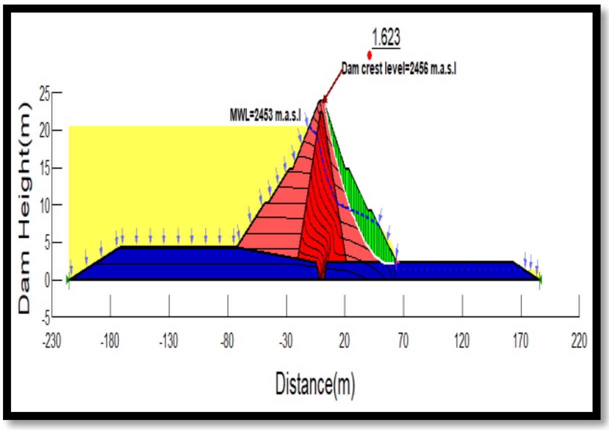

Fig.6 FOS for downstream lope by M-price method (Steady state condition)

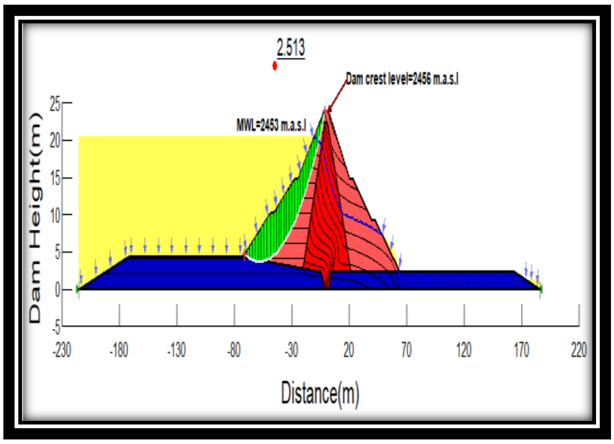

Fig.7 FOS for downstream slope by M-price method (Under steady-state seepage)

The results of the SEEP/W steady-state seepage analysis are used as the parent analysis input for the SLOPE/W limit equilibrium analysis. The stability of the downstream slope is critical in most cases at steady seepage, and the results of a factor of safety with its slip surfaces using the Morgenstern-Price method are shown in Figure 5 and Table 4below. The slope stability analysis result from the all-limit equilibrium methods analyzed in this study ranges from (2.074-2.819) upstream slope and (1.347-1.653) downstream slope.

3.3Rapid Drawdown Condition Stability Analysis

For the case of rapid drawdown, it is assumed that reservoir will be at maximum conservation level i.e., at EL 2445 m for a sufficiently long time so that the steady seepage condition will develop in the dam embankment and reservoir is rapidly emptied. In a rapid drawdown case, stability will be critical for the upstream slope and downstream slope. The pore pressures under rapid drawdown are estimated assuming no dissipation of pore pressures in the shell. All other embankment zones are assumed to be free draining. Summary results of slope stability analysis using all limit equilibrium slope stability analysis method along with minimum acceptable safety factors as adopted in the design criteria are shown below (Table 3) and Figure5. The result revealed that the factor of safety ranges from (2.14-2.295) upstream slope and (1.976-1.985) downstream slope from all limit equilibrium methods analyzed for this study. From the results of the performed slope stability analysis by limit equilibrium methods analyzed in this study, it can be concluded that the dam satisfies all the requirements of USACE, and BDS recommendations as shown in Table 3 above. Therefore, the Legeamara dam shows safe against slope failure at all three loading under the static condition.

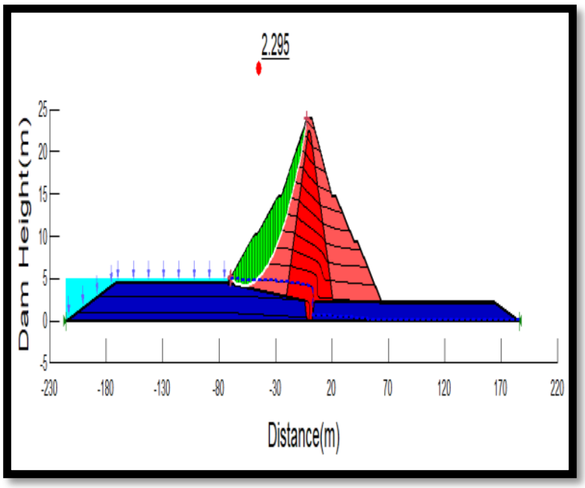

Fig.8 FOS for upstream slope, during rapid drawdown using M-P Method.

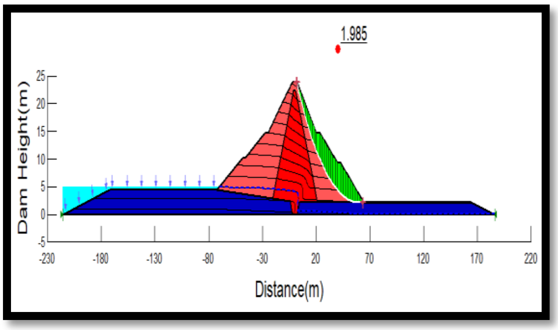

Fig. 9 FOS for downstream slope, during the rapid drawdown, using M-P method

state seepage (upstream and downstream slope) at maximum water level at EL 2449 m, and rapid draw-down for (upstream and downstream slope) with minimum factor of safety 2.099, 1.93, 2.07, 1.35, 2.14, and 1.91 respectively taken from all methods the minimum value accordingly. The detailed summary results of safety factor for stability slope analysis of Legeamara earthen dam are elaborated in Table 4

Table 4.Summarized results of Legeamara dam slope stability analysis using GeoStudio

S.No.	Analysis Type	End of Construction		At steady State		Rapid Drawn	
		U/S	D/S	U/S	D/S	U/S	D/S
1	Crops engineers #1	2.101	1.991	2.074	1.641	2.14	1.981
2	Crops engineers #2	2.09	1.995	2.192	1.542	2.150	1.976
3	Spencer	2.246	1.973	2.803	1.347	2.283	1.981
4	Ordinary	2.137	1.93	2.819	1.49	2.206	1.981
5	Bishop	2.262	2.003	2.831	1.653	2.289	1.976
6	Janbu	2.098	1.947	2.318	1.504	2.20	1.914
7	Morgenstern-P	2.243	2.003	2.51	1.527	2.295	1.985
8	USACE	1.3	1.3	1.5	1.5	1.3	1.3
9	BDS	1.2	1.1	1.25	1.25	1.25	1.25

4. CONCLUSION

The limit equilibrium SLOPE/W software was used to perform static slope stability analysis of Legeamara ear then dam based on the Ordinary, Bishop, Janbu, Morgenstern-Price, and Spencer methods safety factors. The simulation results show that the upstream and downstream side of the dam section has a direct effect on the factor of safety. The analysis has been carried out in terms of effective stresses conditions. The three different loading condition were analyzed i.e., end of construction (upstream and downstream slope), steady The stability analysis results revealed that the dam's critical upstream and downstream slopes are safe within the prescribed United States Army Corps of Engineer (USACE) and British Dam Association (BDS) range of safety factors for the specified loading and operation cases.

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