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Investigating Anomalous Seepage Trends in Selected Earth Dams: A Comprehensive Study

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ABSTRACT

Previous geotechnical reports established that the selected three dams, Igbeti, Awon, and Asa dams' embankments are loosed and permeable and there is possibility of erosion within dam embankment. Geotechnical and seepage analyses of the earth dams were conducted to evaluate the dams' safety against the leakages through the embankment dam.

Samples were collected at three different locations from the upstream and downstream sides of the dams, at depth of 600 mm using auger borer, and geotechnical tests were conducted on the samples, according to BS1377 of 1977 to determine the specific gravity (SG), sieve analysis, cohesion (C), angle of internal friction (ϕ), coefficient of permeability (K), and natural moisture content (NMC). Steady- state analysis, using SEEP2D was employed to investigate the seepage flows within the dams, to simulate flow rates, pore pressure, velocity magnitude, hydraulic gradient, and seepage quantity.

Specific gravity values of the samples ranged from 2.36 to 2.79 (upstream) and 2.27- 2.75 (downstream). The particle sizes passing through sieve number 200 (0.002 mm) varied from 1.00 – 21.21% (upstream) and 0.58- 23.71% (downstream), while maximum dry densities are within the limiting values of 19- 23.5 kN/m^2 (upstream) and 35.5 – 39.5 kN/m^2 downstream. Permeability coefficients obtained varied averagely from 1.36 x 10^{-5} to 8.18x 10^{-4} at upstream and 9.32 x 10^{-6} to 4.45x 10^{-4} at downstream, and values obtained classified the soils as low- permeability, silty clay embankment materials. Natural moisture contents varied from 10.47% - 26.72% at upstream, 10.71%- 23.60% at downstream. Seepage analyses results for Igbeti, Awon and Asa dams were respectively: flow rates (3.9 x10^{-7} – 7.8 x10^{-7}; 2.98x10^{-6} – 3.32x10^{-6}; 6.00x10^{-6} – 6.60x10^{-6} m^3/s); pore pressure (50000 – 16800; 60000 – 93000; 130000 – 185000 kN/m); velocity magnitude (0.0 – 0.000705; 7.93x10^{-11} - 6.30x10^{-6}, 9.24x10^{-11} – 5.85x10^{-6} m/s).

The flow rates through the selected dams showed saturated embankments with the possibility of piping, and excessive leakage. Installation of internal drainage facilities such as sand filters, and toe gravel drains were recommended.

INTRODUCTION

Dams are major engineering structures that are designed and constructed with long life expectancy. An earth dam has its relevance in the supply of water for human and animal consumption and irrigation purposes (IDNR, 2003). Water impoundment is accomplished by the construction of an earth embankment usually 3-8 m high and several hundred of meters long across a river channel. The integrity of a dam embankment can be undermined by the existence of geological features (e.g. faults, fissures, jointed or shear zones), precipitated seepage zones in the bedrock and /or discontinuities in the structure itself (Ali- Zomorodian, 2005). Apart from loss of huge financial investment, other consequences of dam failure can be very devastating. Human, animal and material resources located on the immediate downstream side of such a failed dam are lost. Vast irrigable agricultural resources are wasted, so also are the aquatic lives in the previously impounded water. The cost of rehabilitation of failed dam can be enormous. In most cases, failed dams are completely redesigned and reconstructed at much higher cost. Dams are known to occasionally fail due to a combination of factors. These factors include age, decaying infrastructures, engineering design defects due to poor understanding of the subsurface geology, unstable construction materials, construction defects and lack of monitoring or maintenance of the dams (Olorunfemi *et al*., 2000; Mohammed *et al*., 2006). Adequate assessment of geotechnical properties is an important aspect of dam safety investigations (USDACE, 1986; Agbede and Oladejo, 2011a).

Filter with a simple but effective job is one of the principal parts in an embankment dam which is able to immune the dam against erosion, prevent water escape and seal unfavourable cracks that may occur through the impermeable core (Yasrobi and Azad, 2004). In addition to production, construction and economical aspects, choosing a proper, optimum and fit-to-need filter also should be taken into account.

The common kind of impermeable cores in embankment of dams are clayey soils that can effectively resist water pressure at upstream the dam. However, the occurrence of unfavourable cracks is not avoidable. In this case, filter with a simple job can improve the core duty and immune the dam against erosion and even control and seal the cracks. Therefore, choosing a proper filter for a certain base soil (the soil which should be protected) is needed.

Sherard and Dunnigan (1989) after about 10 years study on the filters, erosion and embankment dams proposed a repeatable test to assess a soil-filter system (for the critical filters). However, this test has not a standard procedure, it is frequently used and it is suggested to be used for filter designing (ICOLD, 1994).

Agbede and Oladejo (2009, 2010) had attempted the application of locally sourced granular filters and drain to model the control of seepage and piping in the fractured foundation of Awba dam, University of Ibadan, Nigeria; also, Agbede and Oladejo (2011b) investigated the dam embankment and its foundation for seepage problems, and modeled the dam with the installation of granular filter-drain, as means to controlling anomalous seepage and piping.

MATERIALS AND METHODS

Important features of the selected earth dams across the Southwestern Nigeria are shown in Table 1, while geometrical dimensions of the selected dams: Igbeti, Awon and Asa dams are shown in Figures 1, 2 and 3.

Geotechnical Analysis

For the geotechnical analysis, disturbed soil samples were obtained from upstream and downstream sides of the selected dams' embankments at four different points located at a depth of 0.6 m – 0.9 m. The tests carried out according to BS1377 of 1977 included, sieve analysis for soil classifications, specific gravity, and Residual Soil Compression tests to evaluate the cohesion(C) and angle of internal friction (AIF). California bearing ratio (CBR) and permeability tests were also carried out to ascertain the strength and the coefficient of permeability (K) of the soil samples respectively. Also, the natural moisture content (NMC) was determined.

Seepage Simulation with SEEP2D

SEEP2D was used to model seepage through the selected dams. Using Galerkin's method, the flow domain was subdivided in finite number of elements of a domain Ω^e and the boundary. The polynomial approximation of the solution is of the form:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t} \quad (1)$$

$$h^e(x,y,t)=\sum_{i=1}^{n}h_i^e(\mathrm{t})N_i^e(\mathrm{x,y}) \quad (2)$$

In which h_i^e are the piezometric head values at the nodes and $N_i^e$are the shape function over the finite element with n number of nodes (Luo, 2025; Mostafa and Zhenzhong, 2023; Zhang, 2025 and Khursheed, 2025).

The process involved:

1. Defining geometric configurations of each dam.
2. Assigning boundary conditions and material properties.
3. Running simulations to obtain flow lines, phreatic surfaces, pore pressure distributions, and velocity magnitude

Table 1: Some features of the selected earth dams across the Southwestern Nigeria

S/N	Dam type	Location	Dimensions (m)	Capacity of reservoir (m^3)	Year of establishment or completion
1.	Igbeti Earth Dam	Igbeti, Oyo State	h – 12 m crest width – 8 m slope 3:1/2:4:1 crest Length – 74 m	518,000 (m^3)	-
2.	Awon Earth Dam	Oyo town Oyo State	h-13.106 m width – 4.5 m l – 76.658 m	9,790,000 m^3 (9.79mcm)	1962
3.	Asa Earth Dam	Ilorin Kwara State	H – 27 m W – 6.0 m L – 154.5 m 1:3/1:2.5	43mcm maximum discharge of the dam is 79,000 cubic meters per second.	1952

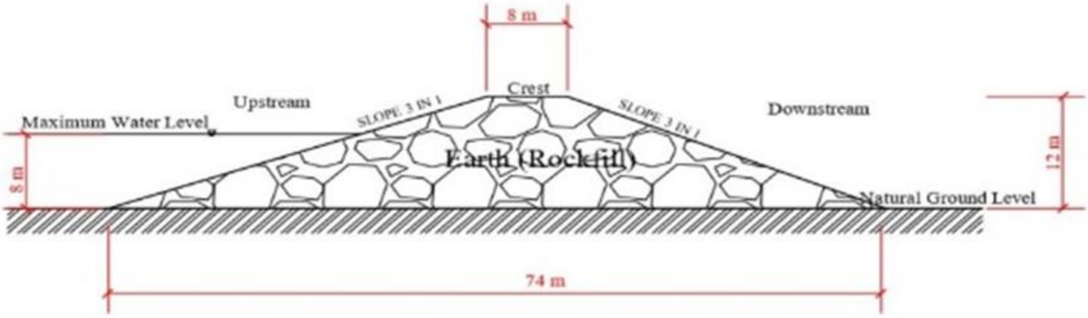
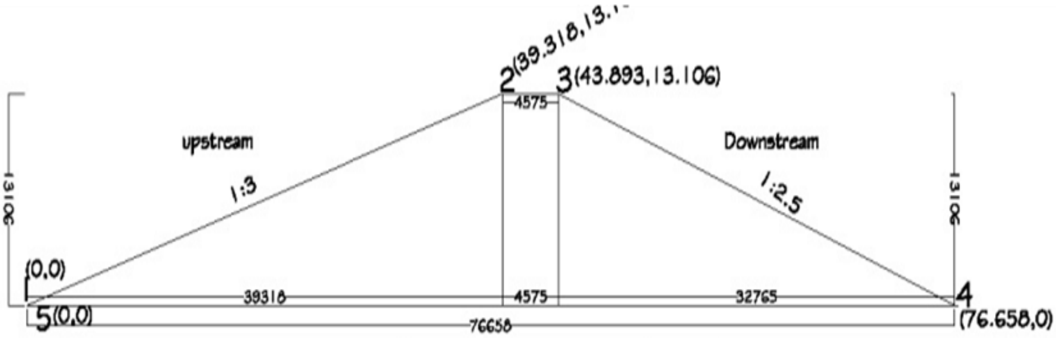


Figure 1: Showing the dimensions of the Igbeti embankment dam



Geometric dimension of Awon dam.
(Erelu water supply scheme,Oyo.)

Figure 2: Showing geometric dimension of Awon Dam (Erelu Water Scheme)

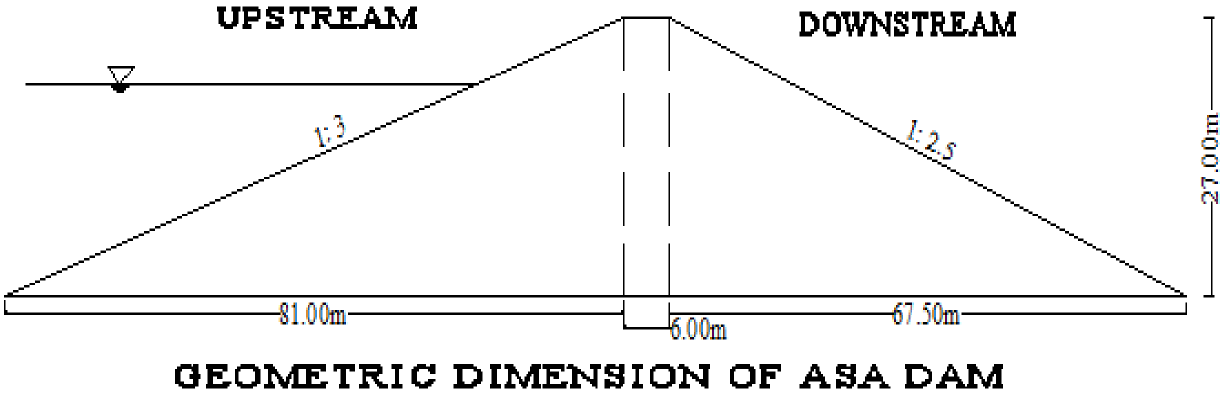


Figure 3: Showing the geometric dimension of Asa Dam

RESULTS AND DISCUSSION

Results and Discussion of Basic Geotechnical Analyses

The summaries of results of laboratory tests from the selected dams are presented in Tables 2, 3, and 4, respectively. The seepage analyses outputs were presented in Table 5.

Table 2: Results of Laboratory Analyses of soil samples collected from upstream and downstream slopes of Igbeti Dam.

Parameters	*Limiting values	Upstream Values n=3			Downstream Values n=3		
		Min. values	Max. values	Mean values	Min. values	Max. Values	Mean values
Specific gravity, Gs	> 2.60	2.31	3.08	2.79	2.46	2.07	2.47
Sieve Analysis (%)	% passing sieve, no 200 ≥ 40	21.60	21.40	21.21	23.50	23.10	23.71
Cohesion (kN/m^2)	> 18.0	18.0	20.0	19.0	28.0	43.0	35.5
Angle of Internal Friction (° - degree)	15 – 20	22.0	26.0	24.0	30.0	33.0	31.5
Permeability (K) cm/s	$< 1X\ 10^{-6}$	$7.23 X 10^{-4}$	$2.16 X 10^{-4}$	$8.18 X 10^{-4}$	$3.84 X 10^{-4}$	$5.24 X 10^{-4}$	$1.35 x 10^{-4}$
Natural		7.80	12.14	10.47	8.74	12.67	10.71

Moisture Content (%)							

Table 3: Results of Laboratory Analyses of soil samples collected from upstream and downstream slopes of Awon Dam.

Parameters	*Limiting values	Upstream Values n=3			Downstream Values n=3		
		Min. values	Max. values	Mean values	Min. values	Max. Values	Mean values
Specific gravity, Gs	> 2.60	2.31	3.08	2.69	2.46	2.07	2.27
Sieve Analysis (%)	% passing sieve no 200 ≥ 40	0.60	1.40	1.00	0.50	1.10	0.58
Cohesion (kN/m^2)	> 18.0	18.0	20.0	19.0	28.0	43.0	35.5
Angle of Internal Friction (° - degree)	15 – 20	22.0	26.0	24.0	30.0	33.0	31.5
Permeability (K) cm/s	< $1X\ 10^{-6}$	$7.23\ X\ 10^{-6}$	$2.16\ X\ 10^{-5}$	$1.44\ X\ 10^{-5}$	$3.84\ X10^{-6}$	$5.24\ X\ 10^{-6}$	$4.54\ x\ 10^{-4}$
Natural Moisture Content (%)		8.80	12.14	10.47	9.74	11.67	10.71

Table 4: Results of Laboratory Analyses of soil samples collected from upstream and downstream slopes of Asa Dam.

Parameters	Limiting values	Upstream Values n=3			Downstream Values n=3		
		Min. values	Max. values	Mean values	Min. values	Max. value	Mean values
Specific gravity, Gs	> 2.60	2.21	2.50	2.36	2.61	2.89	2.75
Sieve Analysis	% passing sieve no 200 ≥ 40	2.30	11.00	6.65	2.10	3.00	2.55
Cohesion	> 18.0	21.00	26.00	23.50	38.00	41.00	39.50
Angle of Internal Friction	15 – 20	28.00	29.00	28.50	27.00	32.00	29.50
Permeability, (K),							

cm/s	< 1X10^{-6}	1.19 X 10^{-5}	1.52 X 10^{-5}	1.36 X 10^{-5}	9.25 X 10^{-6}	9.38 X 10^{-6}	9.32 X 10^{-6}
Natural Moisture Content		24.22	29.21	26.72	11.82	35.37	23.60

Soil Classification and Permeability

Findings from the study indicate variations in permeability among the three dams. Igbeti Dam has lower permeability compared to Asa and Awon Dams. Low permeability soils (such as clayey materials) are more resistant to seepage, whereas high permeability soils (such as sand or gravel) may allow excessive water infiltration, increasing the risk of internal erosion and piping (Fell et al., 2014).

Shear Strength Parameters (Cohesion and Angle of Internal Friction)

The shear strength analysis determined the cohesion (C) and angle of internal friction (ϕ), which influences the stability of dam embankments. Higher cohesion and friction angles indicate stronger soil resistance to shear failure. Weak soils with low shear strength are more susceptible to slope failure under high pore pressures (ICOLD, 2013).

Natural Moisture Content (NMC) and Specific Gravity (SG)

NMC varies across dam sites, with higher moisture content observed in areas with higher seepage. High moisture content can reduce soil strength and contribute to slope instability, increasing the likelihood of embankment failure (Das and Sobhan, 2018).

Seepage Analysis Results

The SEEP2D modeling provided a detailed assessment of seepage flow rates, phreatic surface levels, pore water pressure, and velocity magnitudes and presented in Table 5.

Table 5: Seepage analysis results for Igbeti Dam, Awon and Asa Dams

Parameters	Igbeti dam	Awon Dam	Asa Dam
Flow Line	112.0 – 113.08	113.1 – 114.0	126.90 – 128.70
Flow Rate (m^3/s)	3.9 x10^{-7} – 7.8 x10^{-7}	2.98x10^{-6} – 3.32x10^{-6}	6.00x10^{-6} – 6.60x10^{-6}
Pressure Head (m)	5.0 – 10.3	6 – 9.3	13.00 – 18.50
Pore Pressure kN/m^2	50000 – 16800	60000 – 93000	130000 – 185000
Velocity Magnitude (m/s)	0.0 – 0.000705	7.93x10^{-11} – 6.30x10^{-6}	9.24x10^{-11} – 5.85x10^{-6}
Total Head (m)	0.0 – 10.8	0.0 – 9.0	0.00 – 18.00
Gradient magnitude	0.0 – 0.405	0.0 – 0.405	0.00 – 0.405

Phreatic Surface and Seepage Paths

The phreatic surface is higher in Asa Dam, indicating more water movement through the embankment. A high phreatic surface reduces the effective stress in soil, weakening the embankment and increasing the risk of slope instability (USACE, 2007).

Seepage Flow Rate

There is a higher flow rate at the upstream and it decreases as it moves to the toe of the downstream. The higher the volume, the higher the flow rate and the lower the volume, the lower the flow rate that constitutes the seepage water within the embankment. It is maximum at the face of the water with the head boundary condition, and lowest at the toe. The generated flow rates ranged between 3.9 x10^{-7} – 7.8 x10^{-7} m^3/s/width for Igbeti dam, 2.98x10^{-6} – 3.32x10^{-6} m^3/s/width for Awon dam while 6.00x10^{-6} – 6.60x10^{-6} m^3/s/width for Asa dam. Figures 4a, b and c show the flowrate plots.

Higher seepage rates in Asa Dam indicate a higher risk of internal erosion and piping. If seepage is uncontrolled, it may lead to progressive dam failure

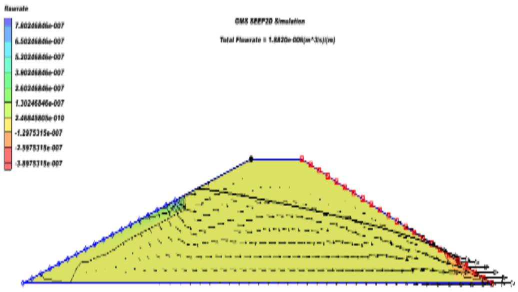


Figure 4a: Flow Rate Plot of Igbeti Dam from the SEEP2D software

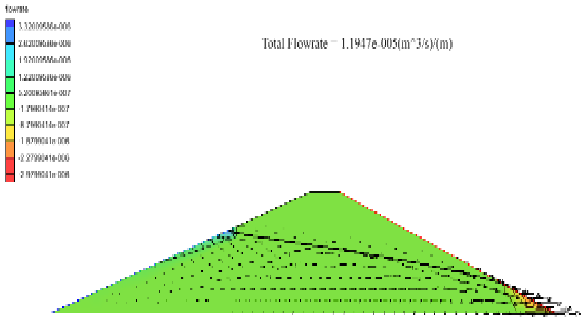


Figure 4b: Flow Rate Plot of Awon Dam from the SEEP2D software.

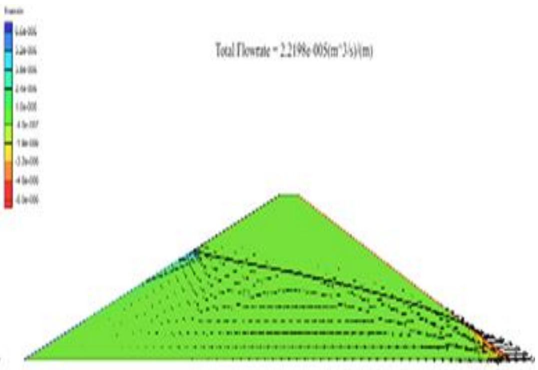


Figure 4c: Flow Rate Plot of Asa Dam from the SEEP2D Software

Pore Water Pressure Distribution

There would be pore pressure at the upstream because at the upstream, there is higher accumulation of water and lower pore pressure at the downstream. These are maximum along the head face of the dam with the base, and gradually increase with height diagonally.

Figures 5a, b and c show plot of the pore pressure with velocity direction in the dam. Excessive pore pressure at Asa Dam suggests a higher risk of seepage-induced instability.

(Foster and Fell, 2001). Mitigation measures such as upstream clay blankets, cutoff walls, or grout curtains may be necessary.

High pore pressures can trigger internal erosion or slope failure by reducing soil shear strength (ICOLD, 1994).

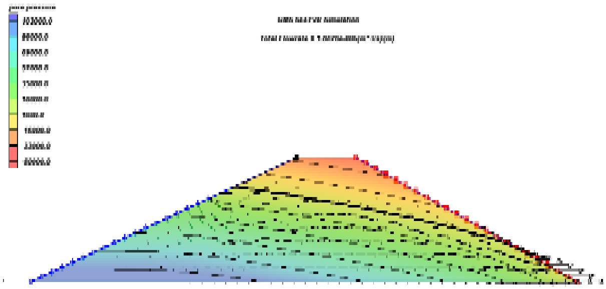


Figure 5a: Pore Pressure of Igbeti Dam from the SEEP2D software

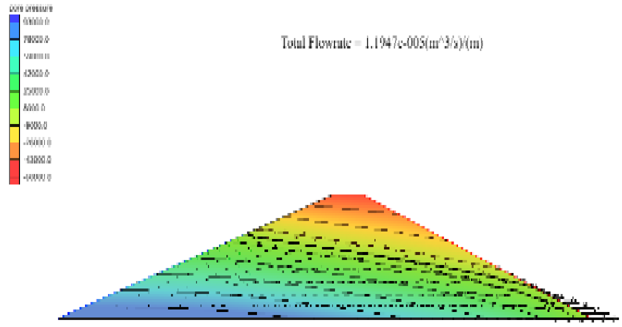


Figure 5b: Pore Pressure of Awon Dam from the SEEP2D software.

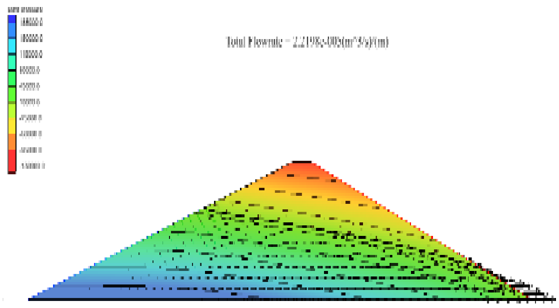


Figure 5c: Pore Pressure of Asa Dam from the SEEP2D Software.

Velocity Magnitude and Risk of Piping

The velocity magnitude of the seeping water decreases as it moves towards the downstream toe which leads to piping in the dam embankment. Figures 6a, b and c show plot of the rate of velocity magnitude in the dam.

Seepage velocity is highest near the upstream face and decreases toward the downstream. High velocity magnitudes increase the potential for piping, where soil particles are gradually removed by flowing water, leading to internal erosion and potential dam failure (Richards and Reddy, 2007).

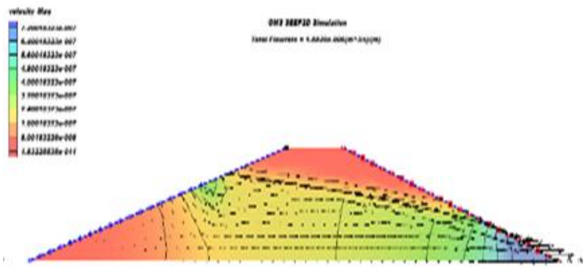


Figure 6a: Velocity Magnitude Plot of Igbeti Dam from the SEEP2D software.

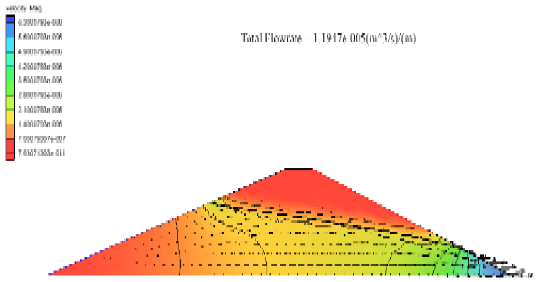


Figure 6b: Velocity Magnitude Plot of Awon Dam from the SEEP2D software.

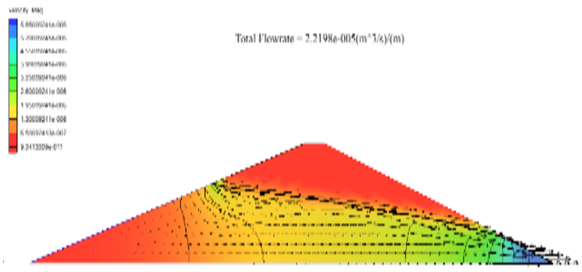


Figure 6c: Velocity Magnitude Plot of Asa Dam from the SEEP2D Software.

Gradient Magnitude

The gradient magnitude decreases as the seeping water flows from the upstream of the dam embankment towards the downstream toe. It is higher at the toe, as it is the exit point of the dam, posing a possibility of break up in the future. Figures 7a, b and c show plot of the gradient magnitude in the dam.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION

1. Seepage exists in all three dams, with Asa Dam exhibiting the highest flow rate and pore pressure, requiring immediate mitigation to prevent piping and embankment failure.

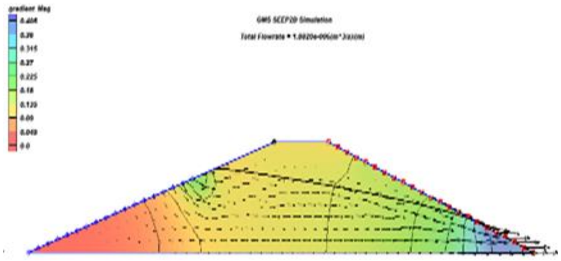


Figure 7a: Gradient Magnitude plot of Igbeti Dam from the SEEP2D software.

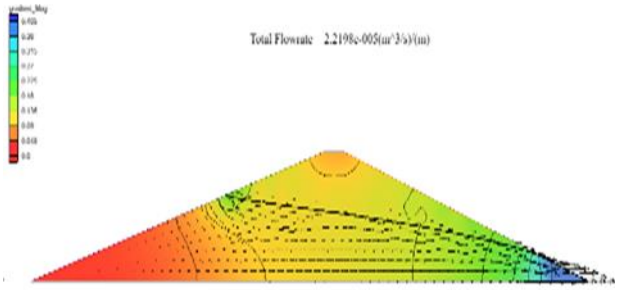


Figure 7b: Gradient Magnitude plot of Awon Dam from the SEEP2D software

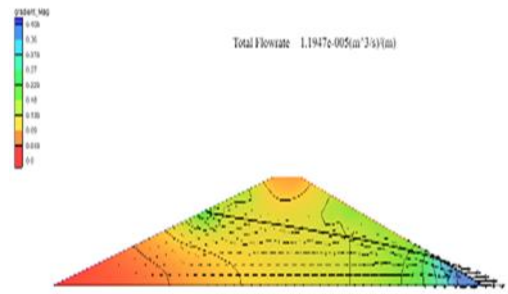


Figure 7c: Gradient Magnitude plot of Asa Dam from the SEEP2D

2. Numerical modeling with SEEP2D effectively visualized seepage flow paths, highlighting areas prone to piping and internal erosion.
3. Awon Dam exhibits moderate seepage rates, which may require additional monitoring and drainage improvements.
4. Igbeti Dam has the lowest seepage rates, indicating better geotechnical conditions for long-term stability.

RECOMMENDATIONS

Seepage Control:

i. Clay blankets or grout curtains should be provided.
ii. Provision should be made for adequate drainage systems

Structural Enhancements:

i. Weak embankment zones should be reinforced using soil cement – mixtures
ii. Cutoff walls for high-risk areas should be given consideration.

Regular Monitoring:

i. Pore pressure variations should be tracked using piezometers
ii. Periodic geotechnical tests should be conducted to detect slightest changes in soil strength.

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