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Seepage and Slope Stability Analysis of Earthen Dam: A Case Study of Koga Dam, Ethiopia

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ABSTRACT

Evaluations of an earth-fill dam throughout its service life must ensure the stability of it against seepage and slope failure. This study presents the seepage and slope stability of the Koga earth-fill dam. The analyses were carried out using a finite element based PLAXIS 2D software, and covers the whole dam body; including 20 m of foundation depth. The behavior of both the body and the foundation of the dam were described using the Mohr-Coulomb criterion. Assessments of safety factor and quantity of seepage through the main body of the dam and foundation were carried out at different critical loading conditions. In this study, seepage analysis was undertaken of flow rate, pore water distribution and location of phreatic line. Additional actual field data measurements and observatory investigation were also carried out. From the simulated results, the average flow rate of seepage for the entire length of the body of the dam at normal pool level was equal to $0.06085 \text{ m}^3/\text{s}$, whereas the figure for that through the foundation of the dam was $0.01937 \text{ m}^3/\text{s}$. Moreover, total seepage through the main body of the dam at the current reservoir level was $0.04982 \text{ m}^3/\text{s}$, while the actually measured quantity of seepage accumulated at the downstream toe of the dam was $0.04644 \text{ m}^3/\text{s}$. The simulated and measured seepage discharges are 93.2 % similar. Based on the result of this study, the resulting factor of safety values during end of construction, steady state condition and rapid drawdown condition were 1.6221, 1.6136 and 1.2199, respectively. Using 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 Koga earth dam at all critical loading conditions are safe.

Keywords: Finite element method, Seepage, Stability analysis, PLAXIS 2D

1. INTRODUCTION

Dam failures are a particular concern because the failure of a large dam has the potential to cause more death and destruction than the failure of any other man made structure [1, 2]. Once the project is commissioned, the operation, management, and periodic maintenance are equally important for attaining the intended purpose and a sustainable project [3]. Ensuring the stability of the dam against the slope and seepage failure is an essential component for the evaluation of an earth fill dam in order to perform the intended function throughout the service life [4].

It is generally accepted that safety does not depend on proper design and construction, but also on monitoring actual behaviors during the service life of the structure [5].

Many seepage problems and failures of earth dams have occurred because of inadequate seepage control measures or poor/incomplete cleanup and preparation of the foundations and abutments [6]. Seepage through the dam and foundation causes seepage forces, pore water pressures and hydraulic gradients. If these forces are not limited to allowable ranges, they may lead to piping and embankment sloughing or sliding, both of which can lead to dam failure [7, 8]. In order to prevent the dam failure, it is essential to control the seepage in the dam. Seepage in dams caused the water waste and the decline of dam stability [9, 10].

Stability of slopes has a great strategic importance due to the fact that failure of slope may cause human, economic, and environmental disasters, especially in large infrastructure projects. Therefore, the slopes should be carefully investigated to minimize the chance of failure and to provide an adequate safety against failure [11, 12]. However, the embankment dam stability must be assessed in relation to the changing conditions of loading and seepage regime, which develop from construction through first impounding into operational service, including reservoir drawdown [13, 3].

Therefore, this study aims to evaluate the seepage and slope stability analysis of the Koga main dam. The analyses were performed using finite element based PLAXIS 2D software.

2. MATERIAL AND METHODS

2. 1. Geographical location

The Koga dam is built on the Koga River, a tributary of the Blue Nile flowing into Lake Tana in Northern Ethiopia. The study area is located in the Amhara regional state. It is specifically located in the West Gojjam zone in Mecha woreda, which is located approximately 35 km southwest of Bahir Dar, capital of Amhara region and 578 km from Ethiopian capital city Addis Ababa. The catchment area of the dam is covering an area of 165 km². The catchment (Fig. 1) is situated between 11°10' and 11°32' N and 37°04' to 37°17' E with an altitude range from 1998 (at the dam site) to 3,200 a.m.s.l. (Figure 1).

2. 2. Topography

Koga River is a tributary of the Gilgel Abay River in the headwaters of the Blue Nile Basin. The Koga watershed can be divided into two parts. The upstream area of the watershed is narrow and mountainous, while the downstream area is wide and fairly flat [14]. The Koga reservoir has a capacity to impound a total of 83.1 million cubic meters of water and 7000 ha of command area. On the basis of field measurements, topographic maps and digital elevation

model (DEM); the topography of the study area was found to be flat to almost flat with slope ranging between 0 to 8% [15].

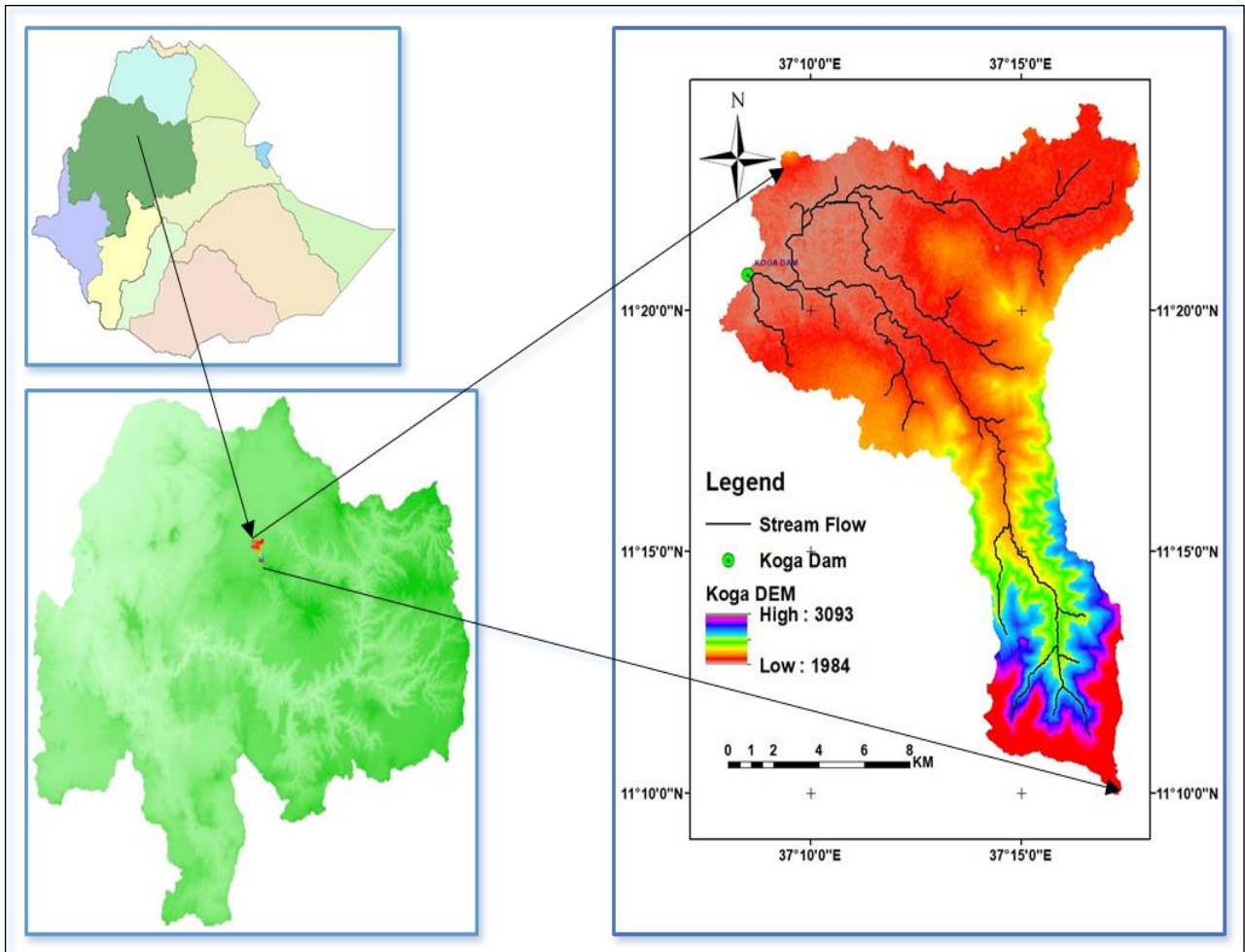


Figure 1. Location of the study area.

2. 3. Site geology

The regional geology of the Koga watershed is dominated by the tertiary volcanic rock and quaternary Basalts. In this watershed, seven main soil types are found which include, Luvisols, Fluvisols, Alisols, Nitisols, Vertisols, Leptosols and Regosols.

2. 4. Data collection

Accurate data collection is essential to maintaining the integrity of research. Both the selection of appropriate data collection instruments and clearly delineated instructions for their correct use reduce the likelihood of errors occurring. Therefore, the primary assignment of the study was getting relevant information and data for the study area. There are two methods of data collection this are primary data and secondary data.

2. 5. Salient features of Koga dam and reservoir

Table 1. Main features of the Koga dam.

Koga main dam		Overflow ogee spillway	
Dam type	Zoned earth fill dam	Spillway crest elevation	2015.25 m
Crest elevation	2019.5 m	Spillway crest length	21.5 m
Riverbed elevation	1998 m	Spillway gates	Uncontrolled crest
		Maximum flood level (MFL)	2017 m
Length of an earth dam	1730 m	Full supply level (FSL)	2015.25 m
Max height	21.5 m	Dead storage level (DSL)	2007.5 m
Koga saddle dam		Maximum water level	2016.94 m
Dam type	Homogenous earth fill	Maximum storage	83.1 MMC
Crest elevation	2019.5 m	Live storage	73.4 MMC
Length of an earth dam	1162 m	Maximum submergence	2041 ha
Riverbed elevation	2011 m	Mean depth of the reservoir	4.41 m
Max height	8.5 m	Design discharge of outlet works	9.1 m ³ /s
Full supply level (FSL)	2015.25 m	The drainage area of a dam site	164.8 Km ²
		Catchment yield	86.72 MMC
		Design flood	517 m ³ /s for T = 1: 10000 yrs

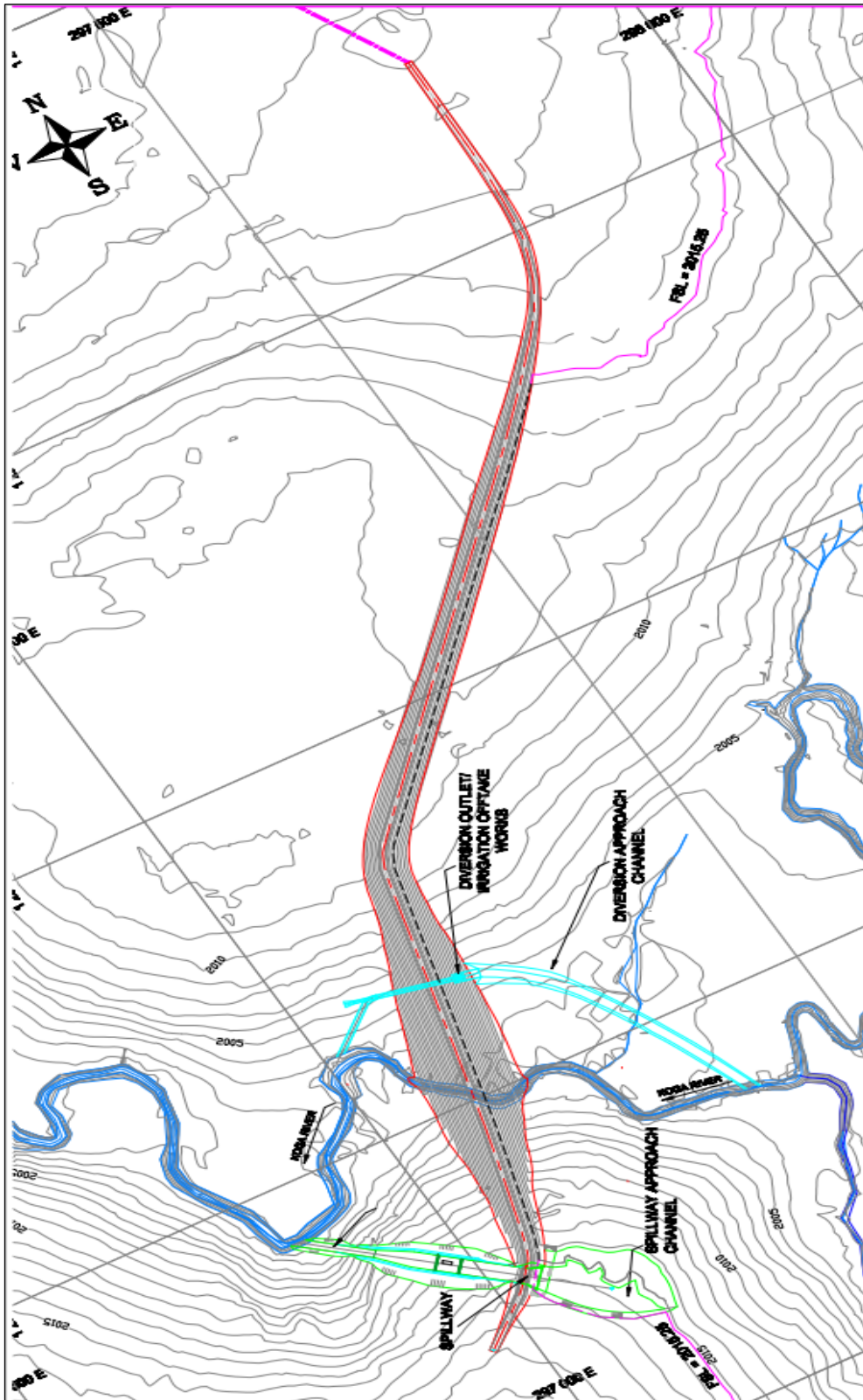


Figure 2. General layout of Koga earth-fill dam

1) Primary data collection

The primary data collected from the field are used for further analysis, interpretation, and comparison. Observation and practical field visit had been carried out with the purpose of;

- Dam site visiting and visual inspection of the current condition of the dam was carried out two times during dry and the rainy season.
- Measuring the quantity of seepage through the body of the dam: - The accumulated quantity of seepage from dam body was measured using a V- notch structure which is designated for seepage measurement at the downstream toe of the dam. The chamber is set at Elv. 2000 a.m.s.l this is to prevent the chamber from being inundated by back-up from the river when the spillway is discharging.
- Interviewing of the residential engineers, hydro geologists of the dam, dam operator and beneficiaries of the command area corresponding to the construction and current performance of the dam.

2) Secondary data collection

Essential input data for the PLAXIS 2D such as, geometrical design of the dam, geotechnical parameters of the embankment, design document and foundation materials from the laboratory were collected from Ethiopian water works construction and supervision enterprise (EWWCSE) and geological reports, project completion report and maps of the dam site and reservoir interfaces are collected from the Ministry of Water, Irrigation and Energy (MoWIE).

In order to achieve the objective of this study, the main data taken from the design document are the dam profile and property of construction materials and foundation. Engineering properties of soils are vital components of any geotechnical analysis. Thus, these geotechnical soil parameters used in the analysis of the present study are extracted from the geological and geotechnical investigation report and final design report of Koga earth fills dam.

Table 2. Geotechnical summarized data sets used

Material Type	Y_{un-sat} ($\frac{KN}{M^3}$)	Y_{sat} ($\frac{KN}{m^3}$)	K_x ($\frac{m}{d}$)	K_y ($\frac{m}{d}$)	E (Mpa)	ν	C ($\frac{KN}{m^2}$)	ϕ ($^{\circ}$)	ψ ($^{\circ}$)
Clay	18.4	19.2	$3.456*10^{-3}$	$3.456*10^{-3}$	5.7	0.3	5	30	0
Fine filter (F ₁)	17.3	20.4	17.28	17.28	10	0.22	0	33	3
Coarse filter (F ₂)	17.8	20.9	12960	12960	12.25	0.25	0	35	5
Compacted fill	18	19.8	118273	543456	50	0.175	0	30	0
Rip Rap	19	22	543456	118273	5000	0.4	0	45	15
Rip Rap bedding	19	22	86400	86400	5000	0.4	0	45	15
Basalt foundation	19	22	0.438912	0.438912	73.2	0.325	25	40	10

2. 5. 1. Model selection and setup

In order to achieve the objective of this study, a FEM based PLAXIS 2D software was used. PLAXIS 2D is a software product based on finite element code that can be used to evaluate the performance of dams and levees with varying levels of complexity and it can consider analysis like stress-strain, seepage, slope stability, dynamic analysis and also fast water drop in the reservoir. This model is selected upon its excellent capability to model geotechnical engineering related problems and its flexible programming capability and although based on its application, availability, loadings and material properties when compared with other applications.

2. 5. 2. Model simulation and analysis

In this study, Finite element based PLAXIS 2D software was used to carry out the performance evaluation of the Koga earthen dam regarding seepage, slope stability, and earthquake analysis. For study area delineation Arc GIS 10.3 was used. To supplement this research work physical tools/equipment and materials such as Geographical Position System (GPS), Digital Elevation Model (DEM), Digital camera, Topographic map, Microsoft Excel, and word are also being utilized.

2. 5. 3. Dam boundary

Finite element method (FEM) is a numerical technique for finding good approximate solutions to boundary value problems for partial differential equations by dividing very complicated problem into smaller, simpler parts called finite elements.

To fix the boundary condition of the problem, an approximate method or Boston rule (2 V: 1 H) was applied for this work. An approximate stress distribution assumes that the total applied load on the surface of the soil is distributed over an area of the same shape as the loaded area on the surface, but with dimensions that increase by an amount equal to the depth below the surface. At a depth z in meter below the ground surface, the total load Q in KN applied at the ground surface by a structure is assumed to be uniformly distributed over an area $(B + z)$ by $(L + z)$. The increase in vertical pressure $\Delta\sigma_z$ in units of KN/m^2 at depth z for an applied load Q is given by:

$$\Delta\sigma_z = \frac{Q}{(B + Z)(L + Z)}$$

where, B and L are the width and length of the foundation in meter respectively.

For the design purpose, we have to apply the boundary depth around 4%, therefore $Z = 20$ m and the horizontal boundary length is $X = 10.0$ m in both left and right sides. The Z depth (boundary depth) starts from Elv. 1998 m to 1978 m.

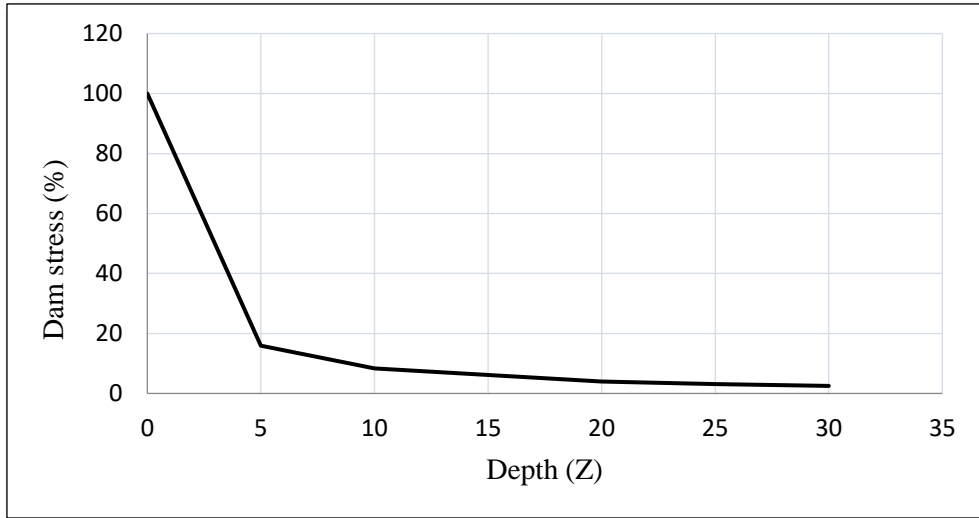


Figure Błąd! W dokumencie nie ma tekstu o podanym stylu.. Dam stress distributions effect vs. depth of the foundation

2. 5.4. Model of the Koga earth fill dam

The finite element model used in this study is composed of seven different materials including the boundary material. The dam has been modeled using PLAXIS 2D software and shown in Figure 4.

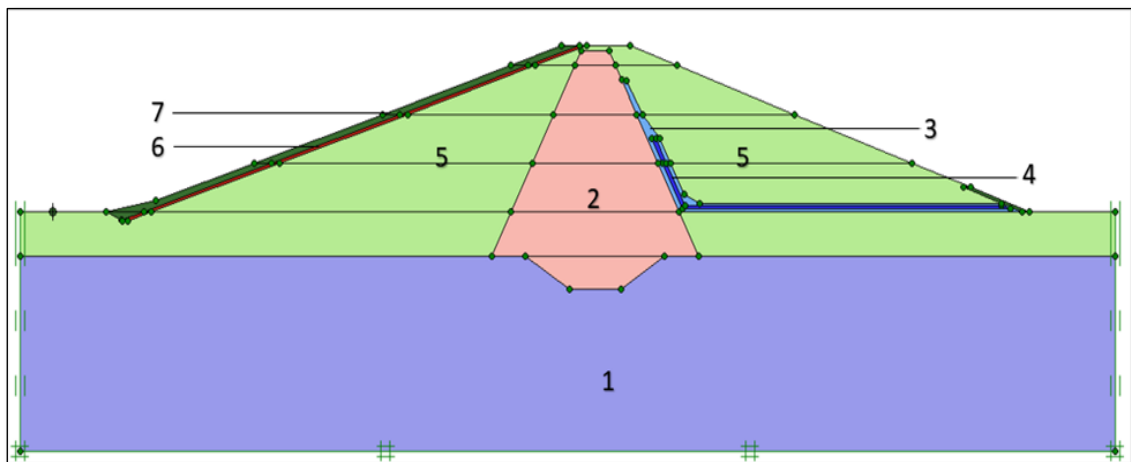


Figure 4. Koga main dam geometry model

where:

- | | |
|---------------------------------|-----------------------------------|
| 1-Basalt foundation | 5- Compacted selected random fill |
| 2- Central clay core material | 6- Rip rap bedding material |
| 3- Fine filter material (F 1) | 7- Rip rap material |
| 4- Coarse filter material (F 2) | |

The PLAXIS 2D finite element model for the maximum section of the dam and soil profile, including bedrock is given (Fig. 5). The model consisted of 2717 node points, 3936 stress points, and 328 plane-strain elements. Standard fixity elements were considered along with the base and vertical sides of the model.

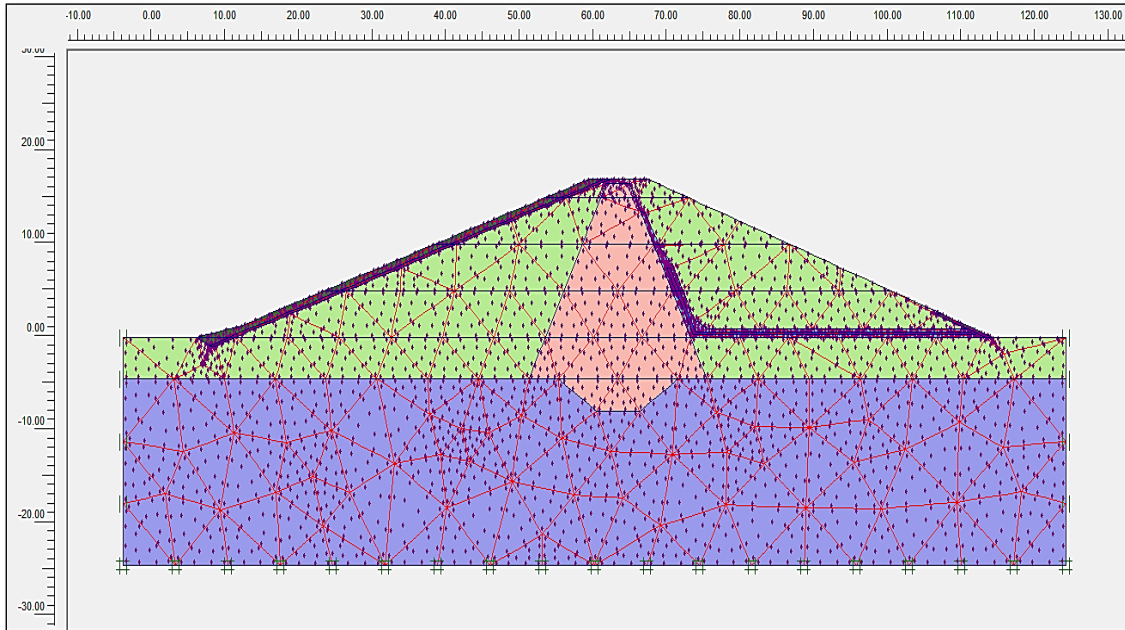


Figure 5. Finite element model of the embankment

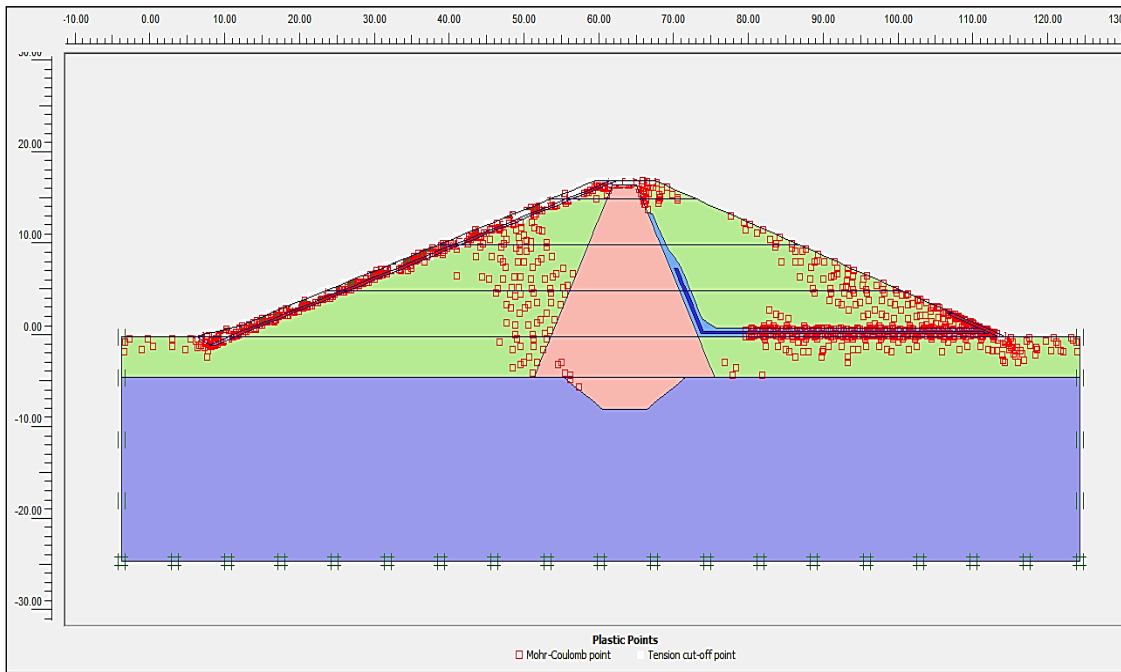


Figure 6. Plastic points during normal pool level

The plastic points are the stress points in a plastic state, displayed in a plot of the undeformed geometry. A red open square indicates that the stress lies on the surface of the Coulomb failure envelope. A white solid square indicates that the tension cutoff criterion was applied. The Mohr-Coulomb plastic points were particularly useful to check whether the size of the mesh is sufficient. If the zone of coulomb plasticity reaches a mesh boundary then this suggests that the size boundary is too small and the calculation is recommended with a larger model [16]. The outputs of the Mohr-Coulomb plastic stress point's shows that the boundary used for the analyses were sufficient enough (Fig. 6).

2. 6. Overall Procedure in Schematic Diagram (Conceptual Framework)

In order to achieve the objective of the research, a logical framework/flow chart prepared for indicating the steps procedure and the methods used in the analysis of seepage and slope stability are shown in Figure 7.

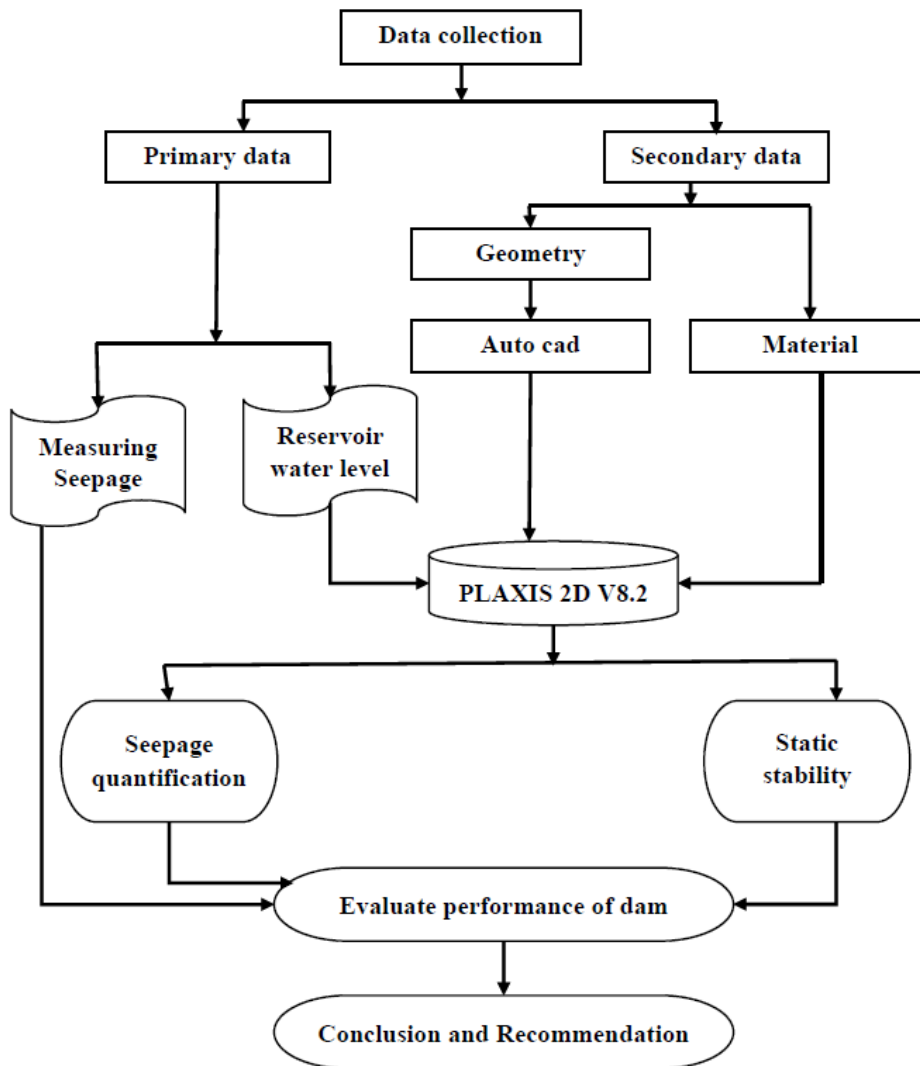


Figure 7. Methodology flow chart of the thesis

3. RESULTS AND DISCUSSIONS

3. 1. Seepage analysis and results

3. 1. 1. Seepage analysis at normal pool level

One of the most important parts of both earth and rock fill dams, is the study of discharging flow through construction materials as well as the hydraulic balance of the dam and the amount of water discharging from the foundation and body of the dam.

During normal pool level (Elevation = 2015.25 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 Finite element mesh of the model in (Fig. 8) presents the phreatic line and seepage quantity through the dam body and foundation. The phreatic surface (zero pressure line) can be viewed as the blue line that crosses the dam. The location of the phreatic line is falling within the downstream transition filter. A vertical line (flux section line) has been drawn through the center of clay core and foundation of the dam and the total entire seepage through the dam body and its foundation are computed at the different cross section.

The phreatic line emerged below the toe of the dam. This indicates that the dam is safe against sloughing problems, which is the main cause of failure of most downstream faces of dams. In all Figures, the horizontal (base width of the dam) and vertical (dam height) are plotted in coordinate system.

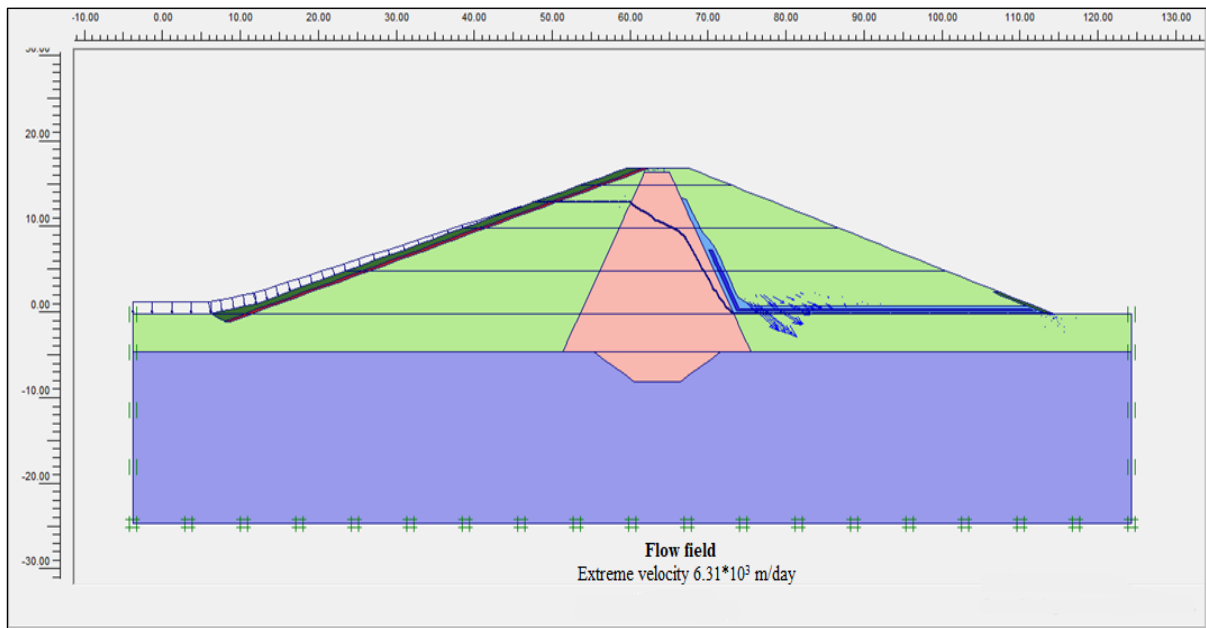


Figure 8. Location of phreatic line at normal pool level

The seepage quantity through the body of the dam was studied (Fig. 9). The quantity of seepage through the main body of the dam is $12.84 \text{ m}^3/\text{d}/\text{m}$ and extreme velocity is $22.67 \text{ m}/\text{d}$. The quantity of seepage through the foundation of the dam is $3.49 \text{ m}^3/\text{d}/\text{m}$ and extreme velocity is $0.22496 \text{ m}/\text{d}$ (Fig. 10).

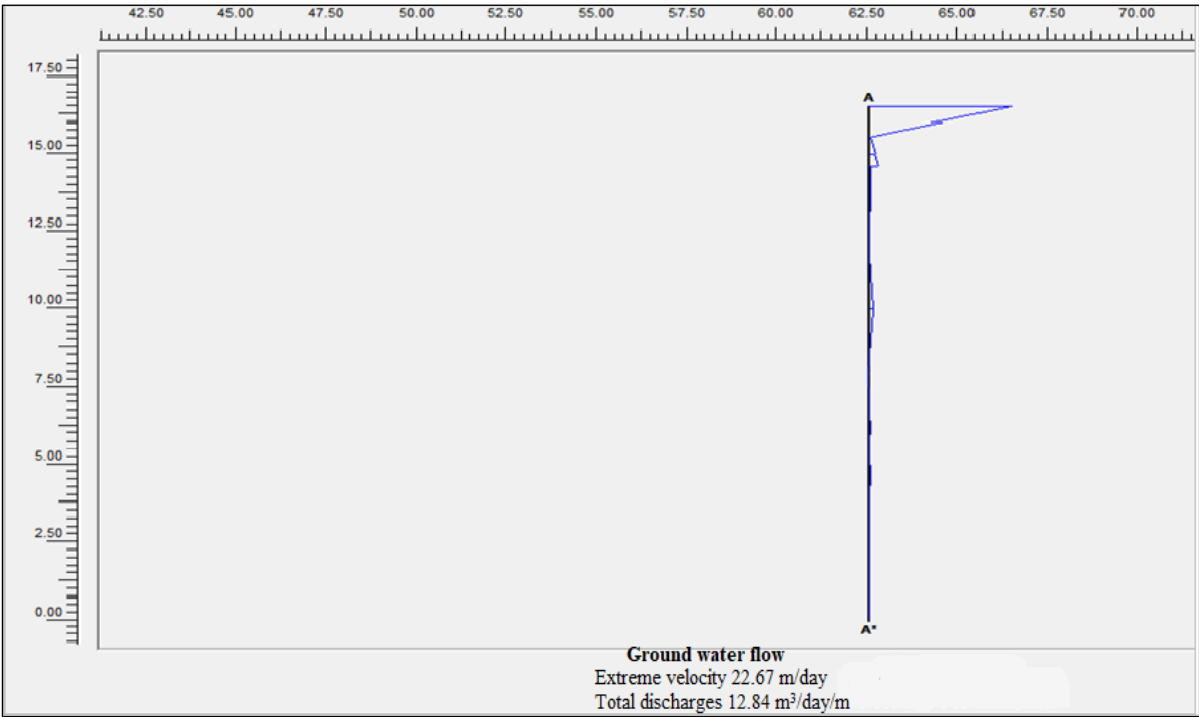


Figure 9. Seepage quantity through the main body the dam

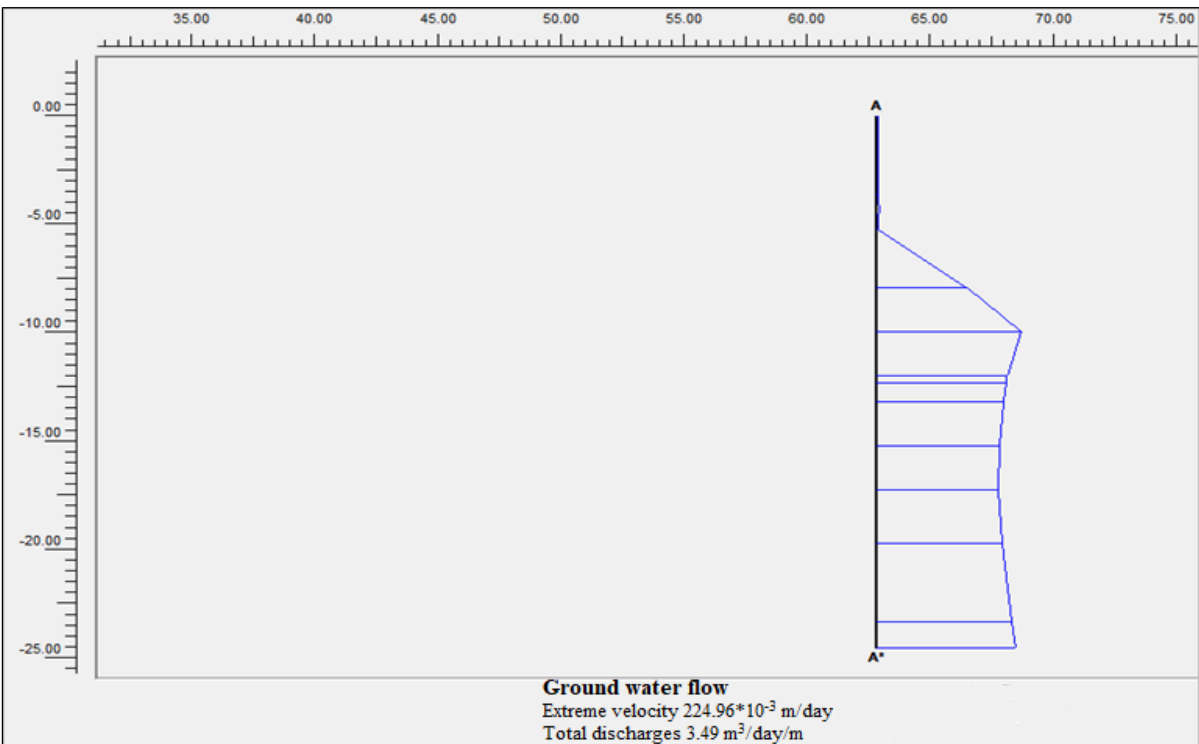


Figure 10. Seepage quantity through the foundation of the dam

In this reservoir level, the analyses result of entire dam body seepage quantity is presented in Table 3 and Figure 11, which makes it possible to describe the conditions in the whole dam at once.

Table 3. Quantity of total seepage water at normal pool level

Chainage	Length (m)	OGL (m)	Quantity of seepage (m ³ /d/m)		Total Quantity of seepage (m ³ /d)	
			Dam body	Foundation	Dam body	Foundation
0-381	0	2019.25	0	0	9.18011	26.305
0-200	177	2014	0.104	0.30	153.594	83.056
0-100	281	2009.4	2.85	1.3	522.55	148.4
0-030	351	2003.8	12.08	2.94	373.8	96.45
0+000	381	2002.5	12.84	3.49	1756.86	453.32
0+140	522	2003.8	12.08	2.94	675.26	148.39
0+200	581	2006.8	10.81	2.09	705.5	168.5
0+300	681	2010.2	3.3	1.28	1038.138	481.056
0+900	1291	2014	0.104	0.29723	22.769	65.242
1+349	1730	2019.25	0	0	-	-
				Sum	5257.646	1670.708

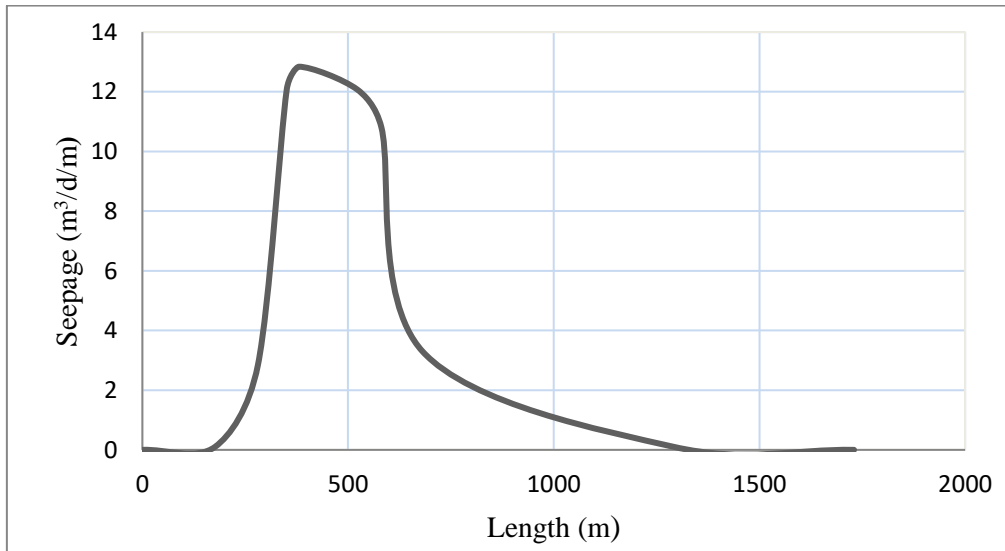


Figure 11. Total seepage through the main body of the dam

The quantity of total seepage through the main body of the dam is 5257.64545 m³/d (0.06085 m³/s).

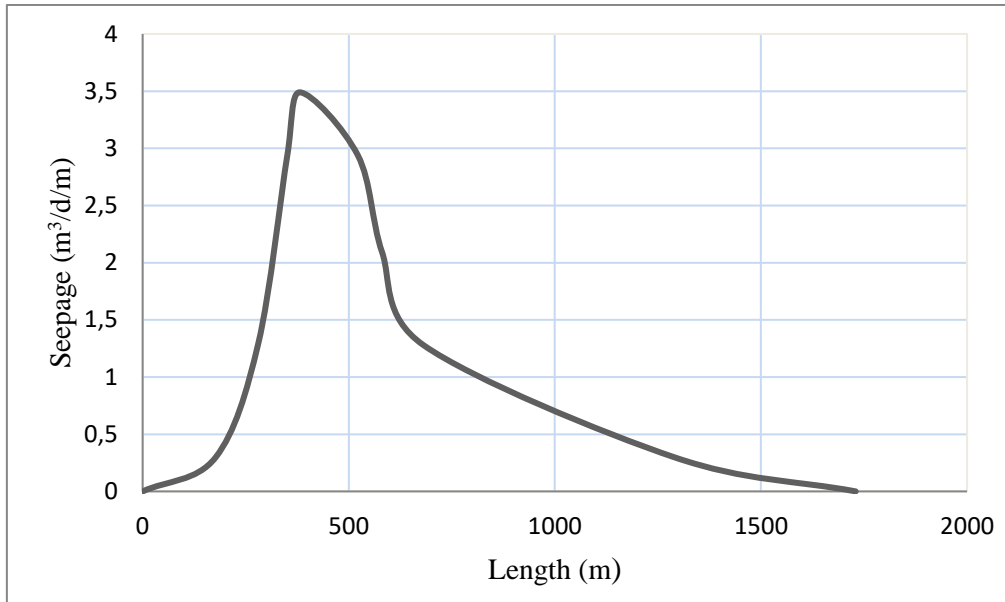


Figure 12. Total seepage through the foundation of the dam

The quantity of total seepage through the foundation of the dam is $1670.708 \text{ m}^3/\text{d}$ ($0.01937 \text{ m}^3/\text{s}$). In this analysis, the pore water pressure distribution was also simulated as expected with a minimum at the top and maximum at the bottom proportionally with the depth of water increment. It is particularly higher below the reservoir bed. The magnitudes of pore water pressure at normal pool level (2015.25 m) and bottom of boundary condition (1978 m) a.m.s.l are zero and 375.00 KN/m^2 , respectively. In the figures shown below the pore water pressure distribution and groundwater head are displayed.

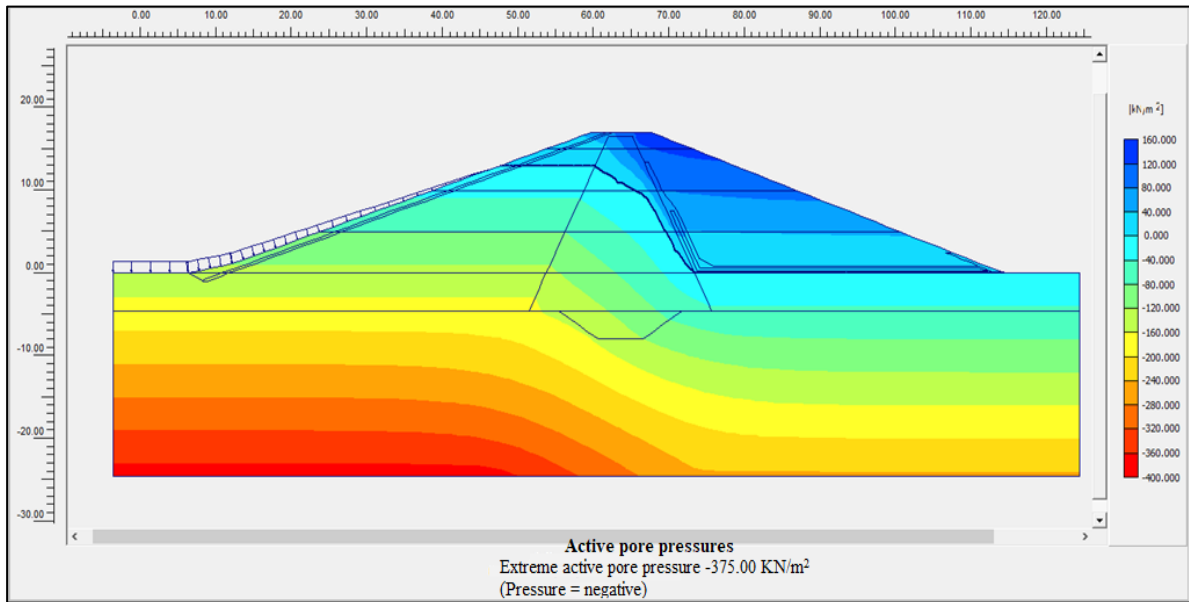


Figure 13. Pore water pressure distribution of the dam body and foundation

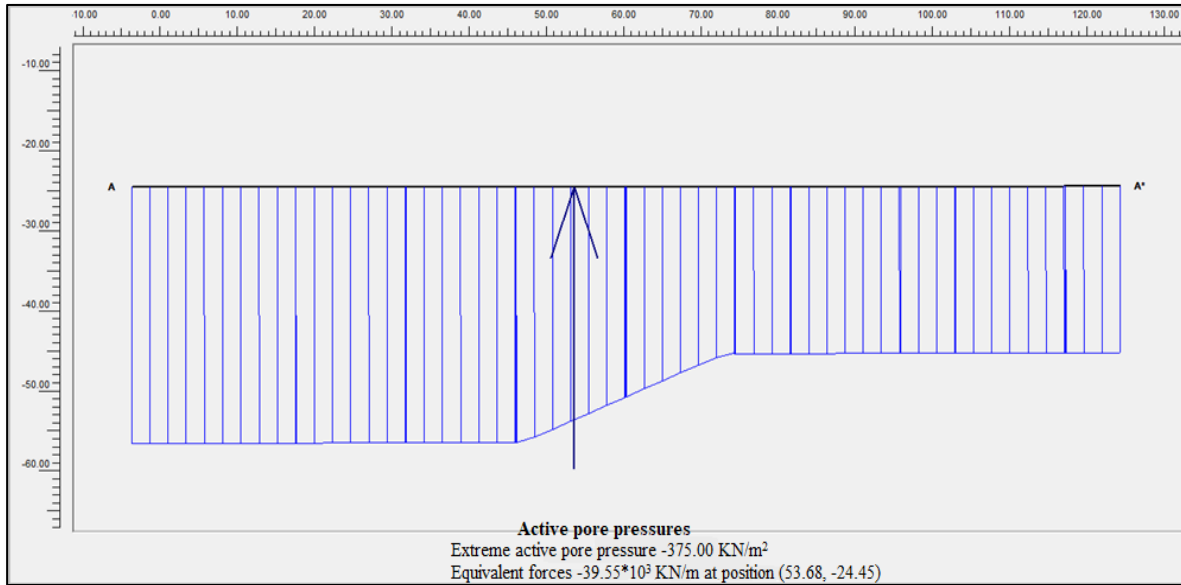


Figure 14. Pore water pressure distribution around the bottom of boundary condition

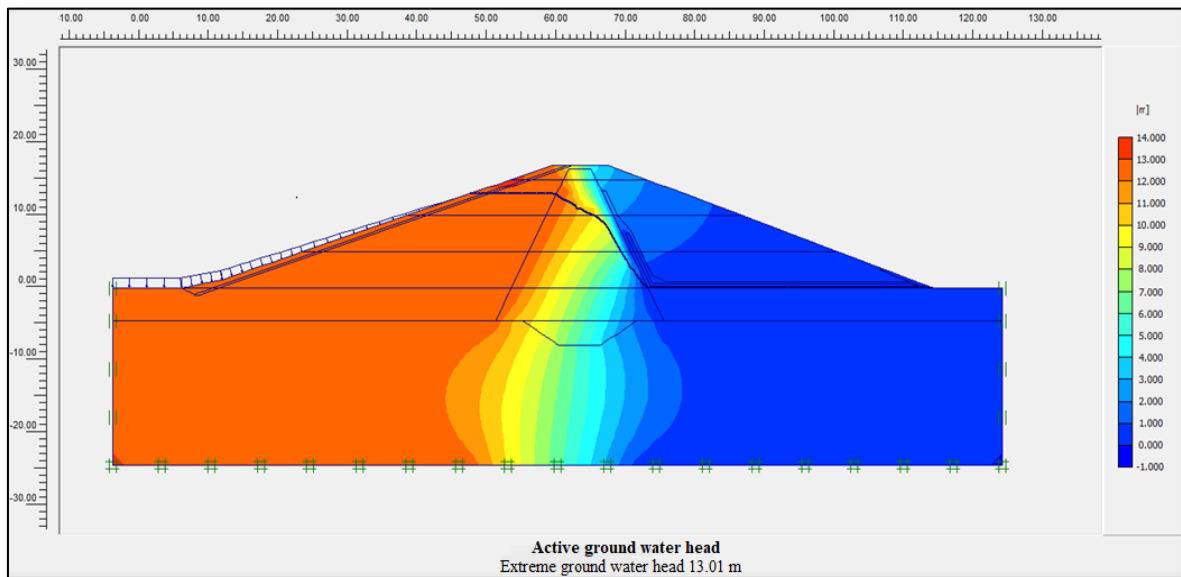


Figure 15. Groundwater head distribution of the dam body and foundation

3. 1. 2. Seepage analysis at current reservoir level (Elevation = 2014.2 m)

This impoundment condition was selected as a scenario due to the semi-constant pool level when the practical seepage quantity measurement was conducted. The boundary condition is that the current water level at the reservoir in upstream is 16.2 m above the bed level of the dam. The numerical analyses of seepage discharge, phreatic surface and maximum seepage velocity for the entire pond level were computed with similar procedures with seepage analysis at NPL. The computed seepage quantity at a maximum section of the embankment dam body was estimated as $1.28472 \times 10^{-4} \text{ m}^3/\text{s}$ per meter length of the dam and extreme velocity estimates

as 2.269×10^{-4} m/s and seepage quantity through the foundation was 3.46065×10^{-5} m³/s per meter length of the dam and extreme velocity is 2.13241×10^{-6} m/s.

At the full reservoir level, the computed seepage quantity through the body of the dam exceeded by 1.74 m³/d per meter length over the current reservoir level. The seepage velocities for the normal pool level and for the reservoir level at an elevation of 2014.2 m a.m.s.l. are computed. At an elevation of 2014.2 m a.m.s.l. reservoir level minimum seepage velocity at the body of the dam (19.6 m/d) was perceived and at full reservoir level (Elevation of 2015.25 m a.m.s.l.) highest velocity (22.84 m/d) occurs.

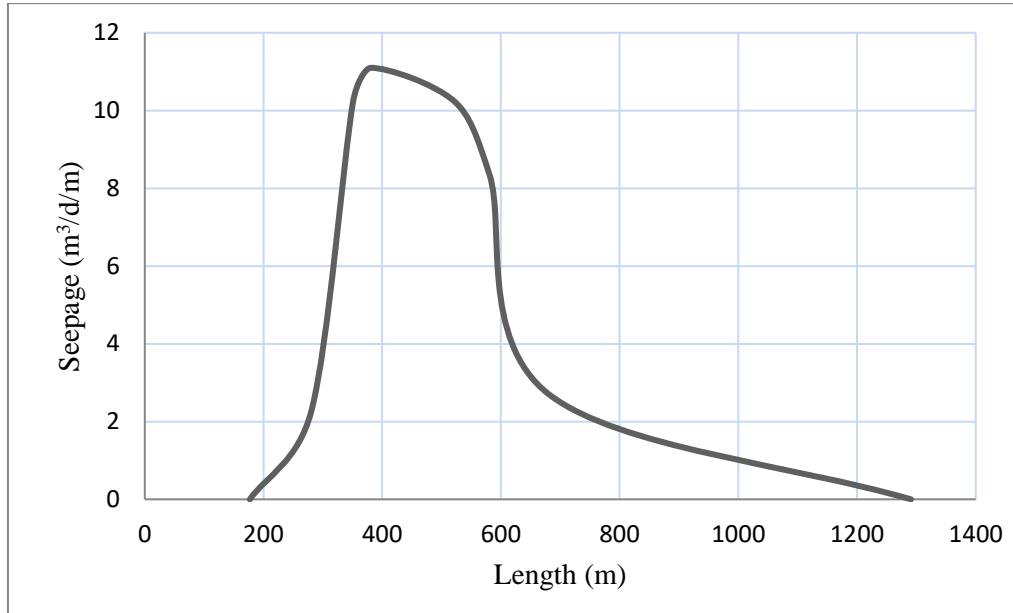


Figure 16. Total seepage through the main body of the dam



Chamber A

Chamber B

Figure 17. Seepage measurements from Chamber A and B

The total quantity of seepage through the main body of the dam is 4304.31 m³/d (0.04982 m³/s) and total seepage through the foundation of the dam is 1162.9 m³/d (0.01346 m³/s).

Two seepage measurement chambers were constructed at the Koga main dam. Seepage measurement chamber A is located on the original river course and collects flow from the downstream toe drain along the left flank and between the draw off works and the old river course. Seepage measurement Chamber B receives flow from the toe drain running along the right flank. Each seepage measurement chamber has a 90° sharp-edged steel V-notch weir, supplemented by a gauge board for depth readings so that the water level upstream of the weir can be recorded and converted into the discharge.

Seepage quantity was estimated using the following equation:

$$Q = 1.343H^{2.47}$$

where, Q is the flow, (m³/s); H is the head of water upstream over the bottom of the V-notch.

The Head in plat from chamber, A is 0.16 m, and from chamber, B is 0.22 m.

The quantity of seepage accumulated from chamber A is 0.01453 m³/s and from chamber, B is 0.03191 m³/s, Therefore the total accumulated seepage discharge through the embankment is 0.04644 m³/s at the downstream toe. Therefore, the simulated and measured seepage discharges are 93.2 % similar this indicates that PLAXIS 2D software satisfies and gives representative results.

Between the measured and simulated values slight differences were observed, these might either due to the aging of the dam which will definitely contribute in reducing the seepage intensity through the dam embankment as a result of settling, or because the embankment and foundation materials used, more especially the clay core may differ in terms of hydraulic conductivity magnitude, being not possible to get it having exact the same value throughout the length of the dam. Another reason might be as a result of the strength of compaction of the materials, which may differ from point to point along the full length of the dam.

According to USBR recommendation, the probability of failures of the dam based on seepage discharge will not be likely to happen because of the seepage water originates from the dam body looks like pure (there is no material transport along flow path) and this indicates that there is no scouring problem.

3. 1. 3. Seepage analysis at normal pool level with upstream filter materials

Basically, the Koga main dam constructs without an upstream filter material for central clay core. Therefore, this seepage analysis was selected as a scenario to see the effect of the upstream filter on the Koga dam. The numerical analysis of seepage discharge, maximum seepage velocity and phreatic surface for the maximum cross section of the dam is computed with similar procedures with seepage analysis at normal pool level the only difference is there is an upstream filter material for the central clay core.

The phreatic line for normal pool level with upstream and downstream filter material shows in the Figure 18, Figure 19 and Figure 20 shows seepage quantity through the dam body and the foundation respectively.

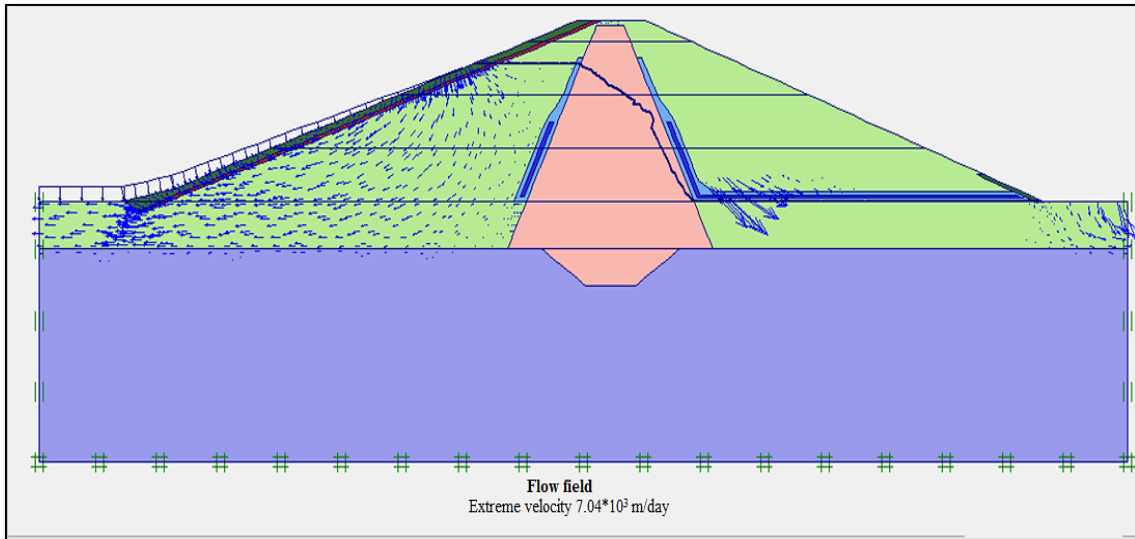


Figure 18. Location of phreatic line at normal pool level with u/s filter material

The result of the analysis showed in the Figure 19 the seepage through main body of the dam is $7.49 \text{ m}^3/\text{d}/\text{m}$ and extreme velocity is $21.28 \text{ m}/\text{d}$. The quantity of seepage through the foundation of the dam is $3.40 \text{ m}^3/\text{d}/\text{m}$ and extreme velocity is $0.21854 \text{ m}/\text{d}$ as shown in the Figure 20. This result shows that the value of seepage estimated at normal pool level without upstream filter ($12.84 \text{ m}^3/\text{d}/\text{m}$) is higher than the seepage analysis with upstream filter ($7.49 \text{ m}^3/\text{d}/\text{m}$).

Due to the upstream filter materials the seepage flow decreases on the central clay part of the Koga main dam. Because, the main purpose of upstream filter material on the embankment dam is to control seepage water in to the central impervious core.

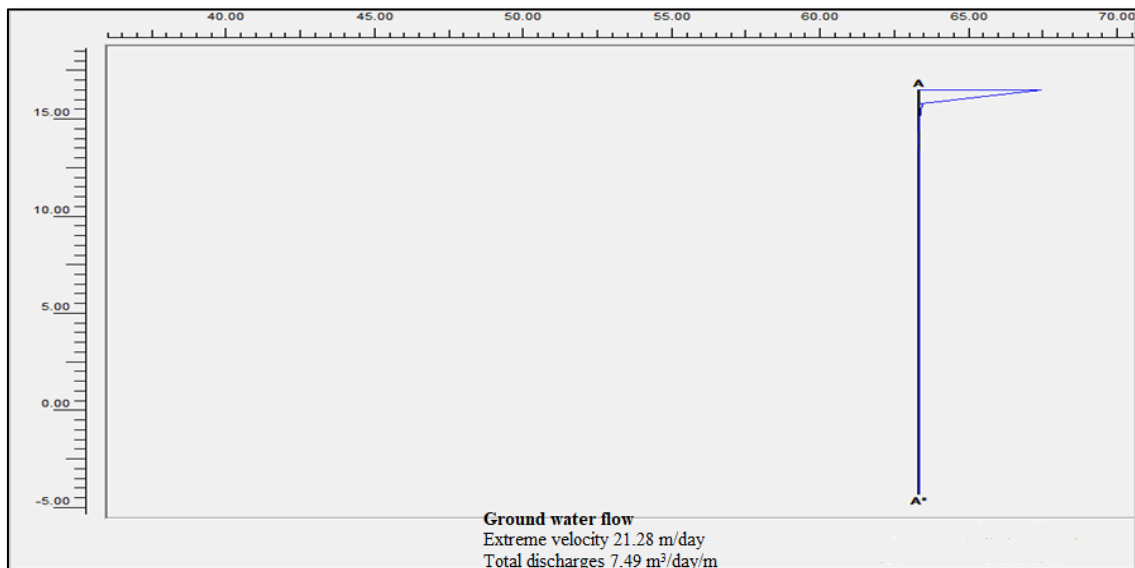


Figure 19. Seepage quantity through the main body of the dam

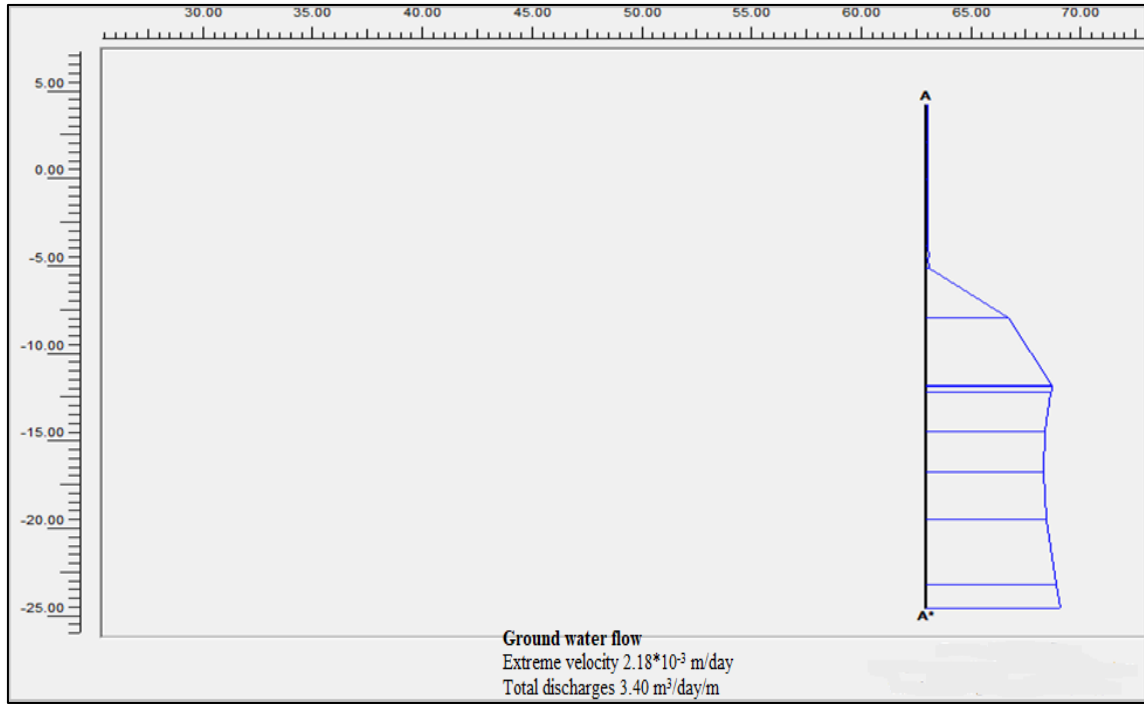


Figure 20. Seepage quantity through Foundation of the dam

The seepage discharge, maximum seepage velocity and pore water pressure for normal pool level (with and without u/s filter material) and for current reservoir level scenario are computed; these are listed in Table 4. From the entire scenario, minimum seepage occurs at normal pool level with u/s filter; that is of the order of $7.49 \text{ m}^3/\text{d}/\text{m}$; at normal pool level without u/s, filter maximum seepage occurs; and which is of the order of $12.84 \text{ m}^3/\text{d}/\text{m}$.

Similarly seepage velocities for all scenarios are computed; at lowest pool level minimum seepage velocity is observed and amongst all the scenario minimum velocity occurs at current reservoir level; which is for body of the dam $19.60 \text{ m}/\text{d}$ and for the foundation of the dam is $0.18424 \text{ m}/\text{d}$; and at highest pool level maximum velocity occurs and amongst all the scenarios maximum velocity occurs at normal pool level without u/s filter material; and which is for body of the dam $22.67 \text{ m}/\text{d}$ and for the foundation of the dam is $0.22496 \text{ m}/\text{d}$. The pressure distribution was also resulted as expected with minimum at the top and maximum at the bottom along with the depth of water increment.

Table Bład! W dokumencie nie ma tekstu o podanym stylu.. Summarized of seepage analysis of Koga main dam for various locations.

Seepage analysis		Normal pool level	Current reservoir condition	NPL with u/s filter
Quantity of seepage ($\text{m}^3/\text{d}/\text{m}$)	Body of the dam	12.84	11.1	7.49
	Foundation	3.49	3.0	3.40

Extreme velocity (m/d)	Body of the dam	22.67	19.60	21.28
	Foundation	0.225	0.184	0.219
Max. pore-water pressure (KN/m ²)	At bottom of boundary	375	365	379.63
	At bottom of cut off	210.35	199	213.10
	At bottom of foundation	175.67	165.52	181.53
	At Original ground level	130	120.24	140.02

3. 2. Slope stability analysis

Finite element based PLAXIS 2D software was used to analyze the stability of the Koga embankment dam. It is essential to do the stability after the understanding of seepage occurring through the dam and its foundation.

The stability of an embankment dam depends on the pore developed either in the dam body or in foundation, characteristics of the foundation and fill materials, on the geometry of the embankment section, and additional factors such as the presence of water, loading conditions etc. The slope stability against sliding risk is represented by a safety factor (FOS). In this analysis, three different cases of operation; the end of construction, steady-state seepage and rapid drawdown are considered.

The soil parameters like cohesion, friction angle and unit weight of the soil have a greater role in the stability of slopes. They have an inversely proportional effect on relative displacements, which literally means that the increase in the value of soil parameters leads to smaller displacements.

3. 2. 1. End of construction

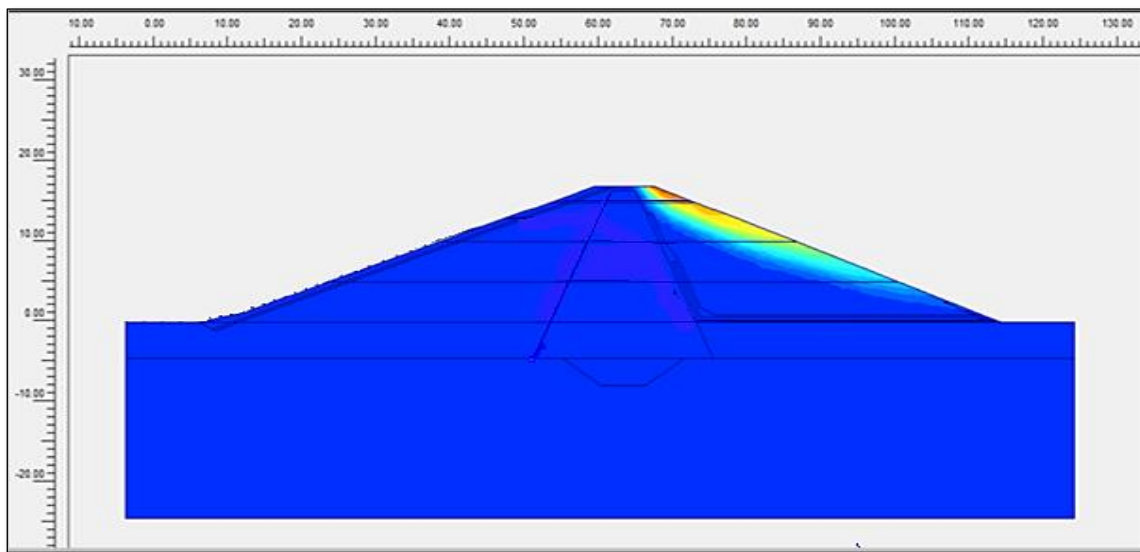


Figure 21. Total displacements during end of construction

At the end of construction, significant pore pressure development is expected in the embankment body and foundation either from rainfall or compaction water. In this case, the stability of the upstream and downstream slope is critical at the end of construction. So the slope stability of the Koga embankment dam was assessed at this loading condition using FEM based PLAXIS 2D software and the results are shown in Figure 21.

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

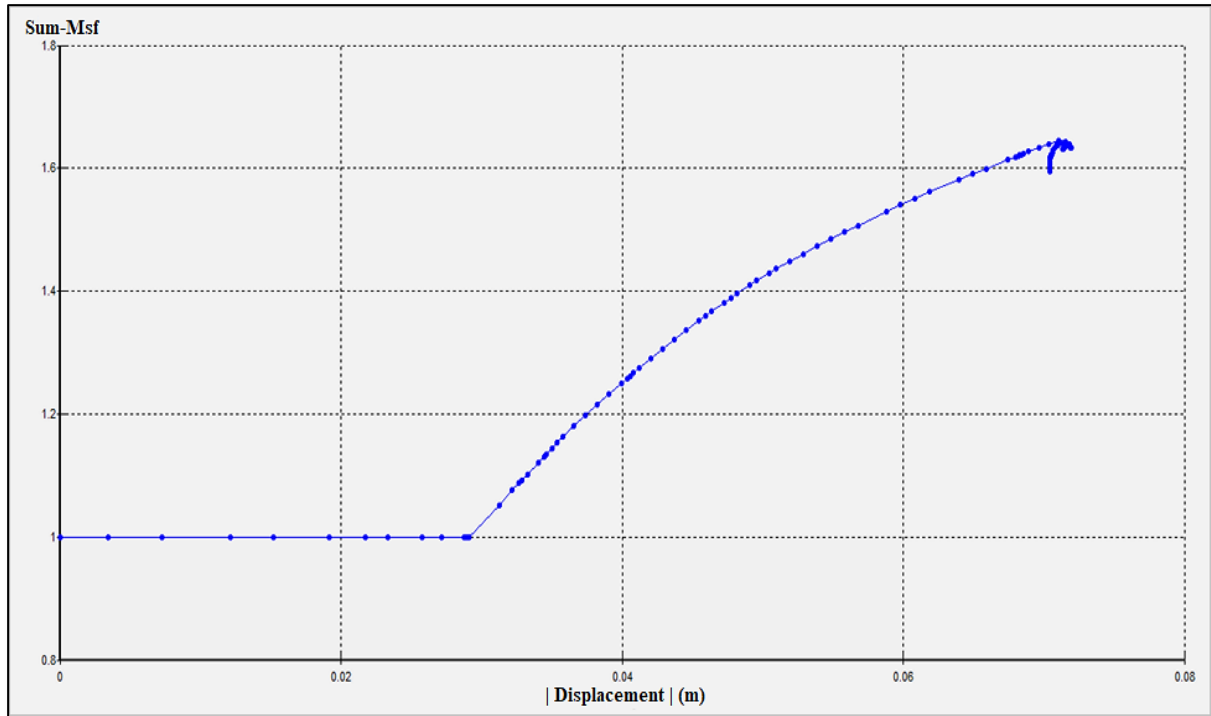


Figure 22. Factor of safety chart for the end of construction

The FOS obtained at end of construction shows 1.6221.

3. 2. 2. Steady-state seepage

This was another critical condition analyzed when the reservoir is full of water and some steady state seepage into the earth embankment dam is established. For the long-term operation, the phreatic surface within the embankment has been established and critical for downstream slope.

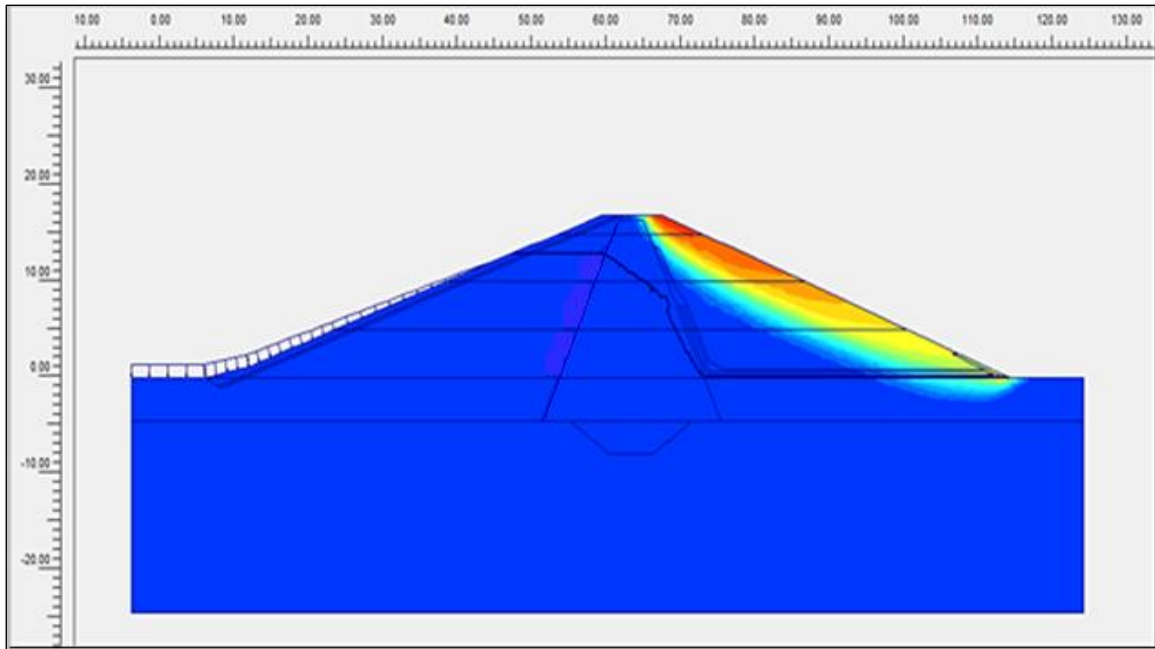


Figure 23. Total displacements during steady-state seepage

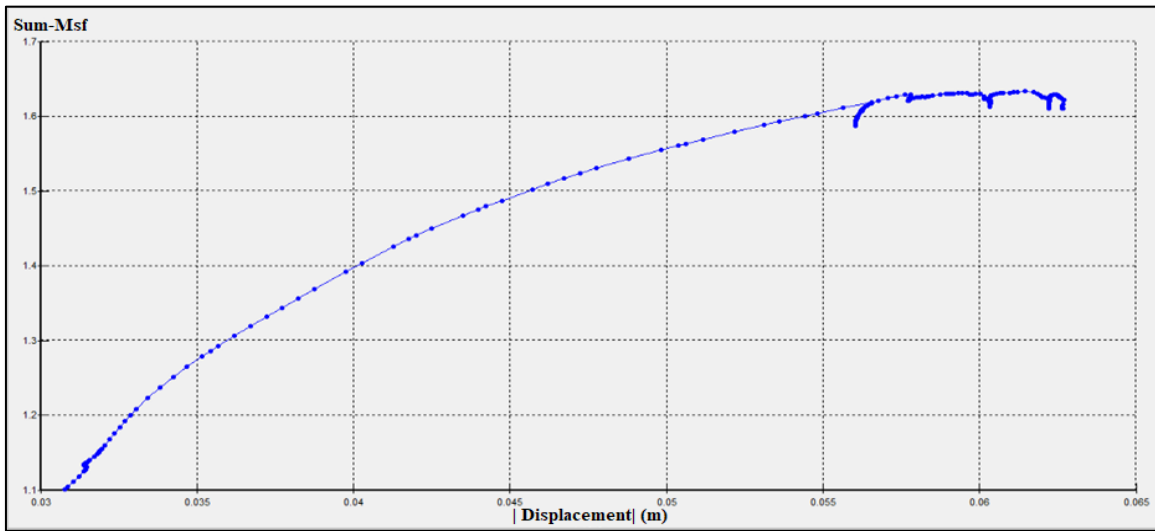


Figure 24. Factor of safety chart for the steady-state

The FOS obtained at this calculation and modeling stage is 1.6136.

3. 2. 3. Rapid drawdown

This condition occurs when the water level in the reservoir reduces quickly, but the earth materials of the upstream slope do not drain simultaneously. It is assumed that the phreatic line of the dam body does not drop from the normal pool level. For analysis purposes, it was

assumed that drawdown is very fast, and no drainage occurs in materials with low permeability, the water level at the upstream dam surface is above dead storage level elevation 2008.5 m or at 6.75 m below from normal pool level and the original ground level elevation is 2002.5 m.

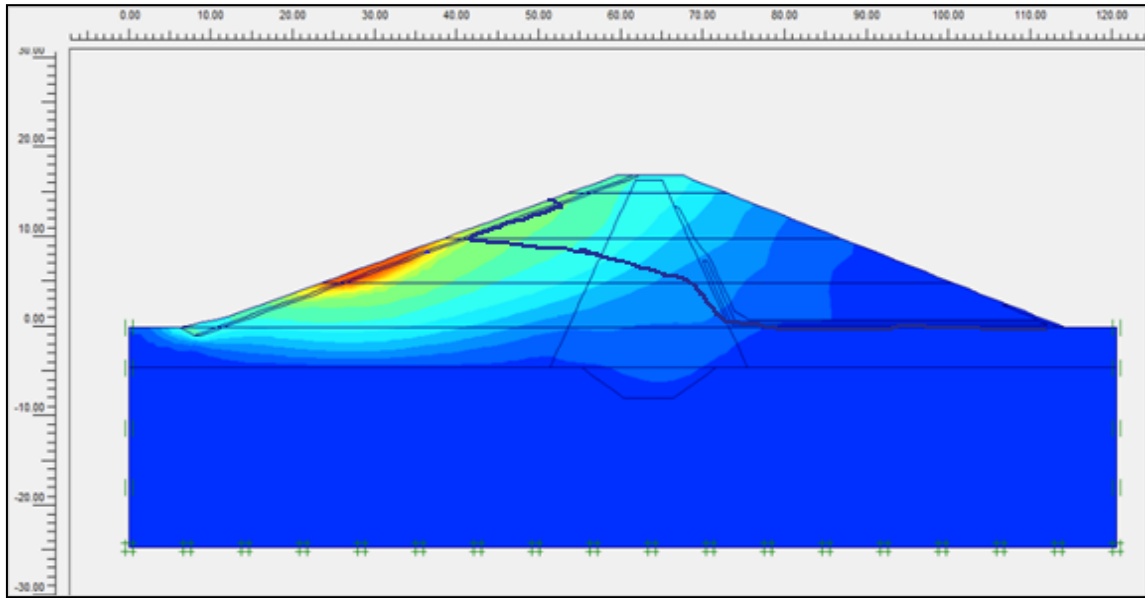


Figure 25. Total displacements during rapid drawdown

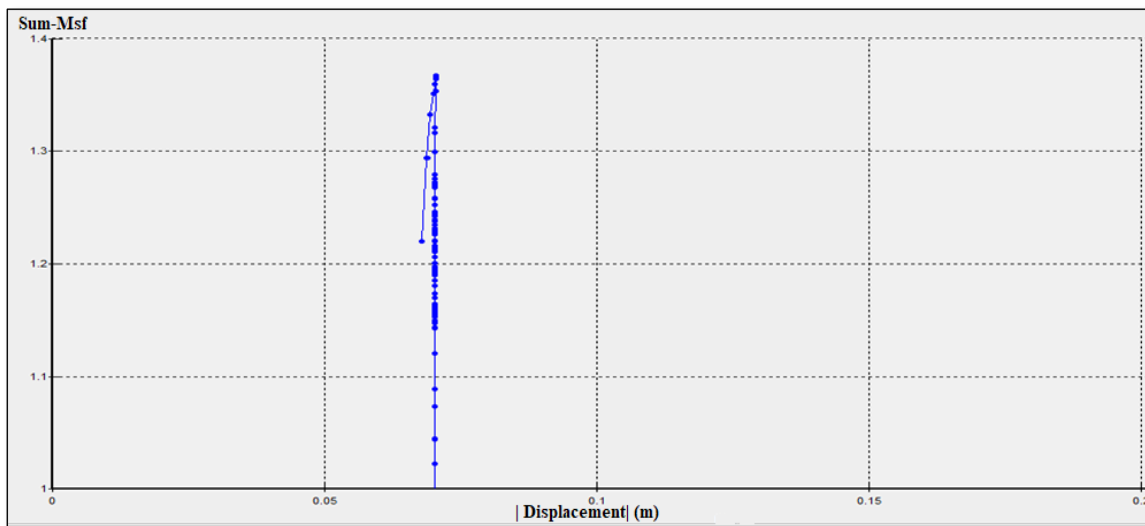


Figure 26. Factor of safety result for the rapid drawdown shows 1.2199

3. 2. 4. Stability analysis with upstream filter materials.

In order to investigate the effect of upstream filter material for slope stability during all loading condition, a Koga main dam is used as the experimental model for this scenario. The factor of safety for end of construction was found to be about 1.6271. It is almost equal with

the initial analysis, which was 1.6221. The factor of safety (FOS) for the steady state condition was found to be about 1.6245. This was greater than those obtained from the initial analysis, which was about 1.6136. The differences in the Factor of Safety could be due to the difference in the upstream filter material.

To conduct a stability analysis of the Koga dam in rapid drawdown condition, it is assumed that the dam is initially full, at a height of 12.75 m, and then reduces quickly to a height of 6 m. In rapid drawdown case, stability will be critical for the upstream slope only. The pore pressures under rapid drawdown are estimated assuming no dissipation of pore pressures in the shoulder material. The Factor of Safety (FOS) for the rapid drawdown condition was found to be about 1.3675. This was much greater than the initial analysis, which was about 1.2199.

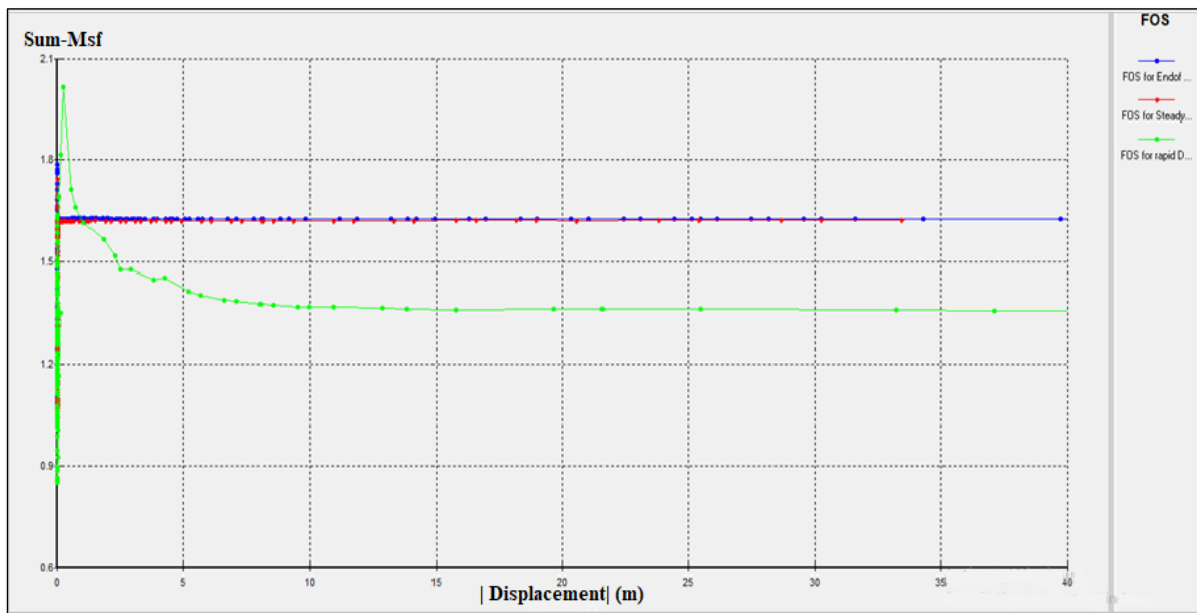


Figure 27. Factor of safety chart for Stability analysis with upstream filter materials

3. 3. Stability analysis result discussions

In the Finite element program PLAXIS 2D, a strength reduction technique is employed to compute safety factors. In this technique, the tangent of the friction angle and the cohesion of the soil are gradually reduced in the same proportion until the geotechnical structure fails. The simulations of the analyses were carried out by classifying the dam into five construction stages [17].

A calculated factor of safety value greater than 1.0 represents the slope being stable under the given conditions (resisting forces > driving forces), and a factor of safety value less than one represents that the slope is unstable (failing); that is the driving forces outweigh the resisting forces and FOS of 1.0 can be dynamically stable based on the FEM deformation analyses and the deformation calculated along the failure plane should not generally exceed 1 m [18].

The FOS at the end of construction is expected higher than the other phases, because of its minimum pore water pressure. In the steady-state phase, due to high pore water pressure, the

expected factor of safety is less than the end of the construction phase. The FOS at the end of construction obtained for both static was 1.6221. For steady state condition, the water level was at normal pool level (Elv. 2015.25 m). The FOS obtained for both static was 1.6136. During a steady-state condition when the reservoir has been full long enough for seepage water to percolate all the way through the embankment, the pressure in the pore water in the downstream portion reaches its highest values and cause to decrease the shear strength of the soil.

The rapid drawdown condition was analyzed with normal pool level of 2015.25 m lowered to 2008.5 m. The analysis results showed that the FOS for the static analysis were 1.2199. From the results, in the upstream slope of the Koga dam, it can be observed that rapid drawdown is more critical compared to the steady state and the end of construction. This is mainly due to the internal pore water pressure in the dam that is unable to dissipate out as quickly as the lowering of water level in the reservoir resulting in unbalance force equilibrium. The upstream slope will tend to be pushed outward by the force of the internal pore water pressure in the dam and thus reducing the stability.

Generally, during the slope stability analysis, the FEM based PLAXIS 2D software analysis shows that the factor of safety decreases as long as the loading condition increases i.e. $1.6221 > 1.6136 > 1.2199$. 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. The stability analysis of the downstream slope is critical at the end of construction and steady seepage. On the other hand, the upstream slope is critical during a rapid drawdown condition.

Table 5. 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	1.6221	OK
	Steady-state	1.5	1.3 – 1.5	1.5	1.6136	OK
	Rapid drawdown	1.2	1.2 – 1.3	1.2 – 1.3	1.2199	OK
Static analysis with u/s filter material	End of construction	1.3	1.3 – 1.5	1.3	1.6271	OK
	Steady-state	1.5	1.3 – 1.5	1.5	1.6245	OK
	Rapid drawdown	1.2	1.2 – 1.3	1.2 – 1.3	1.3675	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 USACE, BDS and CDA recommendations.

4. CONCLUSIONS

In the study, the evaluation of seepage quantity through the main body of the dam and foundation, slope stability at different loading conditions and deformation analyses in static and

dynamic conditions of the Koga earthen dam has been studied using the FEM based PLAXIS 2D software. The analysis covers the whole dam body, including 20 m of foundation depth.

The stability analysis of the Koga earth fill dam also carried out and the stability analysis performed based on three scenarios, these are during end of construction, steady-state seepage and rapid drawdown.

The simulated result showed that the seepage flow rate for the entire length of the dam at the normal pool level of 2015.25 m is 0.06085 m³/s for the body of the dam and for the foundation of the dam is 0.01937 m³/s. The quantity of total seepage through the main body of the dam at the current reservoir level (2014.2 m) is 0.049818 m³/s. But, the actual seepage recorded (2014.2 m) at the downstream toe of the dam is 0.04644 m³/s. Therefore, the simulated and measured seepage discharges are 93.2 % similar.

The seepage flow rate estimated for the maximum cross section of the Koga main dam at normal pool level without upstream filter is 12.84 m³/d/m through the dam body and through the foundation is 3.49 m³/d/m. But, the seepage analysis with an upstream filter through the dam body is 7.49 m³/d/m and through the foundation is 3.40 m³/d/m. This result shows the u/s filter material for embankment dams are playing a vital role to minimize the seepage water for the central impervious core and the dam is safe at all scenarios and there is no possibility of internal erosion due to seepage.

The performed stability analysis indicates that the downstream slope is critical during end of construction and steady-state seepage and the upstream slope is critical during a rapid drawdown condition. Using recommended design standards: basically USACE, BDS and CDA the finite element analysis result shows the dam is stable for static and dynamic analysis at all critical loading conditions.

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