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Evaluation of seepage and slope stability analysis of embankment dam: a case study of Shimburit micro earthen dam, Amhara region, Ethiopia

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ABSTRACT

Nowadays, the primary and most significant reason for ensuring the overall safety of earthen dams is to monitor seepage and slope stability. This study was carried out to evaluate the static condition seepage and slope stability performances of the Shimburit earthen dam, which is located in the Amhara National Regional State, eastern zoning of Gojjam, D/Elias woreda, in particular kebele of Yegdad and Yekomit. PLAXIS 2D software was used to investigate the seepage and slope stability of the dam under various loading conditions in this study. The PLAXIS 2D program was used to simulate seepage analysis, which included determining the quantity of discharge per unit length, pore water distribution, and the location of the phreatic line. The maximum cross-section of the Shimburit main dam is expected to have a seepage flow rate of 10.31×10^{-6} $m^3/s/m$ through the dam body and 28.06×10^{-6} $m^3/s/m$ through the foundation at normal pool level without an upstream filter. Pore water pressure is zero at the normal pool level and 262.60 KN/m^2 at the bottom of the boundary condition. The phreatic line emerged below the toe of the dam. This means that the dam is not at risk of sloughing. The most critical element affecting the stability of an earth dam is seepage. Three different loading conditions are studied for stability analysis: end-of-construction, steady-state seepage, and rapid drawdown. The FOS values obtained at the end of construction, steady-state, and rapid drawdown conditions were 1.5631, 1.4441, and 1.2338, respectively. As the loading situation increases, the factor of safety results drops, i.e. 1.5631 > 1.4441 > 1.2338. All the factor of safety is greater than one, therefore, the dam is safe at all critical conditions, or the probability of failures of the dam will not be likely to happen. Using recognized design standards such as the USACE, USBR, NRCS, and BDS, the dam is found to be stable under all critical loading conditions.

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***Keywords*:** Dam, Seepage, Slope stability, PLAXIS 2D, Amhara regon

1. INTRODUCTION

A dam is a hydraulic structure constructed across a stream, river, or waterway to confine and control the flow of water. Dams are built for specific functions such as water supply, irrigation, and flood control and also to generate hydroelectric power (Heibaum, 2014). There are two types of modern dams namely embankment and concrete dams. An embankment dam is a water impounding structure constructed from fragmental natural materials excavated or obtained close to the dam site. The natural fill materials are placed and compacted without the addition of any binding agent, using a high-capacity mechanical plant. They rely on their weight to resist the flow of water, just like concrete gravity dams (Alonso & Cardoso, 2010).

Subsequent monitoring of seepage and slope stability is the primary and the most important reason to ascertain the overall safety of earthen dams. Earth fill dam must remain stable under all conditions. Because these types of dams have a greater susceptibility to hydraulic, seepage, and structural failure, this main cause such as improper design, lack of thorough investigations, inadequate care in operation, and poor maintenance must be avoided (Song *et al*. 2021). Embankment dams derive their strength from the position, internal friction, and mutual attraction of particles. Relative to concrete dams, embankment dams offer more flexibility, and hence can deform slightly to conform to deflection of the foundation without failure and it consist of homogeneous earth-fill dam, zone type rock-fill dam, impervious core type rock-fill dam, facing type rock-fill dam, roller compacted concrete (RCC) dam, and also blasted rock-fill dam. Besides that, types of concrete dam consist of concrete gravity-type dam, masonry dam, arch type dam, buttress type dam, and trapezoidal-shaped cemented sand and gravel (CSG) dam (Wan & Fell, 2004).

The Shimburit dam was identified and studied by the organization called Amhara national regional state water resources development bureau starting from reconnaissance level to feasibility study level with the goal of food security and improving the living standard level and alleviating the food shortage problems of the drought-affected area of the Amhara Region State, east Gojjam zone, woreda Debre Elias at particular kebele of Yegdad and Yekomit through the use small scale irrigation project, to promote and encourage sustainable agricultural crop production. The dam was built to irrigate 425 ha of command area. Therefore, this study aims to evaluate the seepage and slope stability analysis of the Shimburit earthen dam.

2. MATERIALS AND METHODS

2. 1. Description of the study area

2. 1. 1. Geographical location

Shimburit micro earth-fill dam, the selected study area, reservoir, and its command area is located in the Amhara national regional state, eastern zoning of Gojjam, D/Elias woreda at particular kebele of Yegdad and Yekomit. The geographical coordinate of the dam site using UTM zone 37 is 1147435 m Northing and 324785 m Easting with an average altitude of 2690 m.a.s.l, which is Debre Markos city nearest the study area at a distance of around 30 km.

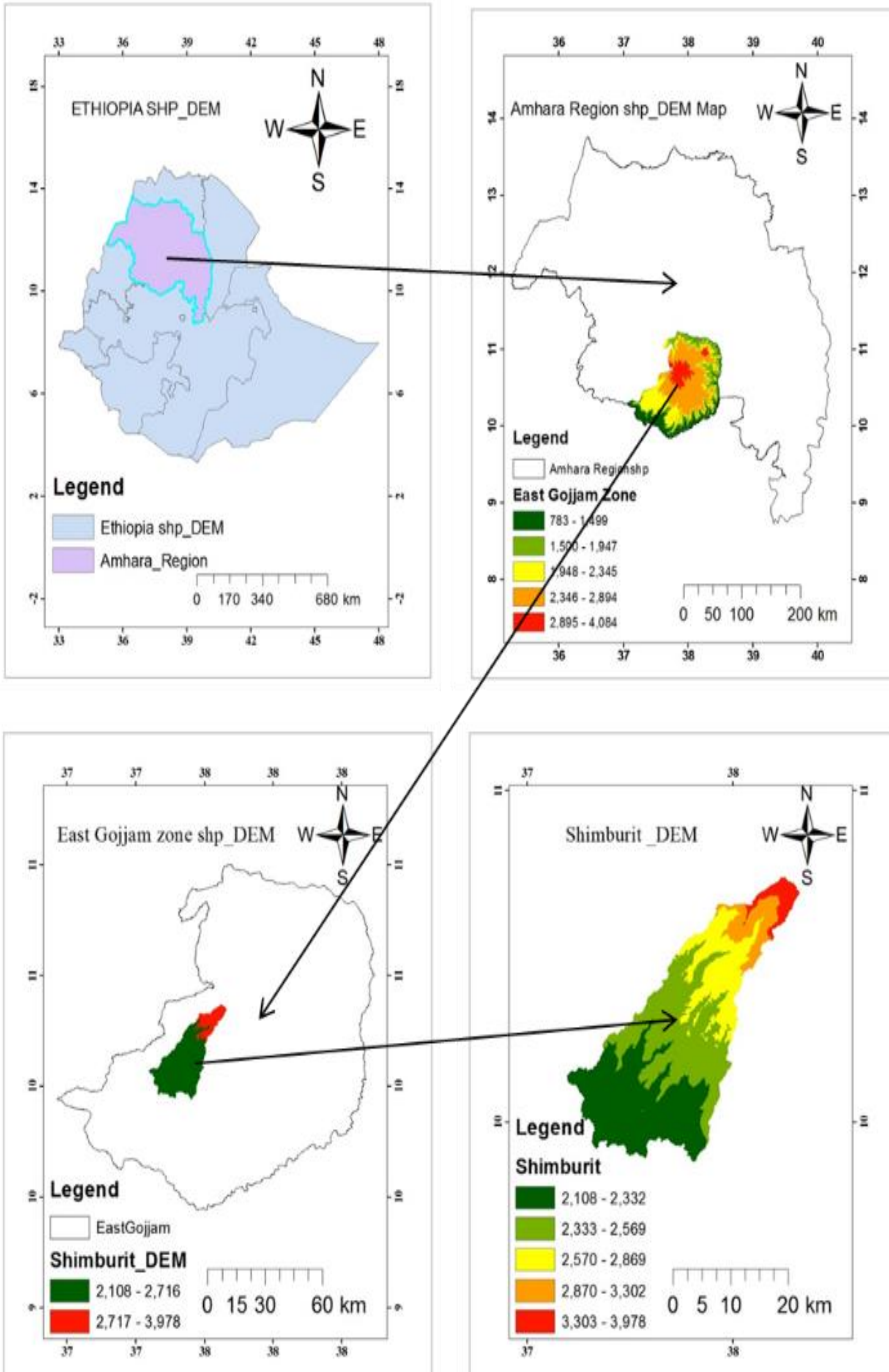

Figure 1. Geographical location map of Shimburit earth-fill dam

2. 1. 2. Salient features of Shimburit dam and reservoir

The type of Shimburit dam is a homogenous type micro earth-fill dam that is constructed for irrigation. The crest length of the dam was 312.5 m and with the maximum dam, height was 16.00 m.

Table 1. Dam and spillway dimension.

Dam type	**Homogenous micro earth-fill dam**
Dam crest length (m)	312.5
Dam height (m)	16
Gross Free board (m)	2.50
Peak discharge (m^3/s)	107.5
Spillway control type	Broad crested weir
Spillway crest length (m)	10
Number of the outlet pipe	One
Pipe length (m)	72
Capacity (m^3/s)	0.74
Reservoir area (ha)	48
Full irrigation(ha)	425
Minimum drown dawn level (MDDL)	2123 m. a. s .l
Design year	25

2. 1. 3. Land use and land cover

The major land-use types in this watershed area are cultivated land, free grazing land, forest land (area closure), and miscellaneous land. The dominant land use type is free grazing land that covers more than 90 % of the total area. It has moderate vegetation cover. The second-largest land-use type that has good vegetation cover is forest land, which covers 23%. It is situated dominantly on moderately steep terrain. This includes shrubs, bushland, and woodlands. The miscellaneous land that has an area of 2 ha represents areas occupied with gullies, footpaths, dry weather roads, rocky outcrops, and rivers (Asmare & Tesfa, 2021).

2. 1. 4. Climate

There is a meteorological station operated by the national meteorological services agency (NMSA) at Debre-Markos city that lies at an altitude of 2690 m a.s.l. This is the nearest and most representative station for the project area. The rainfall direction of the area is from the Debre Markose side that is why we just adopt Debre-Markos metrological station for different input calculations. The estimated air distance b/n the metrological station and the actual site are around 30 km (Belay, 2019).

The climatic data elements observed at the station are rainfall, daily temperature, daily heaviest fall, wind speed, relative humidity, sunshine hours, and radiation. Summarized data of wind speed, relative humidity, and sunshine hours are obtained whereas monthly data of rainfall, daily temperature, and daily heaviest fall of years of record are available for our project analysis.

2. 1. 5. Site geology

Most of D/Elias woreda and vicinity of the area is covered by volcanic rocks of aphanitic and trashy basalt, tuff, and consolidated red ash rock formations. Like the other parts of the Woreda, the areas around Shimburit micro earth dam project and its catchment are dominantly covered by volcanic rocks of aphanitic and highly vesiculated trashy basalt, tuff, and consolidated red ash. Especially all parts of the dam axis and most parts of the reservoir area (both right and left parts) are covered by highly vesiculated and weathered tranche basalt rock and this rock is continuous on both sides (upstream and downstream) the project site and around the spillway site. While the ridge lands which are found on the left reservoir and upstream ends are covered by highly weathered basalt rock and there is a local dyke, which surrounds the pick land (Addis & Abebaw, 2017).

2. 2. Data collection

2. 2. 1. Secondary data

Essential input data for the PLAXIS such as; Geometrical design of the dam, Geotechnical parameters of the embankment and foundation materials from laboratory testing, Geological reports and maps of the dam site and reservoir interfaces are collected from the Amhara Regional State Bureau of Water Resources in collaboration and collected Water Works Design and Supervision Enterprise.

The geometry of the structure and the related upstream and downstream water levels, Construction Material property (Unit weight, Angle of internal friction, Cohesion of soil, saturated unit weight) from Laboratory Testing for Core Material, Rock Fill Material, Foundation Material, Main Dam, Aggregate, Filter and Rip rap, Guideline, Manuals, the standard design of small dams, medium and large embankment dam, Detail description of all materials in the embankment foundation and reservoir abutments such as soil structure, stratification, continuity of strata, bedrock profile and moisture content, and dam monitoring instrument readings are collected from the Bureau Of Water Resource Development, Water Works Design, and Supervision Enterprise and the site.

2. 3. Data analysis

To achieve the objective of this study Shimburit micro-earthen dam which has a problem of seepage and slope stability it is considered to use the PLAXIS software model to analyze the seepage and stability slope failure of the dam. Most of these software programs can be coupled with each other, to enable the results of one software program to be used as the input data for another.

2. 4. Model selection and setup

Nowadays numerous finite element-based software is implemented to evaluate the performance of embankment dams, natural engineering slopes, groundwater flow. To achieve the objectives of this study, finite element-based PLAXIS software was employed. This model is selected upon the easiness of its application, ability to solve complicated geometries, loadings, and material properties when compared with other applications. Accordingly, the zipped setup of PLAXIS software was extracted and installed as a full version in the acceptable Window 10 computer.

2. 5. Model simulation and analysis

For this study, data to simulate these results design parameters and dam geometry is given as input to the PLAXIS software to compute the unknown parameters. Meshing is closely tied to this model and various mesh sizes are attempted to select based on the unnecessarily time-consuming and difficult to interpret results.

2. 5. 1. Seepage analysis

In this research, the finite element method-based computer program PLAXIS was used to simulate the steady-state seepage analysis through the embankment materials. PLAXIS results are calculated using the governing differential equation used in finite element formulation which is written as:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ky\frac{\partial H}{\partial y}\right) + Q = 0 \qquad (1)$$

where: Q is the applied boundary flux, Kx is the horizontal coefficient of permeability and Ky is the vertical coefficient of permeability of soil and H is a total head of water.

General considerations and analysis procedures

Before the simulation, the dam was analyzed for steady-state seepage and rapid drawdown conditions, by taking the reservoir water level at different levels taking the demanded hydraulic conductivity values of the embankment and foundation material.

a) Determination of boundary conditions

For modeling the seepage analyses using the finite element method PLAXIS boundary conditions are essential. In seepage analysis with PLAXIS, there were two fundamental boundary conditions namely, the head boundary condition and the flux boundary condition (Uromeihy & Barzegari 2007). Accordingly, in the seepage simulation of the Shimburit earthen dam, two different scenarios of head boundary conditions have been used. The water level in the reservoir and downstream face of the dam was taken as a head boundary condition and potential seepage face respectively and finally the earthen dam was simulated for the steady-state condition. In case of sudden drawdown, the elevation differences in the reservoir water level are due to rapid drawdown. The upstream face was considered as a flux boundary condition and the downstream face as a potential seepage face and finally, the earthen dam was simulated for the transient state condition.

After the result of the model, the location of the phreatic line, seepage flux (discharge), and pore water pressure distribution for the above head boundary conditions was determined.

b) Determination of phreatic line, pore water pressure, and quantity of seepage

A seepage line is used to estimate the amount of seepage passing through the body of the dam with a horizontal filter. The first step is the determination of the phreatic or seepage line of the dam (Touri et al., 2015). In the design document, the amount of seepage is estimated for the Shimburit dam with a horizontal filter by considering the dam as homogenous. The available data obtained from the design document for estimating seepage is the geometry of the dam and the permeability coefficient of core and shell material.

Phreatic line or seepage line is the line at the upper surface of the seepage flow at which the pressure is atmospheric. For Shimburit dam determination of seepage through the dam body, pore water distribution, and determination of phreatic line was done using finite elements PLAXIS model.

Outcomes of the steady-state and transient seepage analysis were then used to determine the location of phreatic lines, seepage quantity, and pore water pressure distribution on the respective reservoir water level. Besides, the computed PLAXIS results are then used as coupled input for the PLAXIS to analyze the slope stability.

2. 5. 2. Slope stability analysis

The stability of an earthen dam depends on the behavior of the embankment fill and foundation materials. Thus, procedures for static slope stability are well established and have been concisely documented by (Duncan *et al*. 1987). Duncan recommended that evaluation of a slope focus on defining geometry, shear strengths, unit weights, pore water pressures, and imposed loadings.

The analytical method for evaluating the static stability of an embankment method that had been utilized in the analysis is consistent with the anticipated mode of failure, dam cross-section, and soil test data.

Accordingly, stability analyses had been carried out to determine the factor of safety for various critical slip surfaces. This stability of the upstream and downstream slopes of the embankment is analyzed for the most critical or severe loading conditions that may occur during the life of the dam. These loading conditions typically include (1) End of Construction, (2) Steady-State Seepage, (3) Rapid (or Sudden) Drawdown.

General considerations and slope stability analysis procedures

To achieve the slope stability analysis, the following procedures are considered.

a) Defining slip surface for circular failure model

After the material inputs and PLAXIS, coupled pore water pressure was assigned, a slip surface command was defined. From these several methods that are commonly used to define the slip surface for the circular failure mode the entry and exit method was selected (Khadija et al., 2012). This is due to the entry and exit command being relatively accurate when compared with the other commands and it allows the user to identify slip surfaces without difficulties by specifying the assumed portion of the surface where the slip surface will enter and exit.

b) Safety criteria

Safety evaluation of embankment dams should satisfy the recommended criterion by safety regulations or codes issued by authorized agencies. Among the numerous dam safety regulation, both (USACE, 2003) and (BDS, 2010) criteria are considered as the standard for their broad area of validation in the present studies. From this various standard of safety criterion, the most commonly utilized standards (USACE, 2003), (USBR, 2011), and (BDS, 2010) are used to validate the factor of safety of this study. Tables 2 shown below present the safety criteria of stability factor of safety for different cases of operation.

Table 2. Safety criteria standard of various enterprises.

Agency	Loading condition	Stress parameter	FoS
(USACE, 2003)	End of Construction	Total and Effective	1.3
	Long term (Steady seepage condition)	Effective stress (Drained)	1.5
	Rapid drawdown	Total and Effective	1.2
(USBR, 2011)	End of Construction	Total and effective stress	1.3
	Long term (Steady seepage condition)	Effective stress (Drained)	1.5
	Rapid drawdown	Effective stress (Drained)	1.3
(NRCS, 2005)	End of Construction	Total stress for impervious layer effective for the previous layer	1.4
	Long term (Steady seepage condition)	Total and effective stress (Drained and Un-drained)	1.5
	Rapid drawdown	Total and effective stress (Drained and Un-drained)	1.2
(BDS, 1994)	End of Construction	Total stress (Un-drained)	1.3 to 1.5
	Steady seepage condition	Effective stress (Drained)	1.3 to 1.5
	Rapid drawdown	Total stress (Un-drained)	1.2 to 1.3

2. 6. Overall procedure in schematic diagram (conceptual framework)

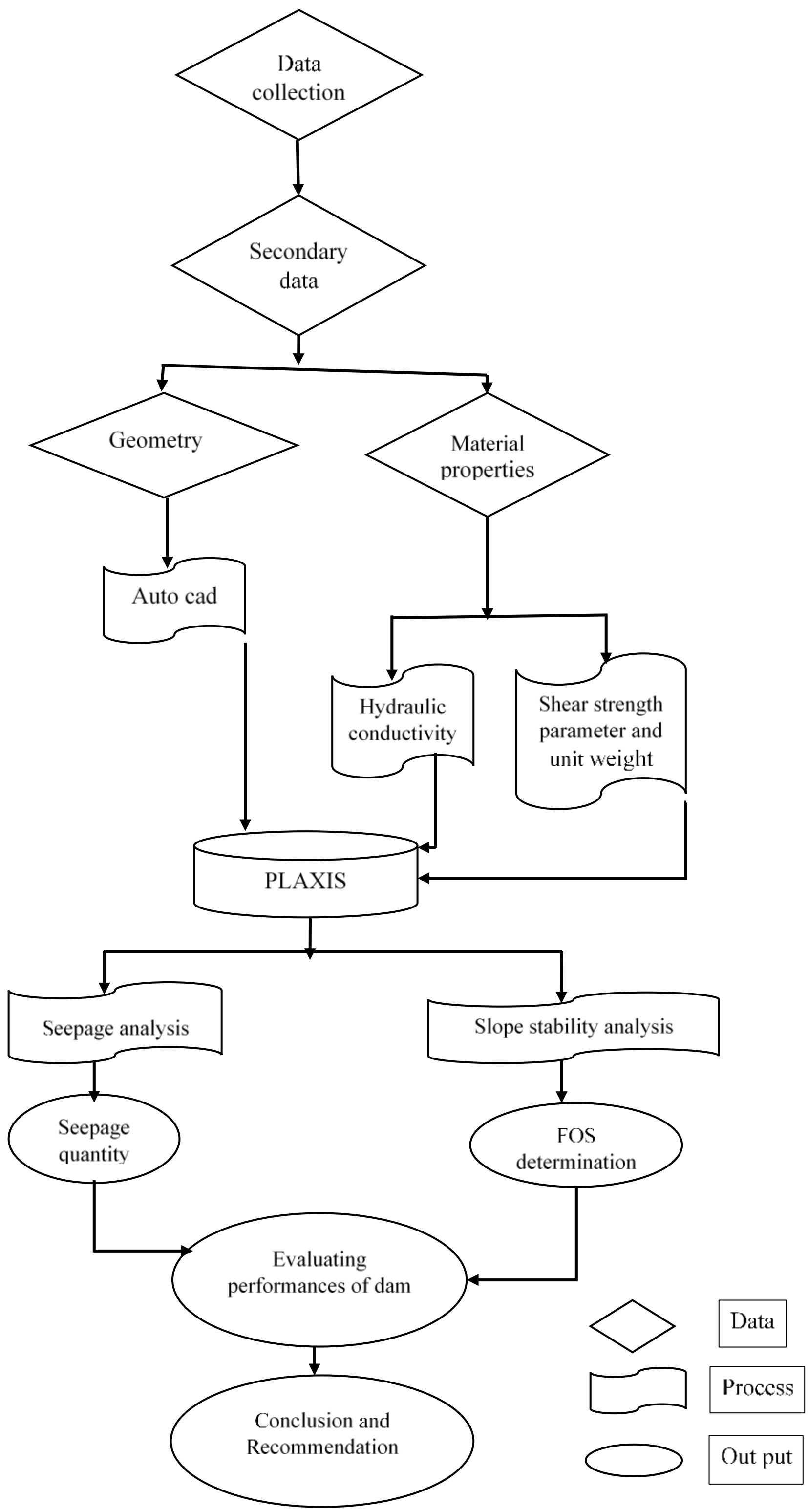

Figure 2. Conceptual framework showing the methodology followed in this study.

3. RESULTS AND DISCUSSIONS

3. 1. Seepage analysis and results

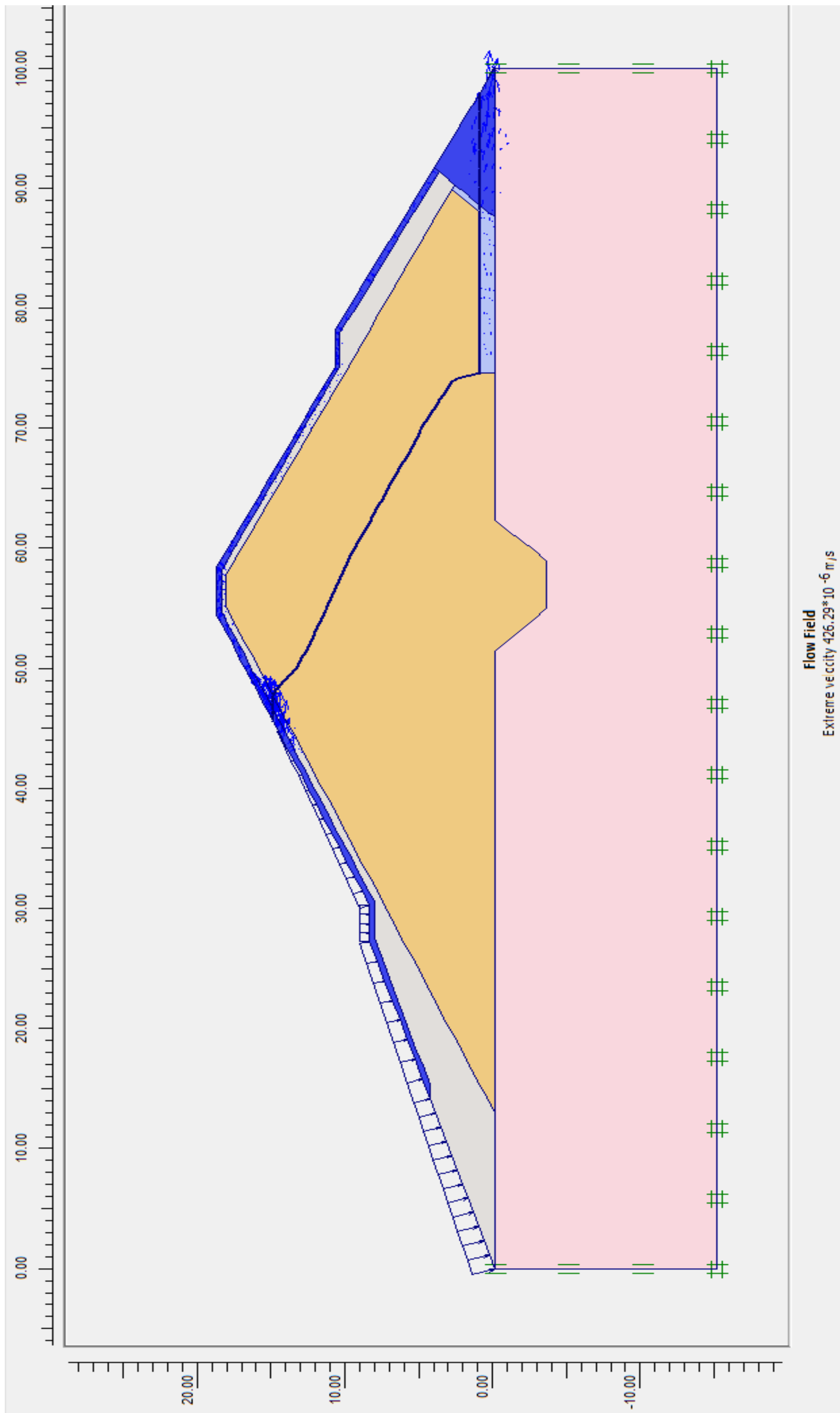

Figure 3. Location of the phreatic line at normal pool level

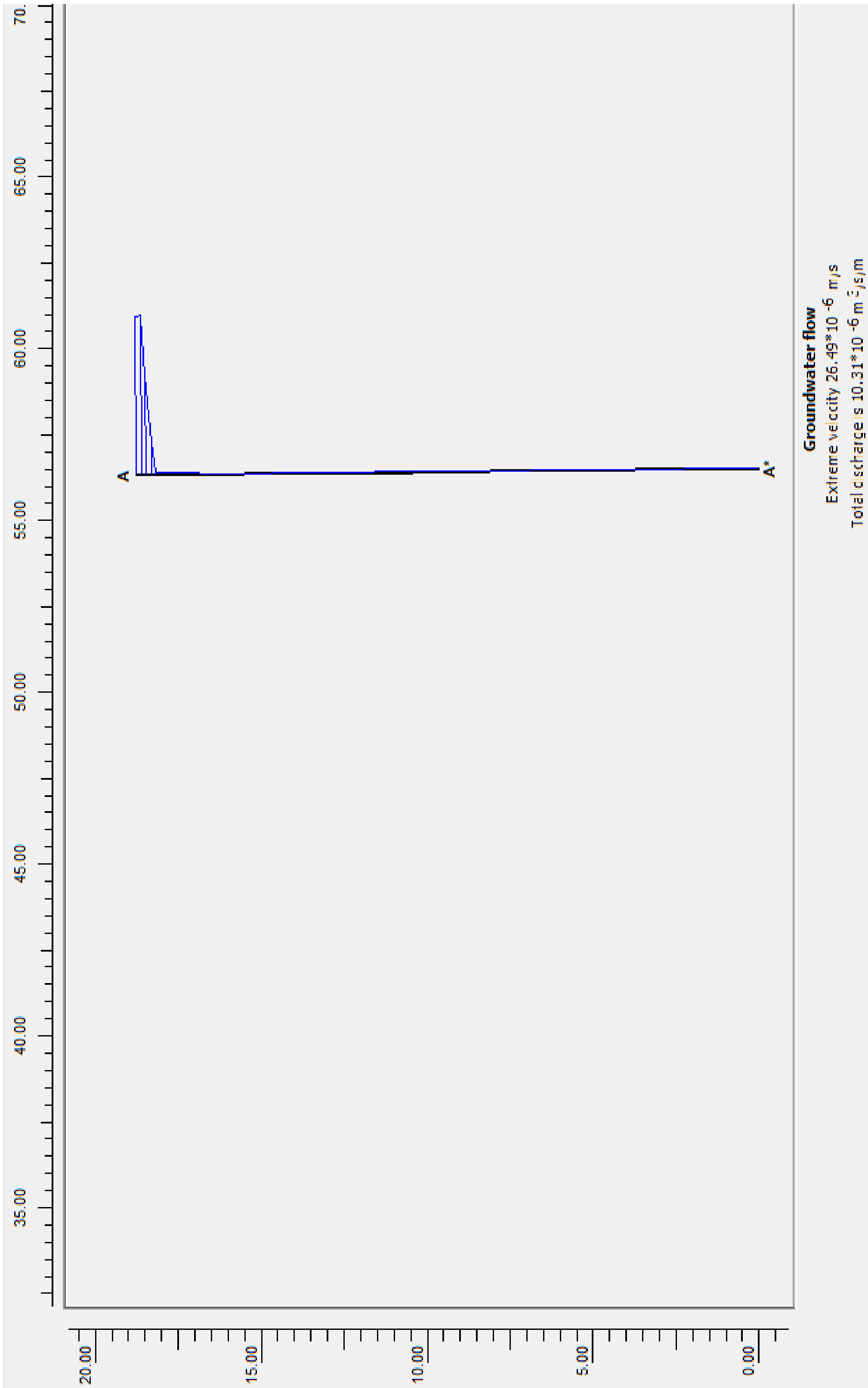

Figure 4. Seepage quantity through the main body of the dam

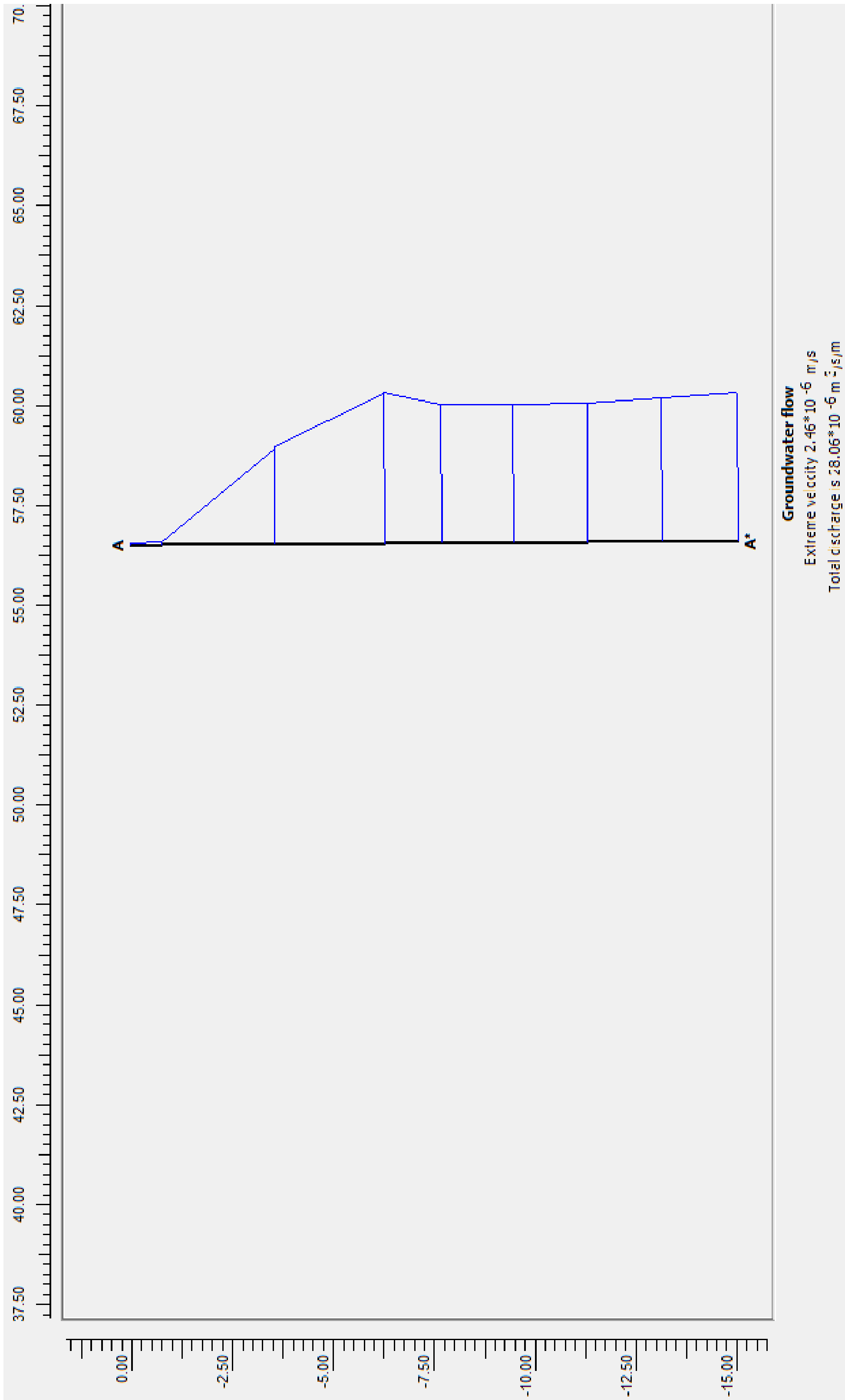

Figure 5. Seepage quantity through the foundation of the dam

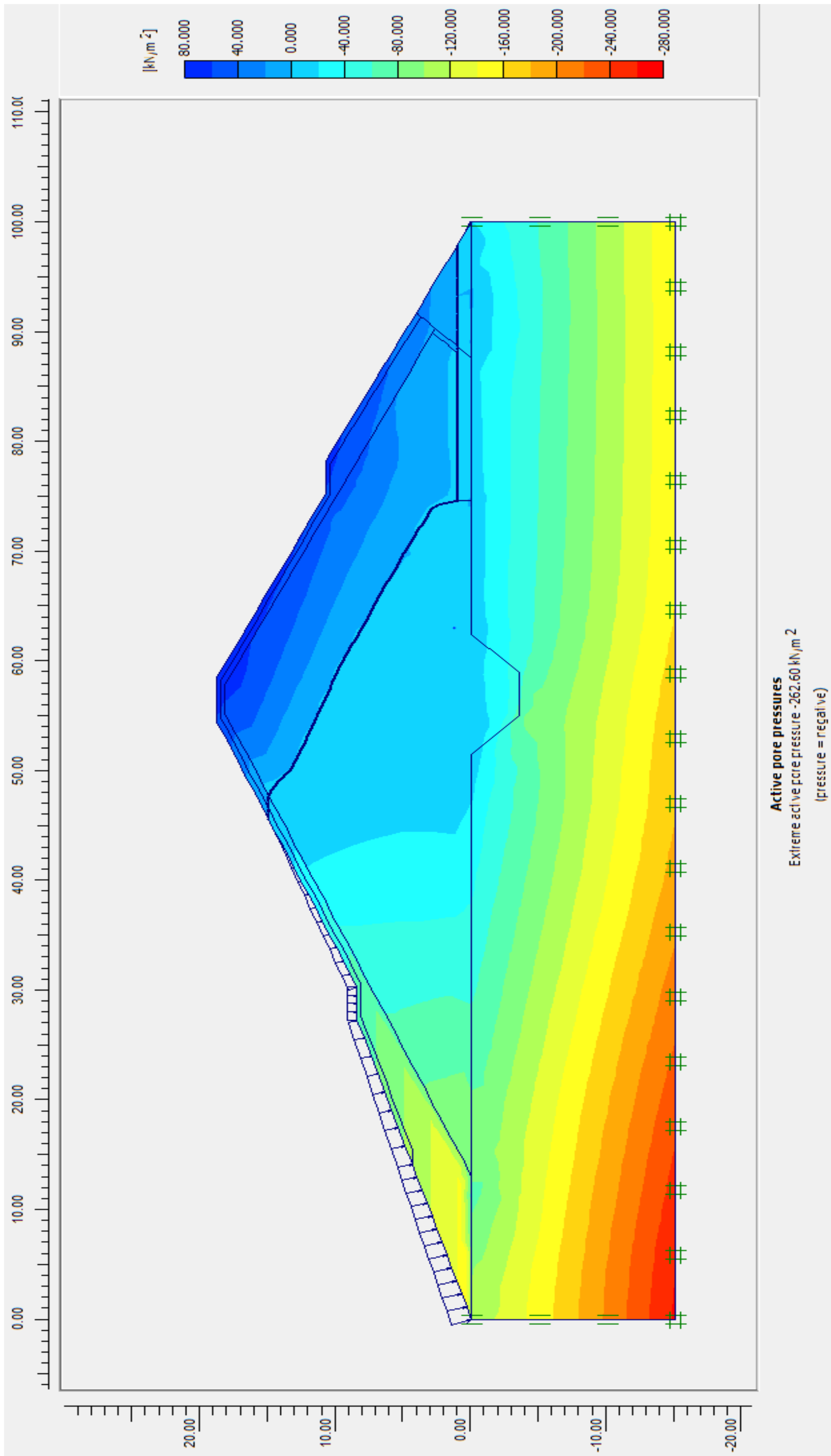

Figure 6. Pore water pressure distribution of the dam body and foundation

The analysis of flow rate through construction materials, as well as the hydraulic balance of the dam and the amount of water discharging from the base and body of the dam, is one of the most essential components of both earth and rockfill dams. During normal pool level (Elevation = 2130 m) the impoundment condition is the maximum active storage. The results of seepage analysis are presented with both the maximum cross-section of the dam and the entire dam body.

The phreatic line and seepage quantity through the dam body and foundation are presented in the model's Finite element mesh. The blue line that crosses the dam represents the phreatic surface (zero pressure line). The phreatic line is inside the transition filter's downstream range. Below the dam's toe, the phreatic line appeared. This means the dam will not fail due to sloughing, which is the most common cause of dam failure downstream.

The seepage quantity through the body of the dam was studied (Figure 4). The quantity of seepage through the main body of the dam is 10.31×10^{-6} $m^3/s/m$ and extreme velocity is 26.49×10^{-6} m/s. The quantity of seepage through the foundation of the dam is 28.06×10^{-6} $m^3/s/m$ and the extreme velocity is 2.46×10^{-6} m/s (Figure 5).

The pore water pressure distribution was also simulated in this study, and it was found to be as expected, with a minimum at the top and a maximum at the bottom corresponding to the depth of water increment. It's very high below the reservoir's surface. Pore water pressure is zero and 262.60 KN/m^2 at normal pool level (2130 m) and bottom of boundary condition (2123) a.m.s.l, respectively. The pore water pressure distribution and groundwater head are shown in the figures below.

3. 2. Slope stability analysis

In this analysis, three different cases of operation; the end of construction, steady-state seepage, and rapid drawdown are considered. The stability of slopes is influenced by soil parameters such as cohesion, friction angle, and unit weight of the soil. The pore developed either in the dam body or in the foundation, the characteristics of the foundation and fill materials, the geometry of the embankment section, and other factors such as the presence of water, loading conditions, and so on all affect the stability of an embankment dam. A safety factor represents slope stability against the risk of sliding (FOS).

3. 2. 1. End of construction

Significant pore pressure development in the embankment body and foundation is expected at the end of construction, either due to rainfall or compaction water. The upstream and downstream slopes' stability at the end of construction is critical in this case. So, using FEM-based PLAXIS software, the slope stability of the Shimburit embankment dam was evaluated under this loading scenario, with the results shown in Figure 7.

The stability results are expressed as a factor of safety (FOS). The FOS values are plotted on the y-axis, while the displacement is plotted on the x-axis in the diagram below.

The FOS obtained at end of construction shows 1.5631.

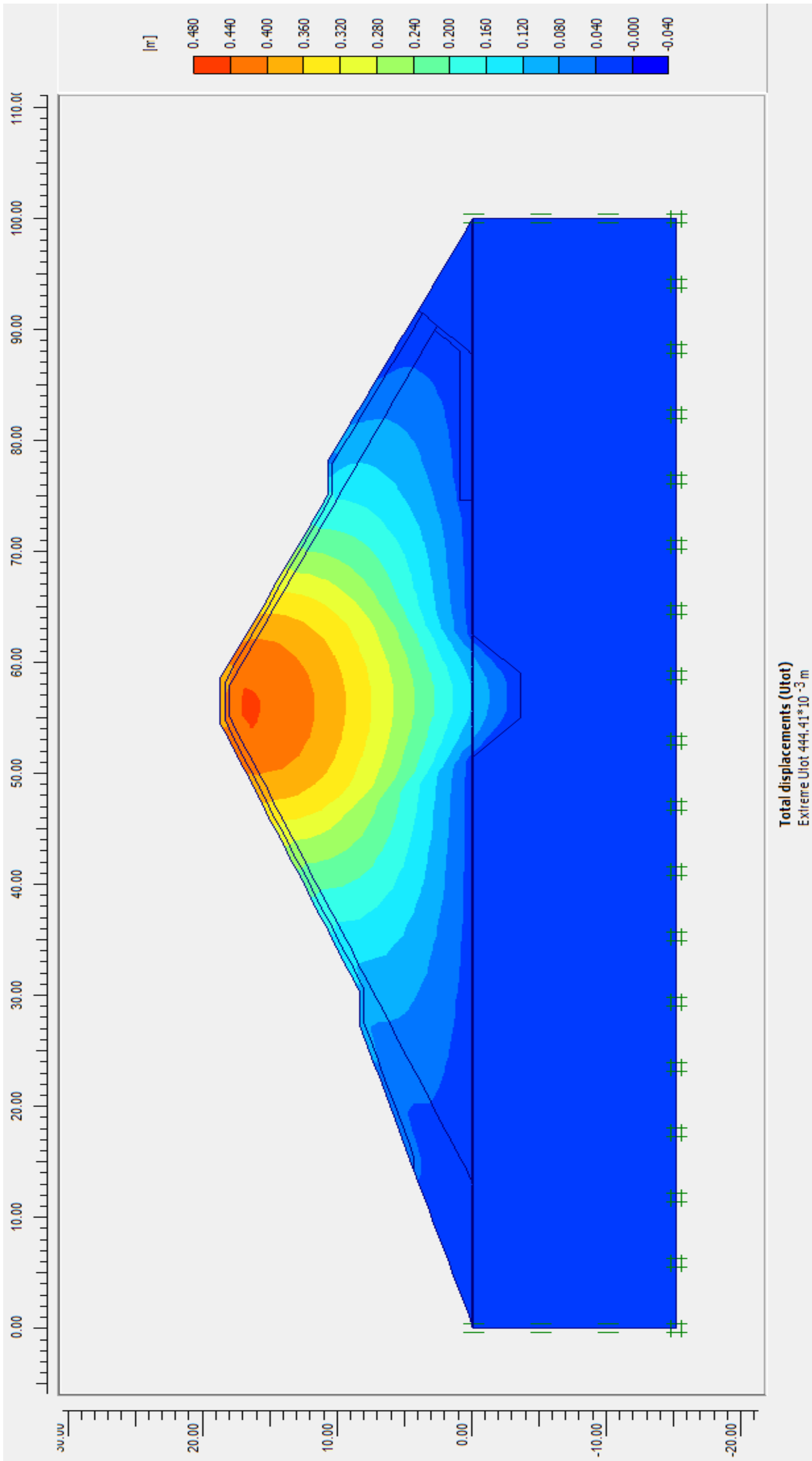

Figure 7. Total displacements during the end of construction

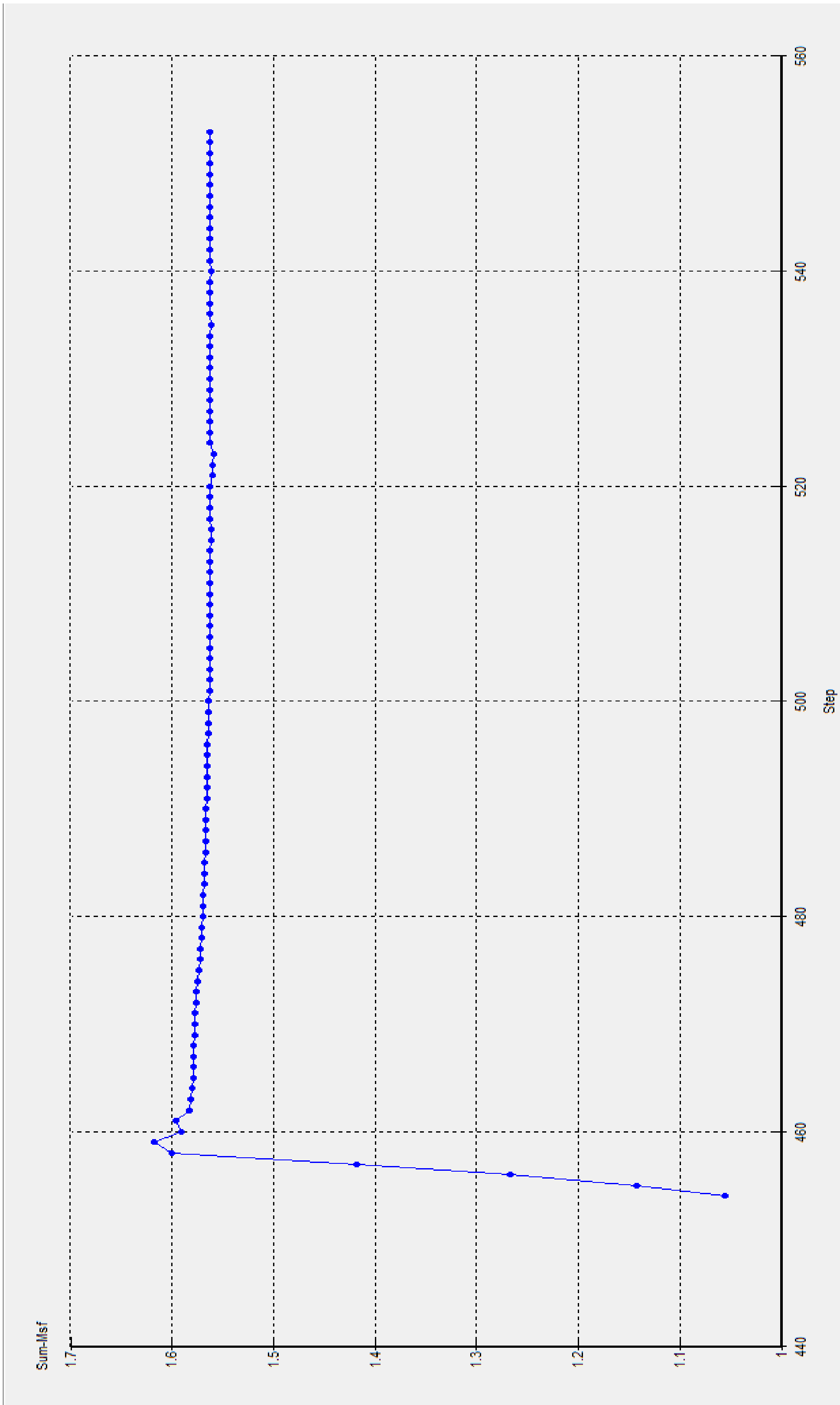

Figure 8. Factor of safety chart for the end of construction

3. 2. 2. Steady-state seepage

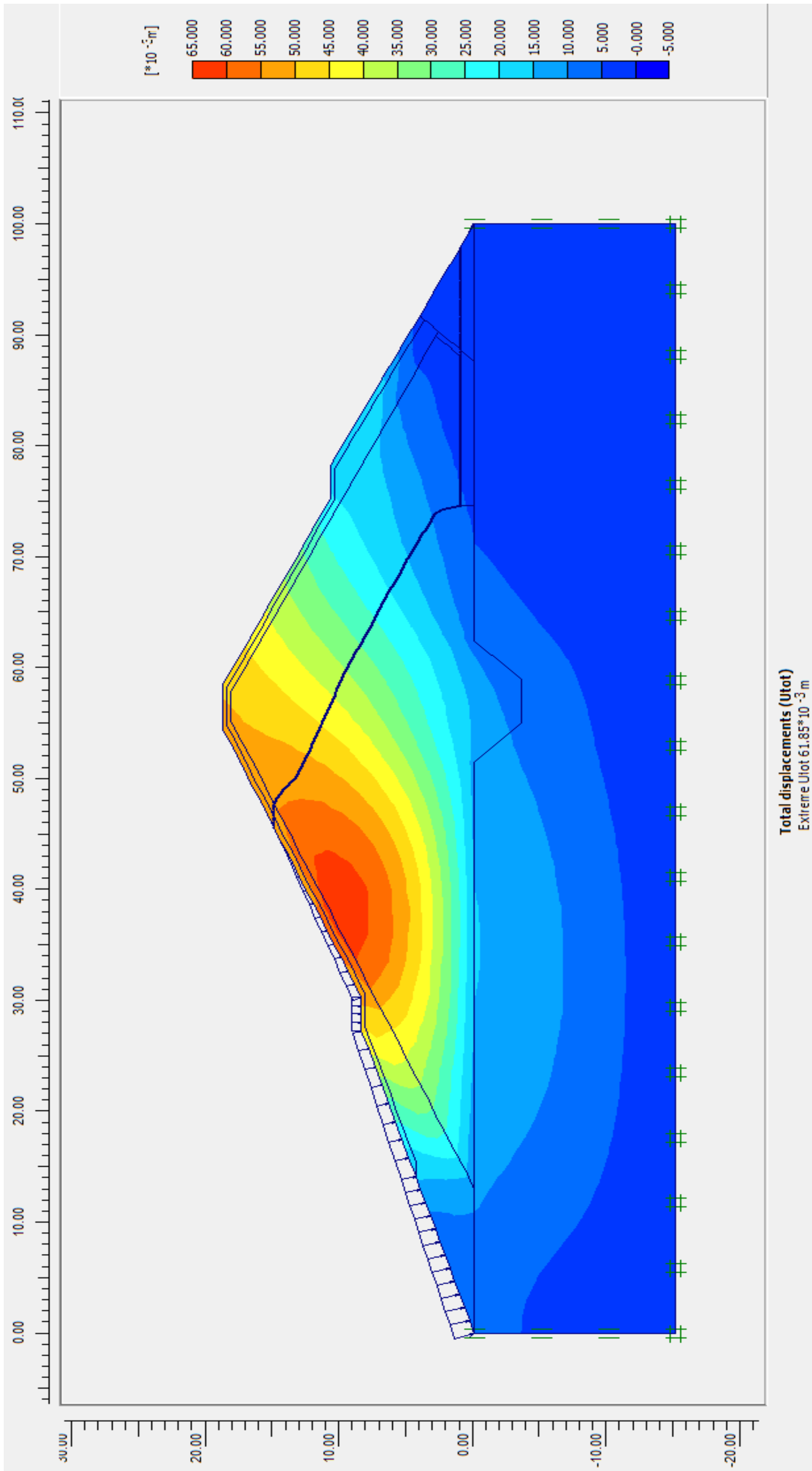

Figure 9. Total displacements during steady-state seepage

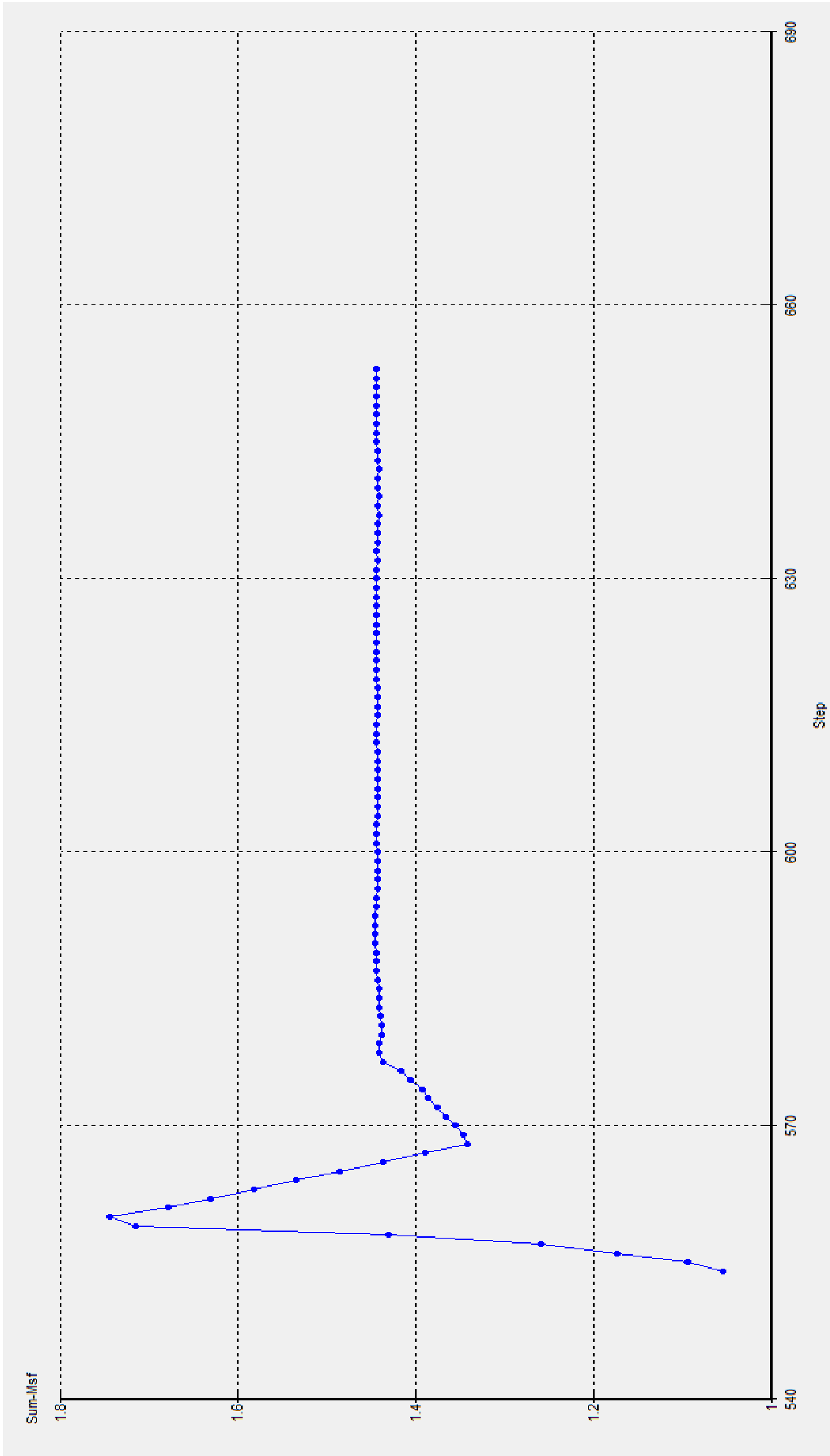

Figure 10. Factor of safety chart for the steady-state

When the reservoir is full of water, another critical loading condition was studied. The phreatic surface within the embankment has been created for long-term operation and is critical for downstream slope. The FOS obtained at this calculation and modeling stage is 1.4441.

3. 2. 3. Rapid drawdown

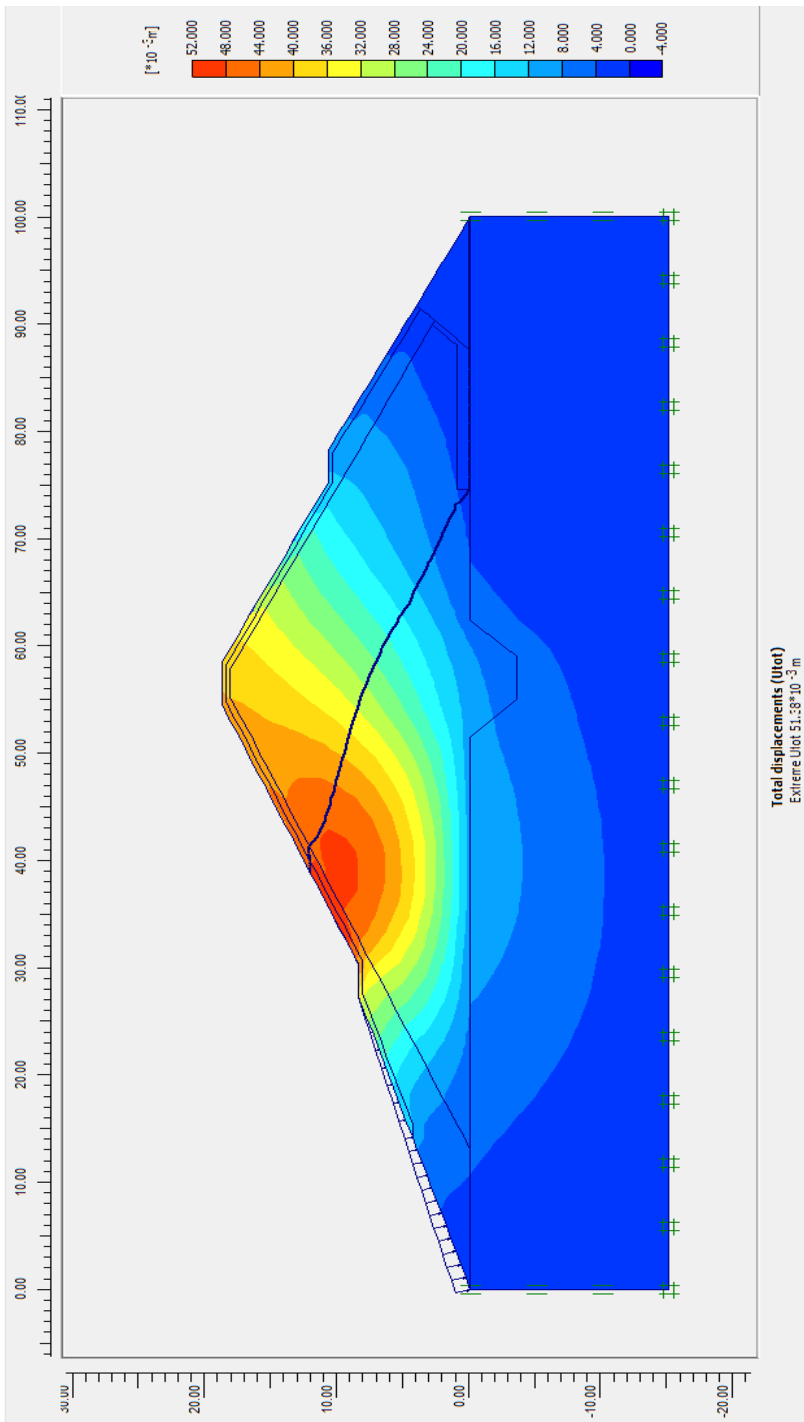

Figure 11. Total displacements during rapid drawdown

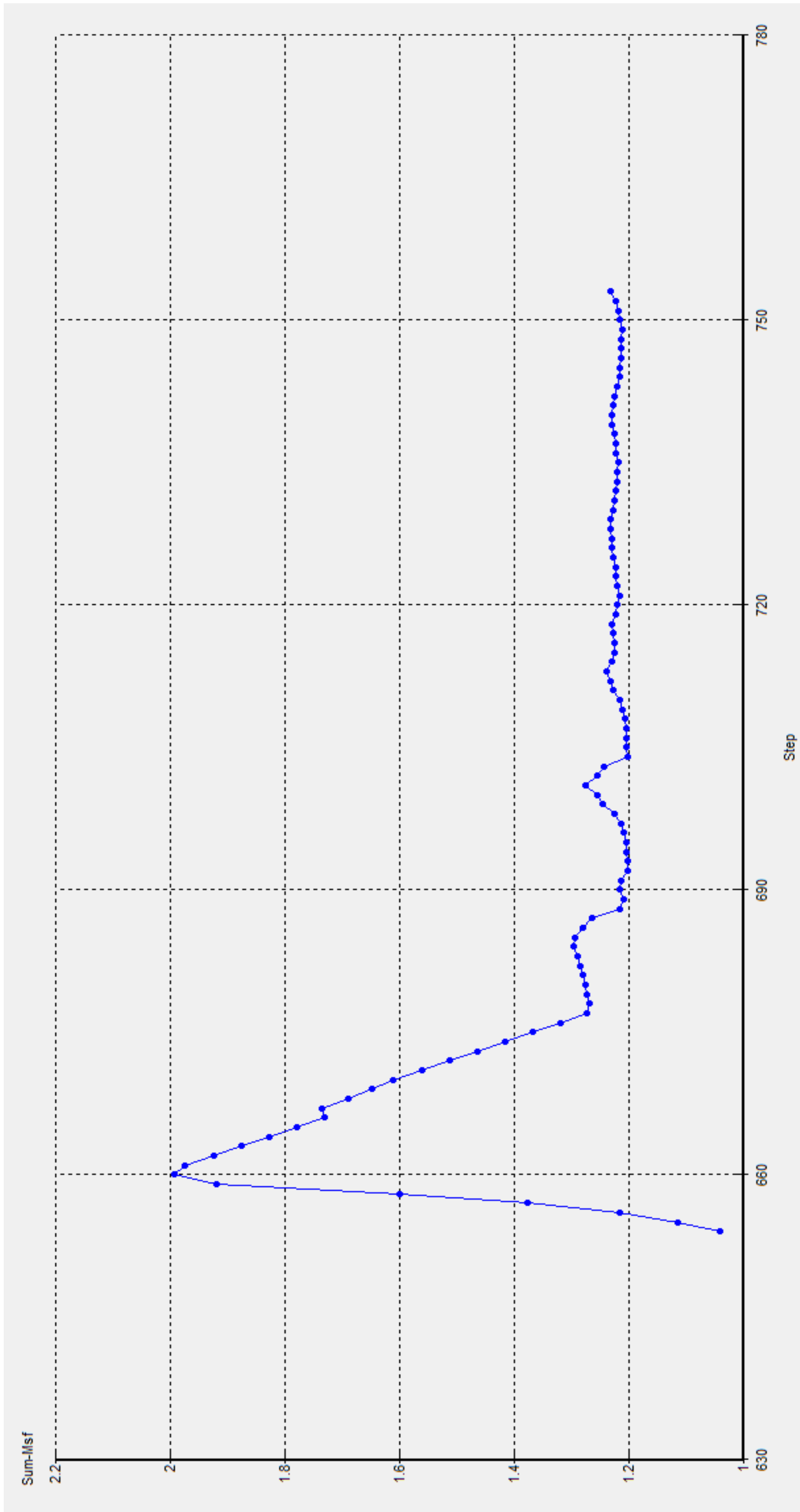

Figure 12. Factor of safety result for the rapid drawdown

This condition occurs when the reservoir's water level drops quickly, but the soil elements on the upstream slope do not drain at the same time. The dam body's phreatic line is considered to remain at the normal pool level. For this analysis, it was assumed that drawdown is very rapid, that no drainage occurs in low-permeability materials, and that the water level at the upstream dam surface is above the dead storage level elevation, which is 6 m below normal pool level.

The FOS obtained at rapid drawdown shows 1.2338.

3. 3. Stability analysis result discussions

A strength reduction technique is used to calculate safety factors in the finite element program PLAXIS. The tangent of the friction angle and the soil cohesion is continuously reduced in the same proportion until the geotechnical structure fails in this method.

Because of the lower pore water pressure, the FOS at the end of construction is expected to be higher than in other phases. The expected factor of safety is lower in the steady-state phase than at the end of the construction phase due to high pore water pressure. The FOS at the end of construction obtained was 1.5631. When the reservoir is full enough for seepage water to percolate through the embankment in a steady-state condition, the pressure in the pore water in the downstream portion reaches its peak levels, causing the soil's shear strength to decrease. The FOS obtained was 1.4441.

With the normal pool level of 2130 m reduced to 2124 m, the rapid drawdown condition was studied. The FOS for the static analysis was 1.2338, according to the results. Rapid drawdown is more crucial than steady-state and end of construction in the upstream slope of the Shimburit dam, according to the results.

This is due to the dam's internal pore water pressure, which is unable to dissipate as quickly as the reservoir's water level falls, resulting in unbalanced force equilibrium. The force of the internal pore water pressure in the dam will tend to push the upstream slope outward, reducing the stability of the dam.

In general, the FEM-based PLAXIS software study of the slope stability analysis shows that the factor of safety reduces as the loading condition increases, i.e. 1.5631 > 1.4441 > 1.2338. Because all of the safety factors are larger than one, the dam is safe under all critical conditions, or the probability of a dam failure is low. At the end of construction and steady seepage, the stability study of the downstream slope is critical. The upstream slope, on the other hand, is critical during a rapid drawdown condition.

Table 3. The 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	1.5631	OK
	Steady-state	1.5	1.3 – 1.5	1.5	1.4441	OK
	Rapid drawdown	1.2	1.2 – 1.3	1.2 – 1.3	1.2338	OK

The dam satisfies all of the requirements of the USACE, BDS, and CDA recommendations based on the results of the performed analysis for three critical loading conditions.

4. CONCLUSIONS

This research is done based on the recently, constructed Shimburit micro earthen dam, Easter Gojjam zone, Ethiopia which has a problem of excessive seepage and vanishes of stored water before it is utilized as it is designed to serve. Excessive seepage from earth-fill dams through dam body and dam foundation should be seen from an economic and dam safety point of view. Excessive seepage from earth-fill dams through the dam body and foundation should be considered in terms of cost and dam safety. Water available for irrigation and water supply is reduced as a result of excessive seepage. If the dam body or foundation materials are washed away with the seeping water, uncontrolled seepage through the dam foundation of the dam body can be a series of problems for dam safety. The Bureau of Water Resources, Energy, and Mines should make dam safety and monitoring a normal activity.

The seepage flow rate estimated for the Shimburit main dam's maximum cross-section at normal pool level is 10.31×10^{-6} $m^3/s/m$ through the dam body and 28.06×10^{-6} $m^3/s/m$ through the foundation. This study shows that the u/s filter material for embankment dams is critical for minimizing seepage water for the central impervious core, and the dam is safe in all scenarios with minimal risk of internal erosion due to seepage.

The Shimburit earth-fill dam's stability analysis was also completed, with the stability analysis based on three scenarios: end-of-construction, steady-state seepage, and rapid drawdown. The downstream slope is critical at end-of-construction and steady-state seepage, while the upstream slope is critical during a rapid drawdown condition, according to the stability study. The dam is stable for all critical loading conditions, according to the finite element analysis results, which are based on recommended design standards such as USACE, BDS, and CDA.

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