Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Integrated Geological, Geophysical, and Geotechnical Site Characterization of Ajima Dam Site, Amhara Region, Ethiopia: Implications for Seepage and Foundation Stability

Nigus Kebede Asmerom
Amhara Design and Supervision Works Corporation, Bahir Dar, Ethiopia
Leulaem Shano Bako
Arba Minch Univesirty
Tadesse Demisie Fenta
tdsgeol09@gmail.com

Injibara University https://orcid.org/0000-0003-1550-4802

Research Article

Keywords: Geological, Rock Mass Rating (RMR), Geotechnical, Seepage Assessment, Geophysical Investigation

Posted Date: July 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10185442/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Integrated Geological, Geophysical, and Geotechnical Site Characterization of Ajima Dam Site, Amhara Region, Ethiopia: Implications for Seepage and Foundation Stability.

Nigus Kebede[1], Leulalem Shano[2], Tadesse Demisie[3]

[1]Amhara Design and Supervision Works Corporation, Bahir Dar, Ethiopia.

[2]Department of Geology, College of Natural Sciences, Arba Minch University, P.O. Box 21, Arba Minch, Ethiopia.

[3]Department of Geology, College of Natural Sciences, Injibara University, P.O. Box40, Injibara, Ethiopia.

Cross ponding author:-tdsgeol09@gmail.com

Abstract

The Ajima Dam, a 48m-high earth fill structure in the Amhara Regional State, Ethiopia, was investigated using an integrated approach combining geological mapping, borehole drilling (19 boreholes, 633m total), geophysical surveys (VES, seismic refraction), and geotechnical testing. This study provides the first comprehensive characterization of the site, identifying a critical load stress mismatch and complex geological setting. The allowable bearing capacity of the upper 5m (<1.1 MPa) is insufficient for the applied dam load (1.154 MPa), indicating a factor of safety <1.0 that requires excavation. Seepage analysis reveals high permeability in the valley floor (Lugeon values up to 75 LU, equivalent to 7.5×10^{-6} m/s) and left abutment (66% of tests >1 LU), while the right abutment shows low permeability (76% of tests <1 LU). Rock mass quality improves with depth, RQD ranges from 25-50% (poor) in weathered zones to 90-100% (excellent) in fresh ignimbrite below 35m, UCS values vary from 1.6 MPa (tuff) to 99.2 MPa (basalt). Seismic hazard assessment places the site in Zone IV (PGA 0.20g), with site amplification potential due to velocity contrasts (Vs <1000 m/s in overburden vs. >3500 m/s in bedrock). Critical geological hazards include faults crossing the dam axis (N86°W), caves in laterite soils, and pervious zones ($k=10^{-5}$ m/s) requiring grouting. Excavation of the upper 5-6m of valley floor materials, 30m-deep curtain grouting with 2-3 rows at 1.5-2.0m spacing, upstream impervious blanket extending 30m from the dam toe, and seismic resistant design modifications are some of the recommendation part to minimize the dam risk.

Keywords: - Geological, Rock Mass Rating (RMR), Geotechnical, Seepage Assessment, Geophysical

Investigation

1. Introduction

1.1. Background

Investigation conducted on earth dam has similarities and difference with investigation conducted on other civil engineering structures like, building, bridge, tunnel, roads, etc. But, as a general geotechnical, geological, engineering geological and geophysical investigations should be implemented before construction of any dam (Sari et al., 2020; Srivastava et al., 2023; Adewoye and Eshoo, 2017; Bell, 2017).

Geological investigation helps to identify composition and properties of rock types, soil type, and groundwater condition. Furthermore, it used to observe existence of geological structures, and geological hazards (Adamo et al., 2020; Barjasteh, 2017; Olasunkanmi, 2018; Birhanu, 2023). Investigating geological condition of the dam site helps to enhance dam foundation stability, seepage control, determine slope stability, identify geological material nearby the dam site and others (Kanik, 2019). Engineering geological investigation of the dam site is a key task for the stability, safety, and life span of the dam. This investigation is performed on soil, rock, groundwater, geological structures, and geological hazards of the dam site (Belete et al., 2024; Ukpai, 2021; Xiang et al., 2024; Taleb et al., 2024; Li et al., 2024). Engineering geological information helps for dam structural designers to choose the most suitable foundation, spillway, and reservoir area of the dam. This investigation helps for engineers to build a dam free from seepage, settlement, subsidence, landslides, seismicity, and groundwater related issues (Gosschalk, 2022; National research council, 2006; Salmasi and Abreham 2022). According to (Ayogu et al., 2024;Jabeen et al., 2024; Dai et al., 2021; Himi et al., 2018) engineering geological investigation of the dam site integrates a lot key tasks which includes geological mapping, geotechnical investigation, seismic hazard assessment, slope stability analysis, hydrological studies, geological hazard assessments, and others.

Geotechnical investigation has an irreplaceable role in dam construction. It helps to civil engineers and geotechnical specialists to understand the properties of soil, rock, groundwater conditions of the dam site (Tanchew, 2014; Iraji and Matahari, 2024; Rana et al., 2024; Demisie et al., 2024; Lyu et al., 2019).

Field surveys, standard penetration tests, cone penetration tests, borehole logging, several laboratory tests, field permeability tests, and others are some of the key tasks performed under geotechnical investigation of the dam (Parry et al., 2014; Fan et al., 2021; Sari and Almdag, 2020). A lot of scholars published papers about the purpose of geophysical surveys for dam sites. According to Tabwasah and and Obiefuna (2012), Forzeri et al.,(2008); Raji et al.,(2017)and Magnekou et al.,(2022) geophysical survey is one of the principal activities to assess and select a suitable dam site. It uses different geophysical techniques for environmental impact Assessment, subsurface geological profiling, characterizing rocks and soil properties, detection of caves and buried objects, and groundwater condition assessments.

According to FAO, (2016) total of 14 embankment dams were constructed in Amhara region, Ethiopia. However, only 1 of 14 dams is functional according to the plan of implementation. Insufficient geological, geophysical, and engineering geological assessment of the dam may cause foundation instability, seepage and leakage problem, geological hazards, reservoir impact, environmental impact, and delay the construction time and other related issues. In addition to this, lack of risk assessment and a lack of monitoring system is the triggering factor for the failure of the dam (Dam safety bureau, 2008).

Some of the Evidence of dam failure in Ethiopia due to poor investigation are, Katar Dam seepage issues due to inadequate foundation characterization (Belete et al. 2025), Tekeze Dam foundation treatment challenges (Anny et al. 2020) and International examples, Malpasset Dam (Duffaut, P. 2013) foundation geology failure, St. Francis Dam (Rogers, 2006) due to inadequate geological investigation.

The Ajima dam site was selected for this investigation for three reasons. Firstly, it is a proposed large-scale irrigation dam (height 48m, crest length 374m) with significant regional importance. Secondly, it is located within the Main Ethiopian Rift, a tectonically active zone that poses challenges applicable to many Ethiopian dam projects, and thirdly, previous dam failures in the Amhara region highlight the need for rigorous pre-construction investigation at this site.

Research gap and novelty of this work lies in its site specific combination Integrated Geological,

Geophysical, and Geotechnical data to identify critical engineering vulnerabilities for the Ajima dam. Let's see some of them.

1. Identification of load-stress mismatch: - The study identifies a critical safety gap, the allowable bearing capacity of the top 5m is insufficient for the expected load stress (1.154 MPa). This finding is a vital contribution to the safety assessment and design modification of the dam.

2. High Resolution Subsurface Characterization: - Using integrating geophysical surveys (seismic and resistivity) with mechanical tests (Packer and SPT), the study provides a precise map of the highly weathered/fractured zone (the top 0–5m) vs. the "fair" rock mass below.

3. Hydraulic Conductivity Mapping: -the study distinguishes between the impervious clay and alluvium (1.3* 10-8 m/s and the pervious laterite 10-5 m/s providing the necessary data to design effective seepage control measures.

4. Integration of geology, geophysics, and geotechnical data into a Geo-Conceptual Model.

This manuscript fills listed gaps which are considered and published as the gaps in Ethiopia's dam site investigations. Furthermore, this study addresses critical scientific and engineering questions regarding the suitability and characterization of the Ajima dam site. Specifically, it evaluates the geotechnical properties of the earth materials, assesses foundation competence and safety relative to expected loads, and identifies primary geological risks such as fracturing and permeability. Furthermore, it demonstrates a multidisciplinary synthesis of geological, geophysical, and geotechnical investigation methods.

While this study focuses on a single dam site, the methodologies and findings have broader implications. The identification of load-stress mismatches, permeability heterogeneity, and seismic vulnerability is relevant to other Ethiopian dam projects in similar geological settings (volcanic terrains within the Main Ethiopian Rift). The quantitative design recommendations (excavation depth, grout curtain parameters) provide a template for foundation treatment in comparable geological environments.

2. Description of the Study Area

Administratively, Ajima Dam is located in the Amhara regional state, specifically at UTM 1048537m N, 558074m E (Fig.1).

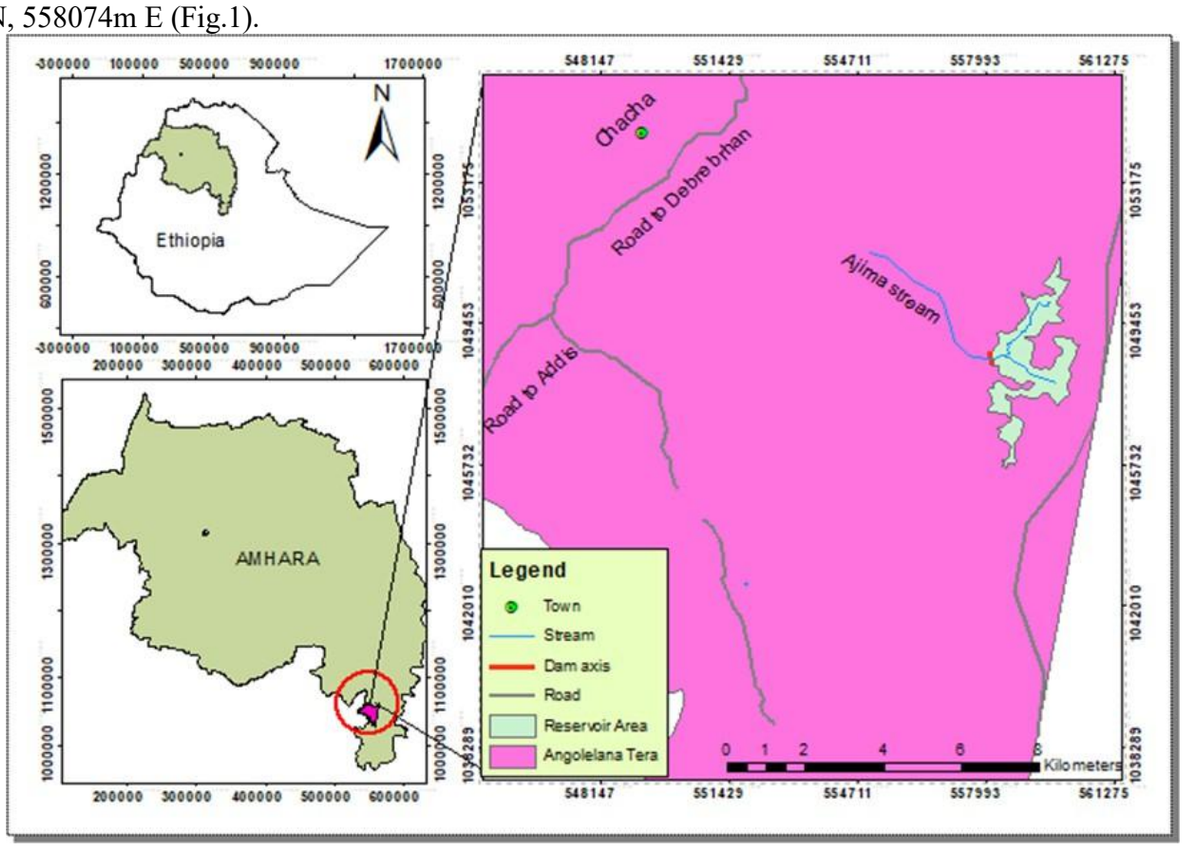


Figure **1**. Location map of Ajima dam site

2.1. Physiography

Topographically, Ajima dam site is located in a wide 'V' shaped valley and its elevation varies from 2650m to 2950 m above sea level. It is located near the central portion of the northwestern plateau. It has a gentle to moderate slope (Fig. 2). The wide V-shaped valley morphology influences dam design in several ways. The relatively broad valley floor reduces dam height for a given storage volume, the valley geometry affects the length of the grout curtain, and sediment transport and reservoir sedimentation patterns are influenced by valley morphology.

It has a dendritic drainage pattern indicative of a well-integrated fluvial system, has the following engineering implications. (1) It suggests relatively uniform lithology and erosion resistance across the watershed. (2) It influences runoff concentration and peak flow rates. (3) It affects reservoir sedimentation patterns, with potential implications for dam longevity.

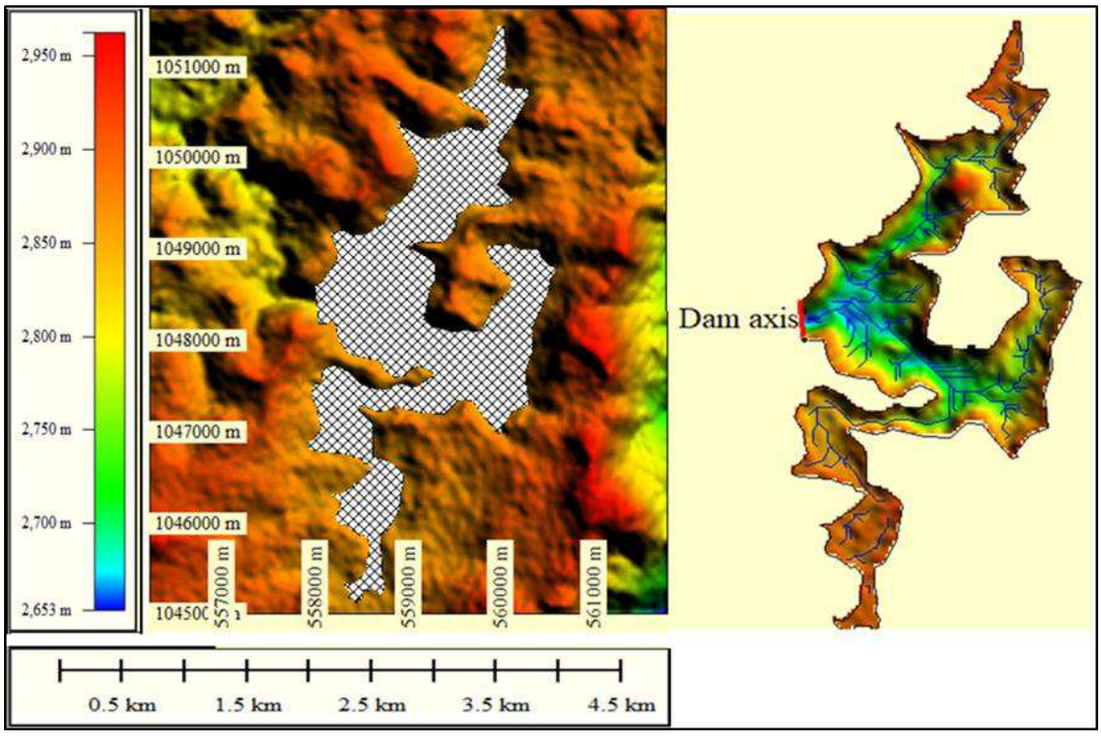


Figure 2. Physiographic map of the study area.

3. Materials and Methods

Different field and laboratory equipment were used for this research work. Geophysical (VES and Seismicity) equipment, drilling machine with full accessory form Amhara design and suppression Work Corporation, nitrogen gas cylinder, water flowmeter and pressure gauge were used. Other standard field (GPS, compass, tap meter, geological hammer, and others) and laboratory equipment (point load test, Atterberg limit test apparatus, sieve shaker, Permeameter and other) were used.

Methods

For this study, various methods including, geological, geophysical and Geotechnical methods were conducted. This study used different techniques for data collection, analysis and interpretation. These were generally preliminary and detailed field surveys, surface and subsurface investigations, field and laboratory tests, and overall data analysis and data interpretations.

Field Survey

In the field, several tasks were performed which includes, preliminary field survey, detailed field survey, field tests / insitu field measurements, and others. The base map was prepared for the study area from the topographic map of the dam site at the scale of 1:1,000. Measuring, describing and collecting basic information of soils and rock exposures were conducted using traverses through three grid lines aligned towards SE-NW directions at an average space of 500m difference. The surface data collection on rock

outcrops was mainly through discontinuity measurement using the scan line surveying method from the outcropped surface in the abutment foot and stream bank exposures within the dam foundation. During field activity, some important insitu tests (water pressure test and standard penetration test) were conducted within the dam foundation. The water pressure test was carried out to determine the permeability of the seepage suspected geological materials.

The SPT was conducted to evaluate the bearing capacity (strength) of foundation materials (weak or soft rock).

Then, the field investigation was accomplished according to (EAIG, 1981) which supports in detail the description and classification of soils and rocks for engineering geological mapping.

Seven samples were selected from the 22 test pits based on, (1) spatial distribution across the reservoir area to capture lateral variability, (2) representativeness of major lithological units (alluvium, laterite), and (3) depth intervals corresponding to the foundation zone. This sampling strategy follows the approach recommended by IAEG (1981) for reconnaissance level investigations.

Laboratory Testing

Performing laboratory tests on samples collected from test pits or boreholes is used to conduct soil classification and shear strength tests (Zhan et al., 2014; Horton et al., 2015).

For this study, laboratory tests such as particle size distribution, Atterberg limits, and permeability laboratory tests were performed.

Grain size analysis and Atterberg limit tests

For this investigation, twenty-two (22) test pits were dug at 1m to 2.5m depth in the reservoir area and seven (7) representative disturbed soil samples were collected for laboratory testing. Grain size analysis tests were conducted based on ASTM, 2000 standard and Soil Classification was performed based on unified soil classification system Atterberg limit tests were conducted based on the Casagrande, 1932 standard.

Permeability Test

For this study, two types of laboratory tests (Falling head test and Constant head test) were done to estimate the permeability of disturbed soil samples.

According to ASTM, 2000, falling head test was performed and it allows the load to decrease as water

penetrates the sample, thereby reducing pressure during the test. This method is usually limited to fine-grained soils in the laboratory. Moreover, constant head test was conducted for coarse grain soil and it refers to a test in which the relative elevation of the top of the water column (pressure head) remains over the sample throughout the test.

While disturbance can affect permeability measurements, the falling-head and constant-head tests on disturbed samples provide conservative estimates of hydraulic conductivity (Head, 1992), and conducted in-situ permeability testing in boreholes for final design verification.

Rock Mass Rating (RMR) System

Details on a classification method for rock mass known as the geo-mechanical classification or rock mass rating (RMR) system were suggested by Bieniawiski (1978).

Rock Quality Designation, RQD

To quantify the quality of the rock from drill cores, Deer and Miller (1966) developed the concept of the RQD. $RQD = \frac{\Sigma \text{ length of core pieces } >10\text{cm} \times 100\%}{\text{Total length of the core}}$.....(3.1)

RQD can also be calculated from the correlations by Hudson and Priest (1976), using the following equations.

$RQD = 100^{e-0.1} \lambda (0.1 \lambda+1)$.....(3.2)

Where, λ is 1/joint frequency.

Finally, the Correlation between RQD value and Rock Quality was determined based on Deere (1988).

Spacing of discontinuities and unconfined compressive strength

The measurement was conducted on a rock unit to measure surficial discontinuity distribution. It was characterized based on (ISRM, 1981). Unconfined compressive strength (UCS) was used to characterize the intact rock of the dam site. The unconfined compressive strength of intact rock or rock materials was done based on (ISRM, 1981).

Geophysical Methods

Subsurface investigation for engineering geological data collection was conducted using geophysical surveys, borehole drillings & test pits. Two common types of geophysical methods (electrical resistivity

and seismic refraction survey) were used to determine the engineering geological conditions of the dam foundation and reservoir area.

Electrical resistivity method

Raw VES data one profiling data were collected in the reservoir. Electrical profiling (EP) survey was conducted in the area across the Ajima River on the reservoir area of the dam. The main target of the EP survey is to identify the relative position and orientation of geological structures and lithological contacts which may have an importance for the dam construction. To conduct this survey the equipment, ABEM Terrameter LS2 was used. The data for this work Acquisition was Winner array configuration for both profiling and sounding. For Electrical Profiling (EP), a fixed electrode spacing (a = 15m, 30m, 50m) was maintained along a 170m traverse. For Vertical Electrical Sounding (VES), electrode spacing (AB/2) was progressively maximized to achieve the desired depth of investigation. Raw apparent resistivity data were processed using SeisImager/2D or Rayfrac and mapping golden surfer software. Inversion was performed with a smoothness constrained least squares algorithm to derive true subsurface resistivity models and generate iso resistivity depth slices (profiling) and 1D resistivity-depth curves (VES).

Seismic refraction method

Seismic refraction method was performed to determine the subsurface geological conditions of the upstream, downstream, and the dam axis. It measures the precise arrival timings at a series of geophones of compressional waves caused by an explosion or the impact of a falling weight. To perform this survey 24-channel seismograph, 14 Hz geophones, hammer/plate source instrument was used. Data acquisition for this survey involved the deployment of three 2D seismic profiles, as detailed in Table 5. Shot gathers were systematically recorded at each geophone location and at specified offset positions using a manual hammer source. P-wave first arrivals were manually picked and processed using SeisImager/2D. Through iterative tomographic inversion, a 2D velocity-depth model was generated by minimizing the residuals between observed and calculated travel times.

Generally, field survey, field test, geophysical survey, and laboratory test analysis were conducted and followed by producing geological map, geophysical map, engineering geological map, and engineering geological cross-sections using different software (Auto CAD, Global Mapper, and GIS). After overall analysis, some mitigation and remedial plans were suggested based on the investigated results (Fig. 3).

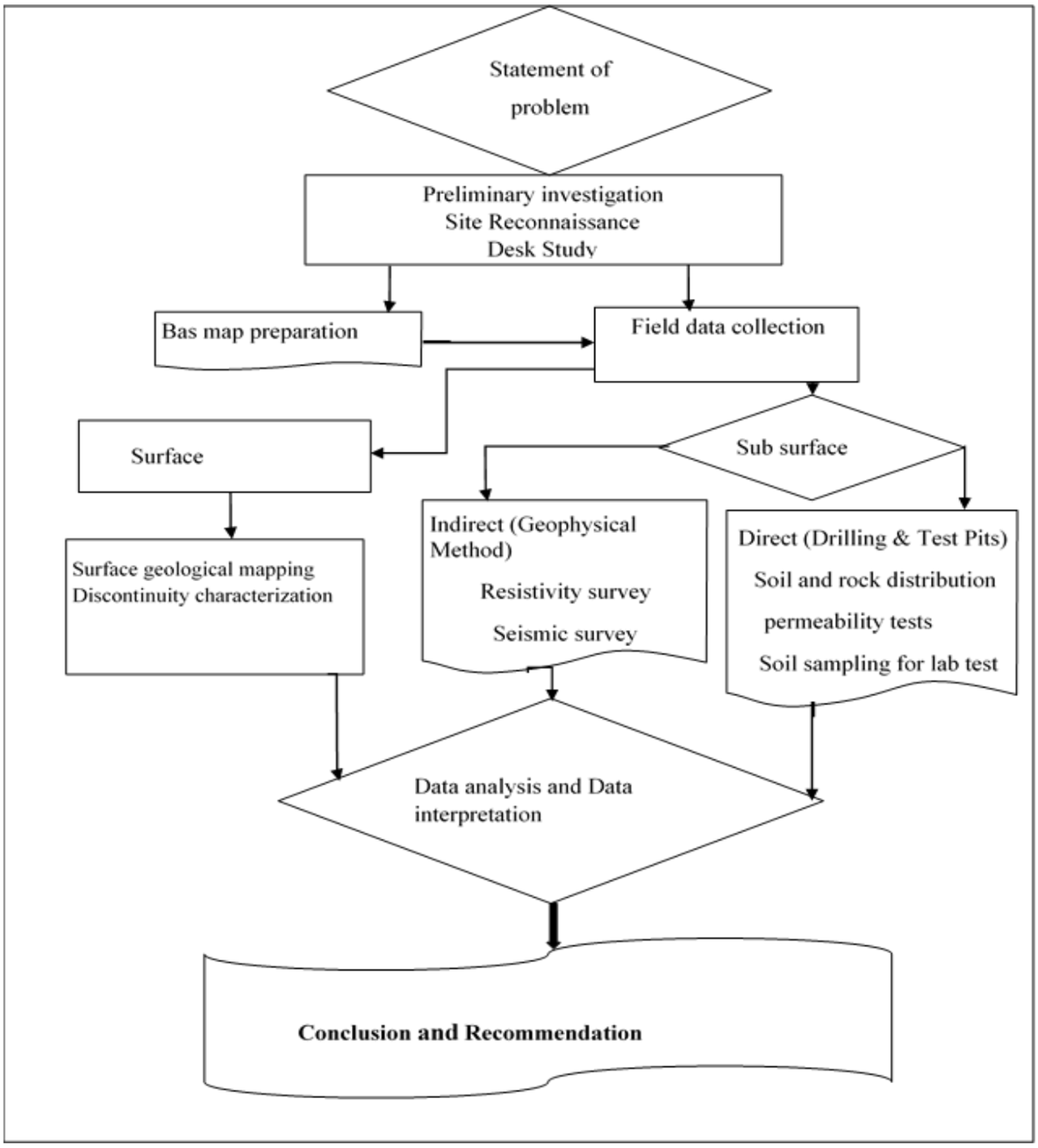


Figure **3**: Overall methodology flowchart

Integration was achieved through iterative cross validation, (1) geophysical interpretations were calibrated against borehole logs, (2) laboratory UCS values were correlated with seismic velocities, (3) RMR classifications were validated using borehole RQD data, and (4) seepage zones identified by Lugeon tests were cross-referenced with resistivity anomalies.

Data quality assurance included, (1) SPT measurements following ASTM D1586 with hammer energy monitoring, (2) laboratory tests conducted in duplicate with precision <5%, (3) geophysical data processing with iterative inversion (RMS error <5%) and (4) borehole logging by experienced engineering geologists. Uncertainty in geophysical interpretations is estimated at ±10-15% for velocity and ±20% for resistivity based on inversion residual analysis.

4. Results

4.1. Surface and Structural Geology

4.1.1. Lithological Units

Regionally, the Ajima dam site lies within the Tarmaber Formation, part of the Ethiopian volcanic province. The formation comprises alternating sequences of tuff, scoria lava flows, and laterites, with minor intercalations of ignimbrite and basaltic flows. Structurally, the area is influenced by the Main Ethiopian Rift, which trends SSW from the Afar Depression, characterized by normal faulting and associated fracturing (Fig.4).

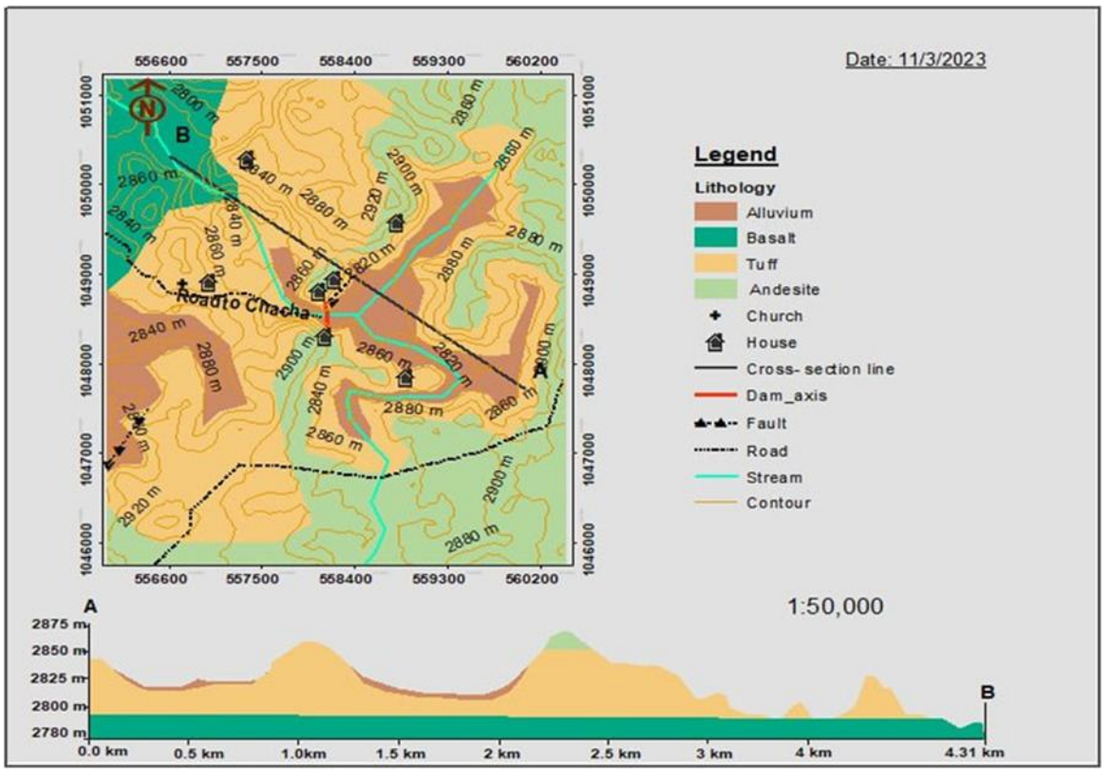


Figure **4**. Geological map and it cross section of Ajima dam site

4.1.2. Discontinuity Survey

The study area is located in the part of Main Ethiopian rift zone and it is affected by fault, fracture, and joints. At the dam site, faults were mapped crossing the dam axis nearly perpendicular and having an extension into the reservoir with an orientation of N860W. Furthermore, Natural openings or caves are also observed at the right abutment downstream slope face within the laterite soils. The presence of cave on laterite soil at downstream will cause geological hazard (Fig. 5). Moreover, Joint 1 orientation 620/0580, Joint 2 orientation 850/0260 and fault orientation 680/1840, respectively. Both joint set

orientations are towards the northwest which is nearly along the stream flow direction, whereas the fault is aligned towards the west. The discontinuity data were analyzed using “Dips” which is based on stereographic projection technique (Fig.6 and table 1).

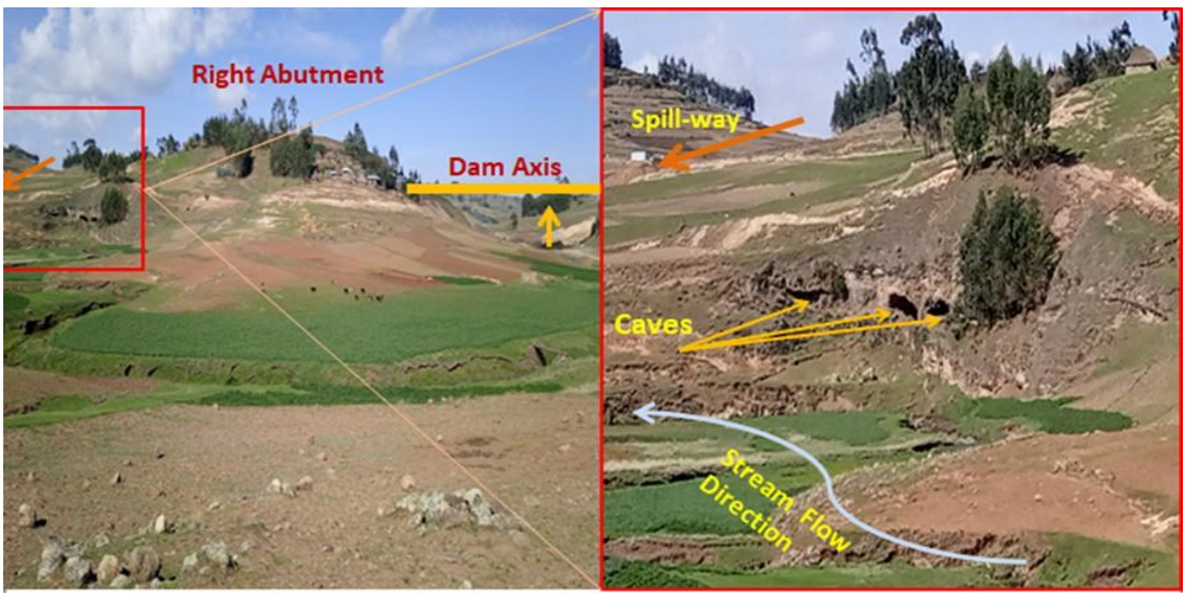


Figure **5**. Cave at the downstream of Ajima dam

Table **1**. Quantitative distributions of joints of each rock unit.

Parameter	**Range**	**Description**	**Distribution (%)**		
			Right bank	Right Abutment foot	Valley Floor Area
			Basalt	Tuff	Ignimbrite
Spacing (cm)	< 2	Extremely close	-	-	12
	2 - 6	Very close	-	-	50
	6 - 20	close	-	-	18
	20-60	Close	10	1	10
	60-200	Moderate	0	0	-
		Wide	-	90	
Persistence (m)	1 - 3	Low	27	88	23
	3 - 10	Mediu m	73	12	27
	10 - 20	High	-	-	50

Aperture /Separation (mm)	0.25 - 0.5 0.5 - 2.5 2.5 - 10 10 - 100	Partly open Open Moderately wide Wide	12 50 38 - -	94 6 - -	37 16 33 - 14
Infillings	Calcite Clay Open		6 50 44	- 5 5 45	-48 58 -
Roughness (JRC)	0 - 2 2 - 4 4 - 6 6 - 8 8 - 10		15 35 50 - -	60 20 20 - -	- 29 31 40 -

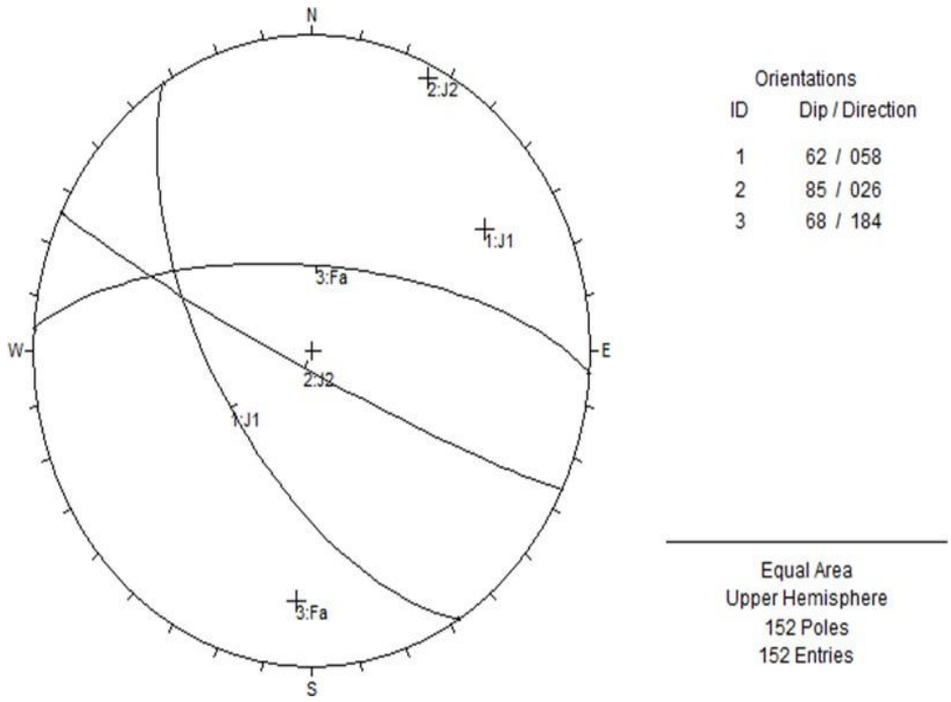


Figure **6**. The discontinuity data at the dam foundation.

4.2. Subsurface Geotechnical Properties (Borehole Data)

At the dam site, a total of nineteen (19) boreholes were drilled with a total depth of 633m, out of which seventeen (17) boreholes were at the dam foundation. The drilling was made to conduct field or in situ tests such as Lugeon or Packer tests to determine rock quality designation (RQD) values, and to collect rock samples for laboratory testing. The seventeen (17) Boreholes were drilled during a detailed field investigation.

4.2.1. Rock Strength (UCS)

The uniaxial compression test is a laboratory test used to derive the uniaxial compressive strength (UCS) of a rock material. The UCS values of foundation rocks at the Ajima dam site are categorized as very low to high-strength rocks (Table 2).

Table **2**. Average UCS values of intact rock strength of the foundation rocks (ISRM, 1981).

Location	Rock Unit	UCS (MPa)	Intact rock strength, MPa
Valley Floor	Ignimbrite	7	Low
Right Abutment	Basalt	99.2	High

Left Abutment	Tuff	1.6	Very low

4.2.2. Rock Quality (RQD & RMR)

Rock Quality Designations (RQD) of Rocks

The average RQD values of each rock type in every borehole concerning the dam foundation are described in (Fig.7.). These values show that the frequency of fracture is relatively high in the left and right abutment while low fracture frequency is at the valley floor.

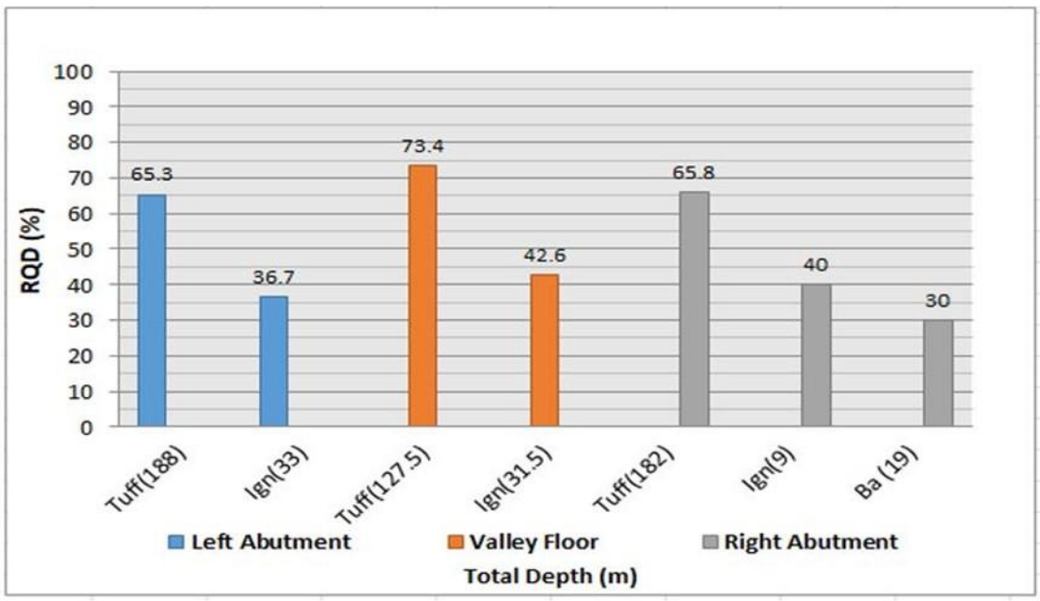


Figure 7. RQD value of rocks at dam foundation

Rock Mass Rating

For this study, data that helps to determine RMR were collected from the surface exposed outcrops and the borehole data to classify Ajima dam foundation rocks. The data collection regarding discontinuity conditions; persistence, infillings, roughness discontinuities, and groundwater conditions was performed through visual observations and measurements in the field, and core samples were used from the borehole.

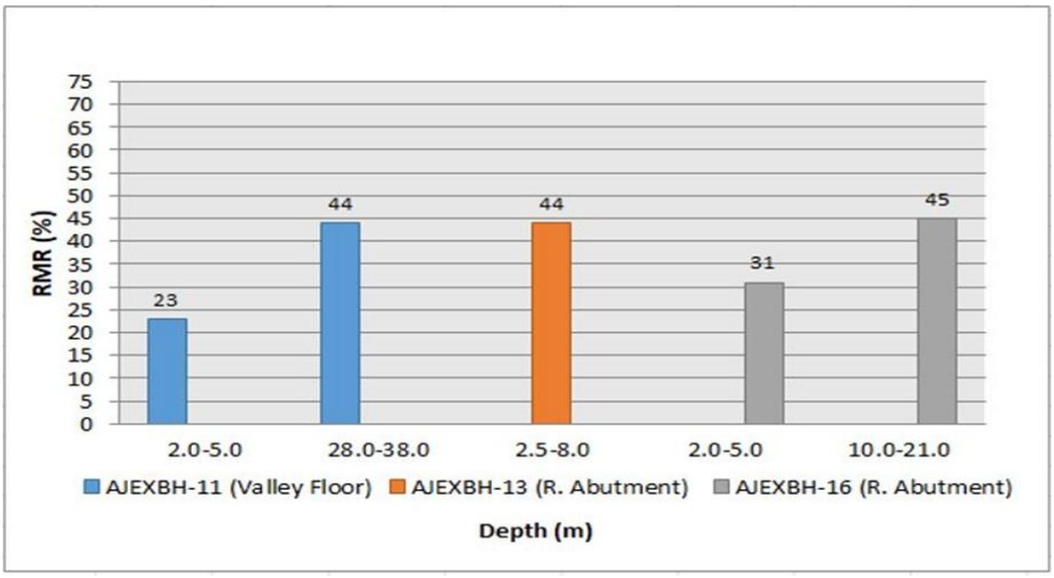


Figure 8. RMR values in the valley floor and the right abutment.

4.2.3. Weathering Profile

For this study, the foundation rocks in the dam site are affected by various degrees of weathering. The depth and degree of weathering of each rock are essential parameters to determine the foundation level. The top foundation section with an average of 5m is mapped by highly weathered rocks. According to field survey data and core drilling samples, the weathering grade of the rock ranges from highly weathered to fresh rock based on (Wahlstorm, 1974) standard.

4.3. Soil Properties (Laboratory Tests)

4.3.1. Classification & Atterberg Limits

Disturbed soil samples were characterized and the important index properties were described in the following sections based on laboratory test results (Table 3).

Table 3. Grain size distribution and Atterberg limits test results

Sample Code	**Grain Size Distribution, (%)**				**Atterberg Limits (%)**			**Soil Classification (USCS)**
	Gravel	Sand	Silt	Clay	LL	PL	PI	
AJCO-1	2.0	10.5	57.5	30.0	69.0	26.4	33.7	High plastic Silt, **MH**

AJCO-2	0.0	9.9	31.6	58.6	60.0	29.9	30.1	High Plastic Clay, **CH**
AJCO-3	0.0	12.7	61.2	26.1	50.0	28.0	22.0	Medium Plastic Clay, **CI**
AJCO-4	0.0	14.0	31.6	54.5	56.0	22.7	33.3	Medium Plastic Clay, **CI**
AJCO-5	0.0	2.67	50.0	47.3	65.3	34.0	31.3	Medium plastic CLAY, **MH**
AJLa-1	37.6	49.4	7.5	5.6	53.2	21.1	12.1	Silt Sand, **SM**
AJLa-2	49.9	50.1	0.0	0.0	-	-	-	Well Graded Sand, **SW**

More than 50% by weight of the laterite soil (AJLa-1) retained in sieve No.200 was classified as coarse-grained soil.

4.3.2. Soil Permeability

To determine the permeability of soils that covered the reservoir area, a falling head permeability test and constant head permeability tests method were conducted. Since, most of the reservoir area is covered by alluvial soil or fine-grained soil, the permeability is very low except in some sections (Table 4). Except the dam site covered by previous soil it will have good water carrying capacity or low permeable. While, there may be water pore pressure, since most of the area is covered by impervious soil.

Table **4**. Permeability test result of the soil sample from the reservoir area

Sample Code	**Depth (m)**	**Soil Type**	**Permeability (m/s)**	**Permeability Classification**
AJCO-1	1.0-1.5	MH	$1.04*10^{-8}$	Impervious
AJCO-2	1.5-2.0	CH	$6.24*10^{-9}$	Impervious
AJCO-3	1.5-2.0	CI	$5.66*10^{-9}$	Impervious
AJCO-4	1.2-2.5	CI	$5.64*10^{-10}$	Impervious
AJCO-5	1.5-2.0	MH	$1.88*10^{-9}$	Impervious

AJLa-1	1.5-2.0	SC	$1.17*10^{-5}$	Pervious
AJLa-2	1.5-2.0	SW	$1.01*10^{-5}$	Pervious

4.4. In-Situ Field Test Results

4.4.1. Standard Penetration Test (SPT)

The dam load stress at the center is about 1.154 MPa. Three soil sample bearing capacity value is < 1.1 Mpa.

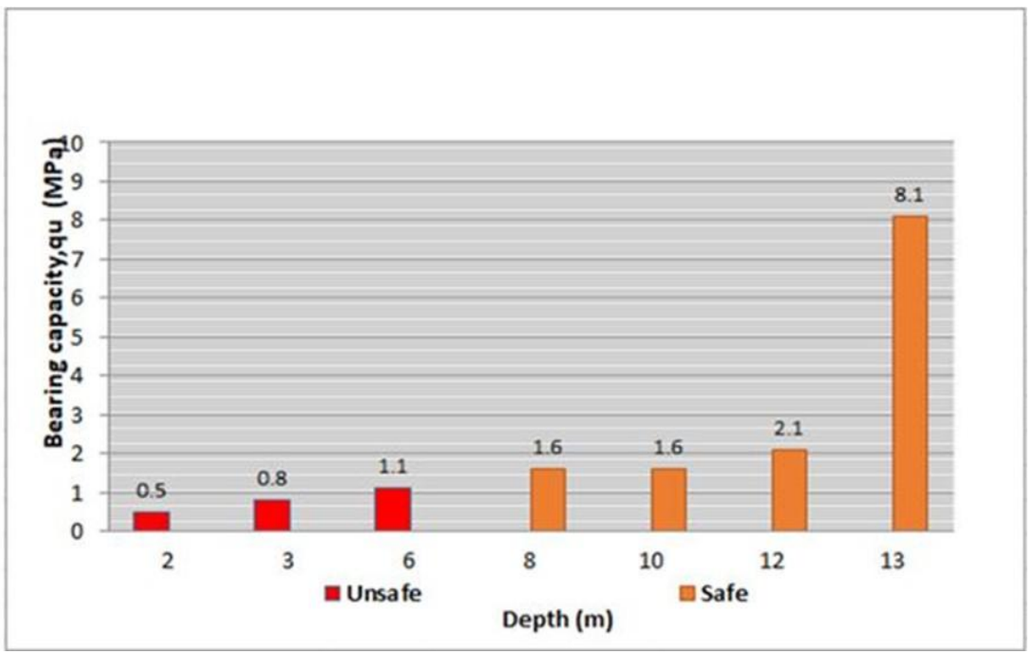


Figure **9**. SPT value

4.4.2. Packer (Lugeon) Tests

During core drilling time, a total of 123 packer tests were conducted in the Ajima dam foundation directly in the vertical and inclined boreholes in descending order. The main objective of these tests was to determine the permeability of each section of rock masses of the dam foundation and its abutments, which enables the identification of various zones that require different treatments.

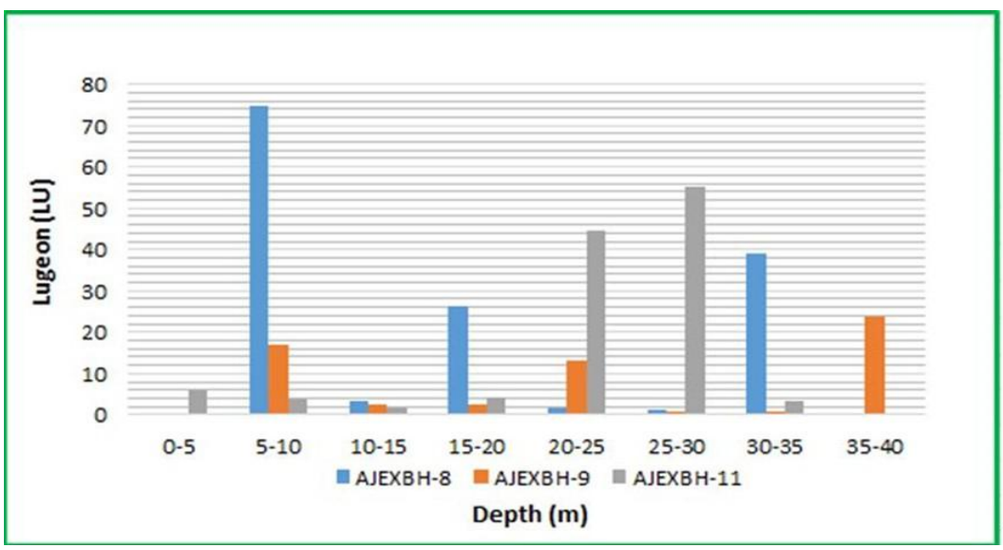


Figure **10**. Lugeon Value with depth at the left abutment.

The Lugeon value of exploratory holes in the left abutment shows that 66% is greater than > 10^{-7} m/s.

Generally, the rocks in the left abutment are mainly permeable up to a depth of about 30m.

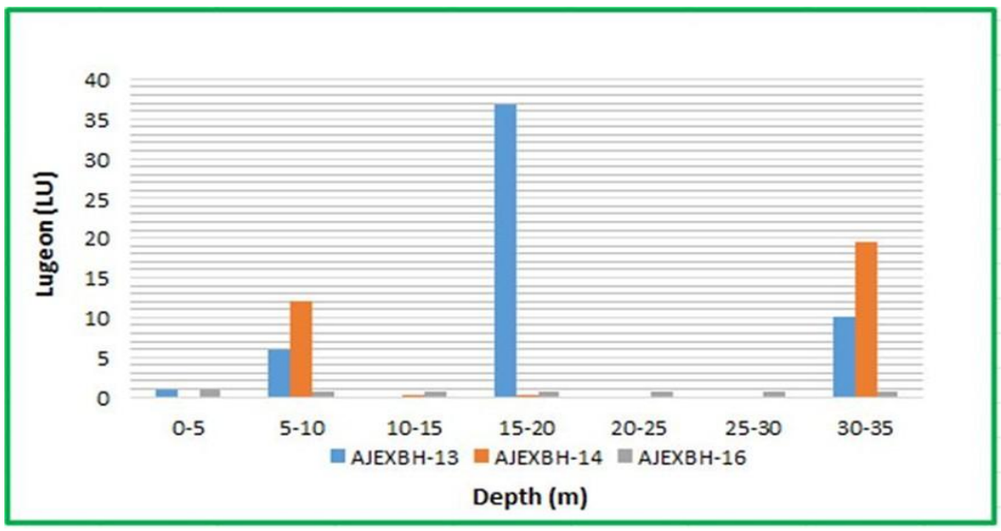


Figure **11**. Lugeon Value with depth at the valley floor area.

The Lugeon value of exploratory holes in the valley floor area indicates that about 75% is greater than >1LU or 10^{-7} m/s.

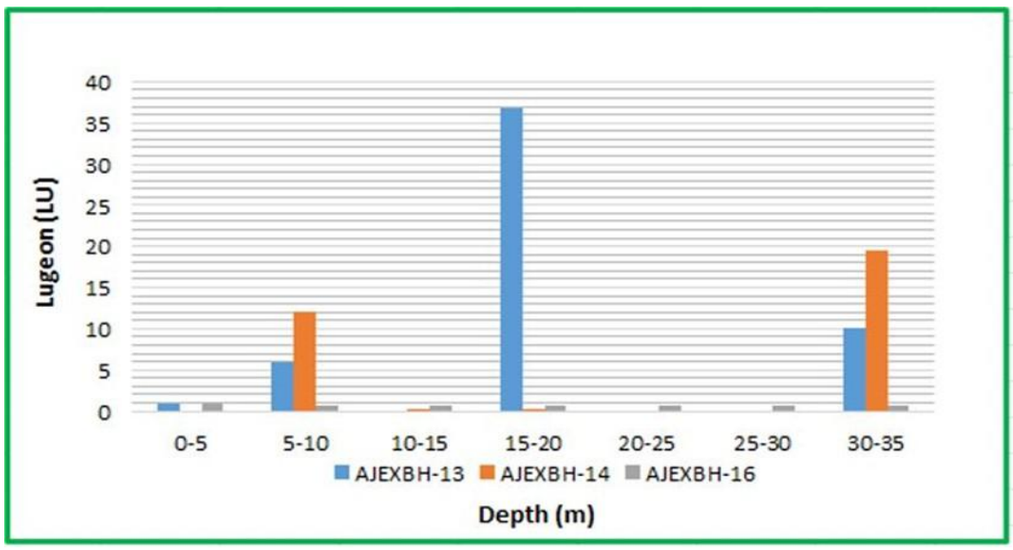


Figure **12**. Lugeon Value with depth in the right abutment

Lugeon value of exploratory holes in the right abutment illustrates about 76% is <1 LU or 10^{-7}m/s.

Table 5. Weathering- RQD- RMR- UCS and Permeability correlation.

Weathering Grade	RQD (%)	RMR Class	UCS (MPa)	Permeability (m/s)
Highly weathered	25-50	Poor (21- 40)	<5	10^{-7} - 10^{-5}
Moderately	50-75	Fair (41-60)	5-25	10^{-8} - 10^{-7}

weathered				
Fresh	90-100	Good (61-80)	>50	$<10^{-8}$

Spearman's rank correlation shows strong positive correlation between RQD and UCS ($\rho=0.82$, $p<0.01$) and RQD and RMR ($\rho=0.91$, $p<0.01$), indicating consistency in the rock mass characterization.

4.5. Geophysical Survey Results

Indirect methods are usually used at the initial stage of investigation to loosely estimate the zone of discontinuities, the thickness of overburden, and lithological contact (Sani et al., 2017). Recorder the used geophysical methods according to the following paragraphs. Recorder used geophysical methods according to the following paragraphs. Seismic refraction of p-wave velocity and electrical resistivity in the form of electrical profiling and vertical electrical sounding were applied at the Ajima dam sites

4.5.1. Electrical Resistivity (VES)

The electrical profiling contour map plotted for profile line three at 50m depth is also characterized by heterogeneous resistivity, highest resistivity values at the corners and smallest resistivity values at the middle (Fig. 13 and Fig. 18).

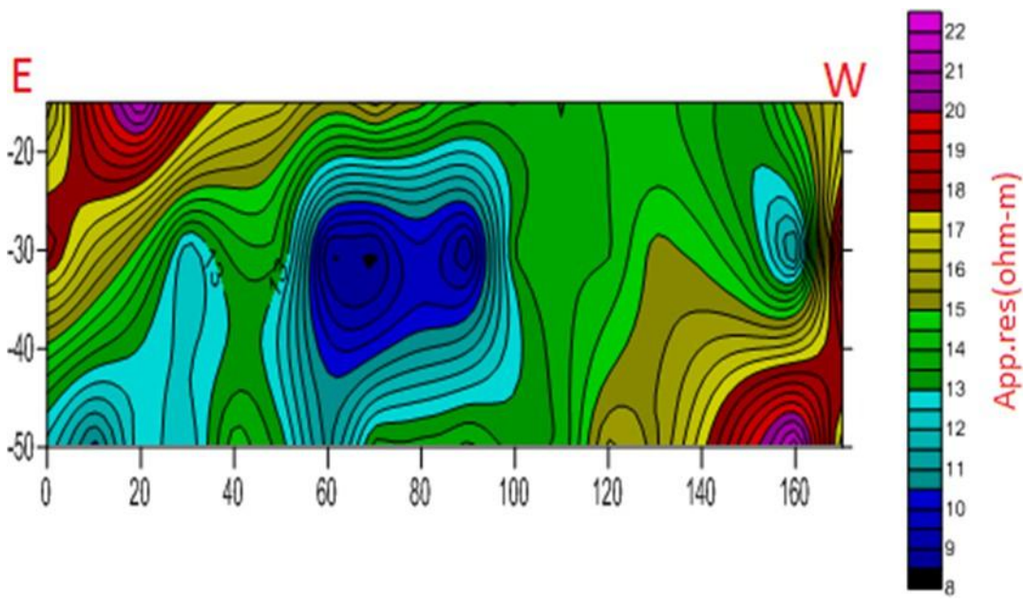


Figure **13**. Electrical profiling of subsurface map on reservoir area.

4.5.2. Seismic Refraction (P-Wave Velocity

Three lines of raw seismic refraction 2D P-wave velocity data at the dam axis were collected. The thickness of this top unit varies widely from about a few centimeters to a maximum value of 12m. The next velocity unit is marked by 1000-1500m/sec probably attributed to weathered, closely spaced fractured ignimbrite,

highly weathered open fractured aphanitic basalt as compared with BH-10, BH-12, and BH-13 data and silt with sand laterite soil as referred from borehole (BH-6 and BH-7) data. This unit is exposed to the surface around the river and the maximum thickness of this unit is 5 to 10m.

Table **6**. Layouts of the three seismic survey lines

Site	Line Code	Co-ordinates (UTM)				Remark
		Start		End		
		Easting	Northing	Easting	Northing	
1	Line-01	558192	1048338	558109	1048701	Along the Center of the dam axis
2	Line-02	558253	1048413	558177	1048655	Upstream of the dam axis
3	Line-03	558123	1048402	558077	1048630	Downstream the dam axis

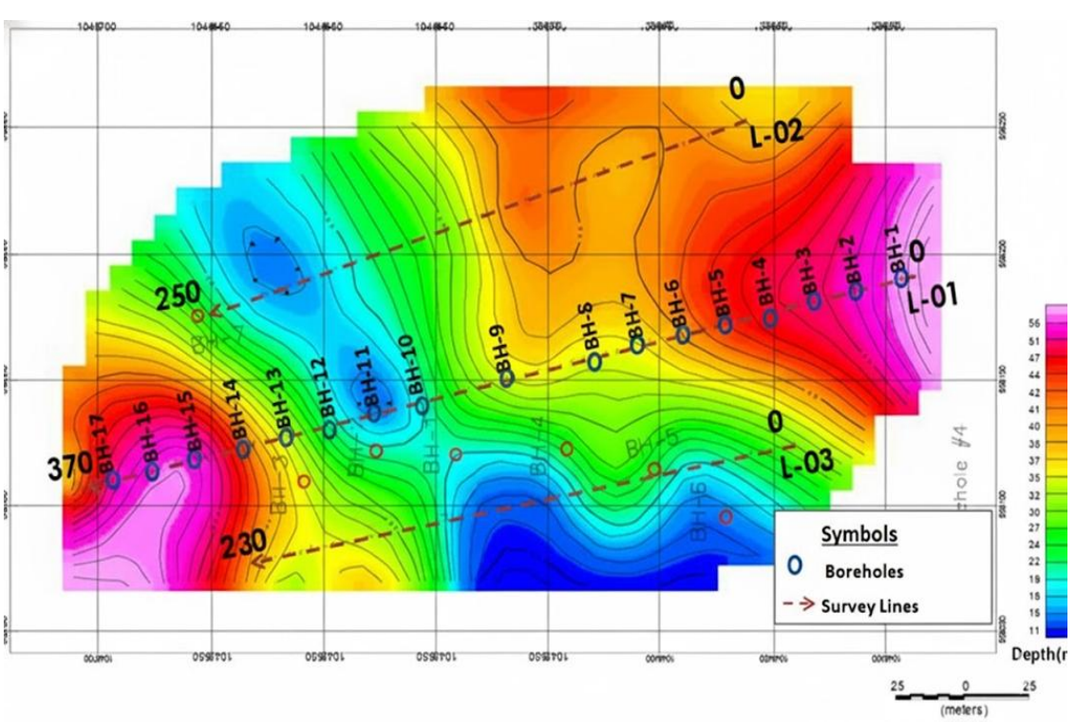


Figure 14. Base map of seismic survey line

Line 01/ Center of the dam axis

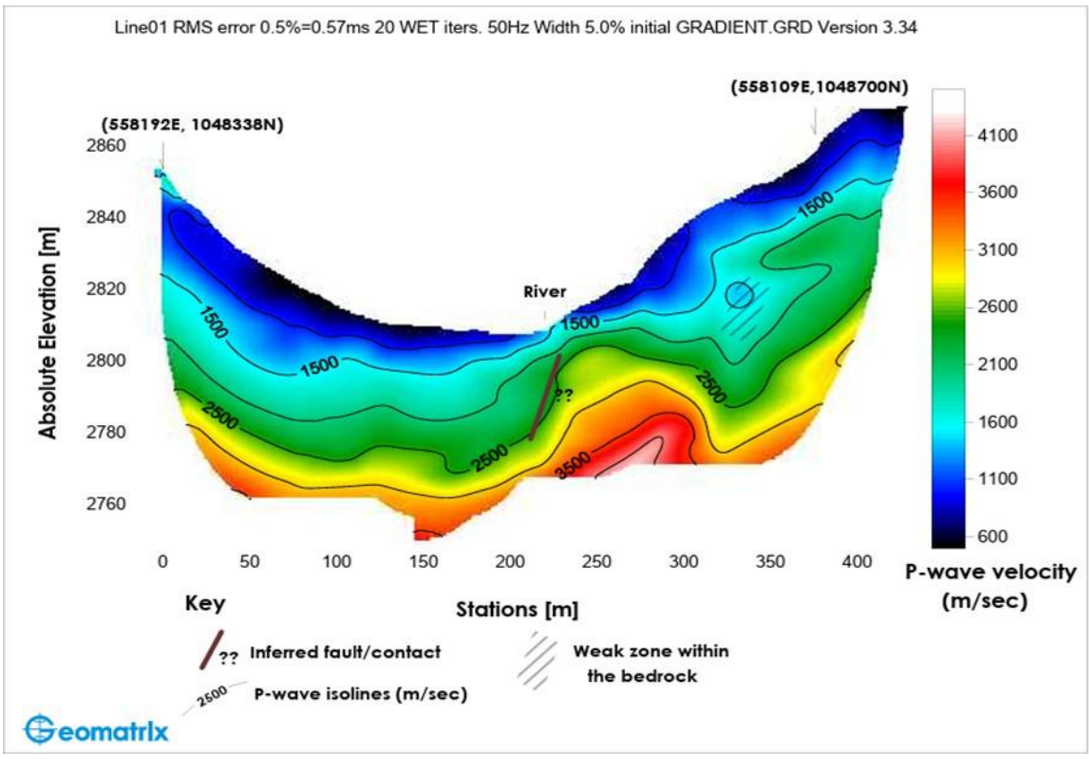


Figure **15**. 2D P-wave tomography along the line at the center of the dam axis

Line 02 / Dam Upstream Section

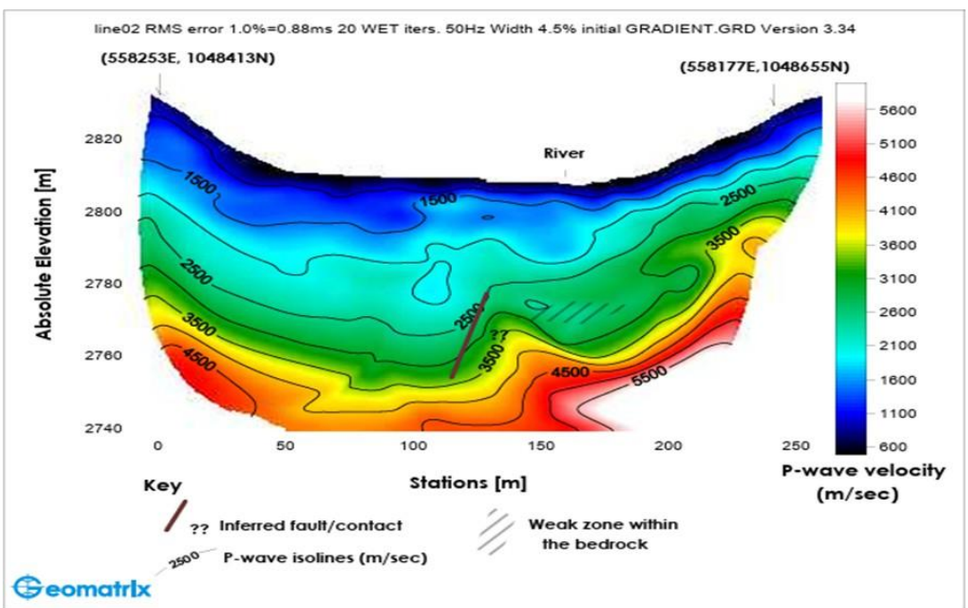


Figure **16**. 2D P-wave tomography along the dam upstream section

Line 03/ Dam Downstream Section

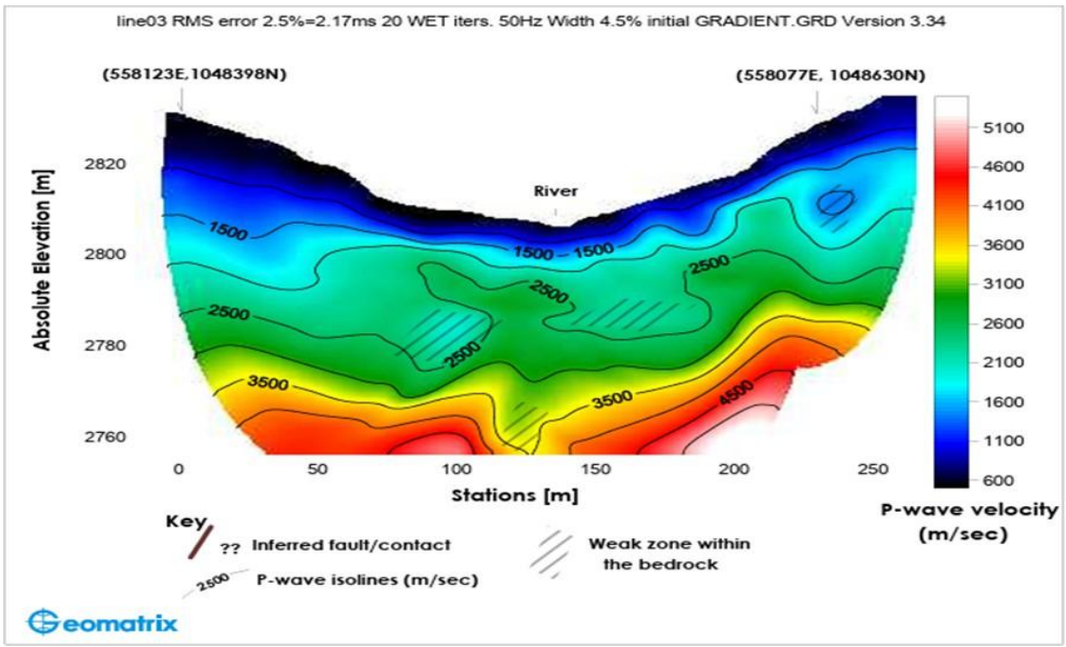


Figure 17. 2D P-wave tomography along line 03

Table 7. Geophysical validation

Borehole	Depth (m)	Lithology	Seismic Vp (m/s)	Resistivity (Ωm)	Validation
BH-10	0-5	Weathered tuff	800-1200	15-20	Matches
BH-10	5-15	Fractured ignimbrite	1200-2000	20-40	Matches
BH-10	>35	Fresh ignimbrite	>3500	>50	Matches

4.6. Regional Seismic Setting

The Main Ethiopian Rift (MER), which trends SSW from the Afar Depression, is one of the well-developed continental rift segments in East Africa that marks the boundary between the Nubia and Somalia plates (Kibret et al., 2023: Kinde et al., 2011). Ajima dam is located at Zone IV at the rift margins (Fig. 17).

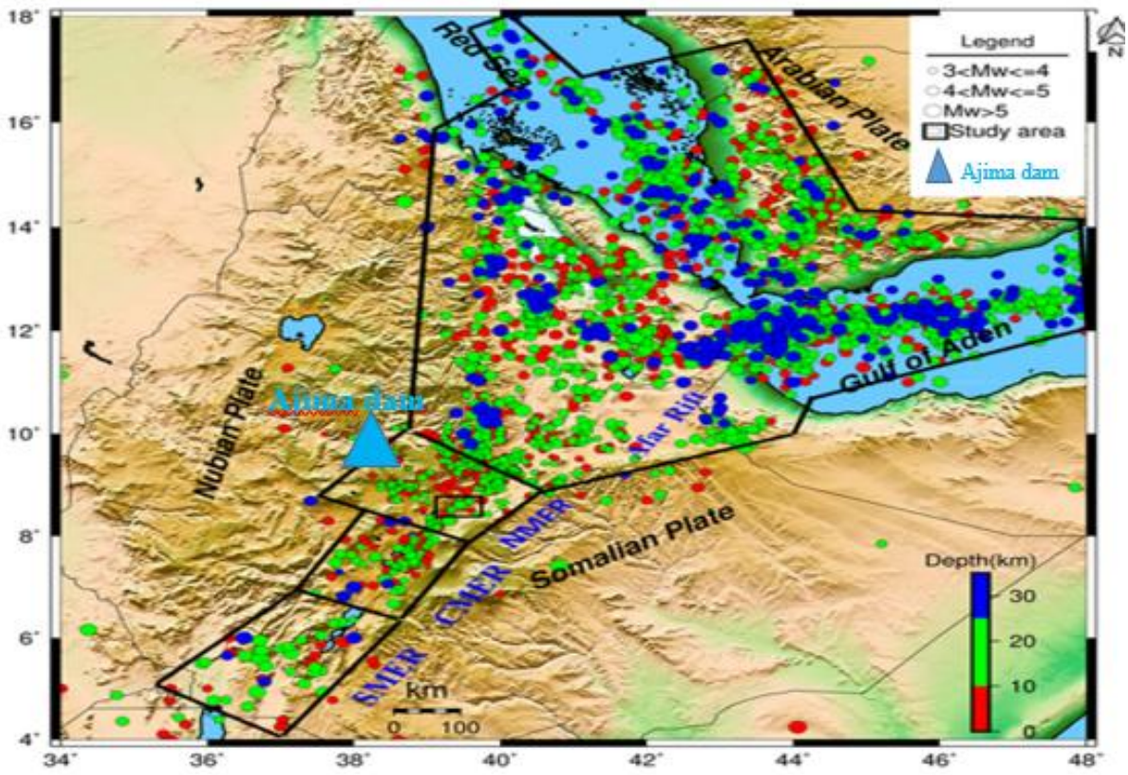


Figure 18. Earthquake distribution map of Ethiopia and Ajima dam site (Modified from Lamessa et al, 2019.)

Engineering geological mapping of the dam site

The dam site is covered by medium to high plastic silt clay, low permeable alluvial soil, and coarse grained partially cemented medium permeable laterite soil. In addition to this, the area is covered with highly weathered, closely to moderately spaced, partially opened, very low strength, medium permeable ignimbrite rock. Not only this but also the area is covered by moderately to highly weathered, moderately spaced open fracture, moderate strength, and medium permeable basalt rock. Furthermore, in the study area there is spring and caves (Fig. 19).

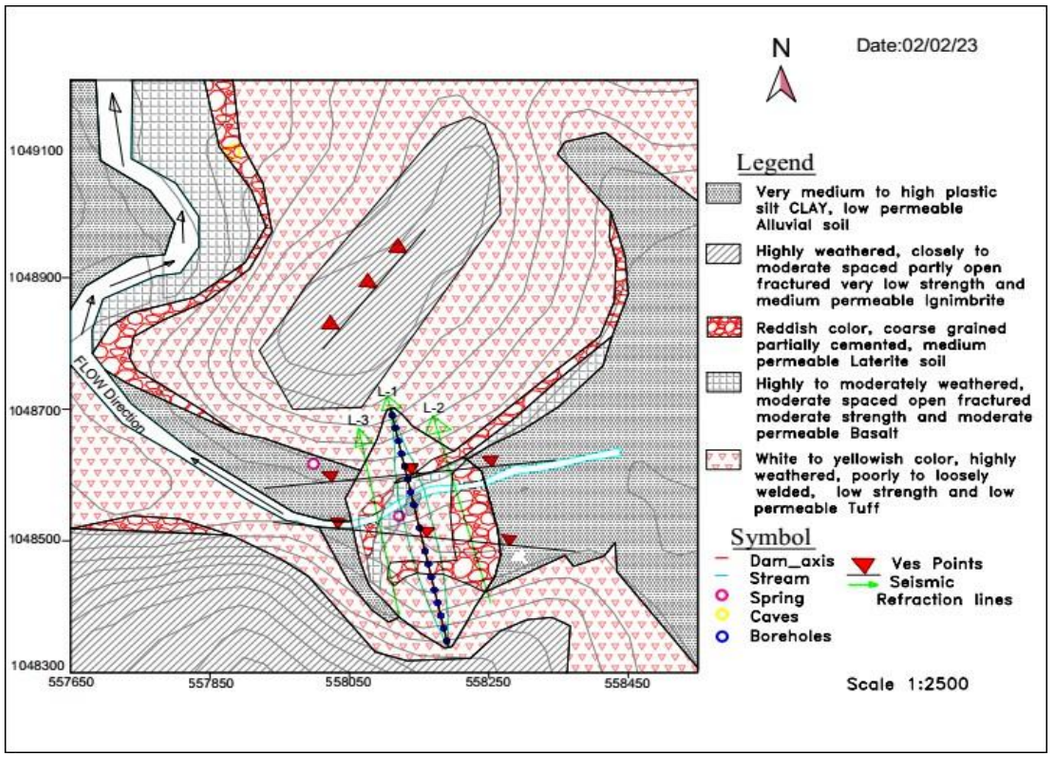


Figure **19**. Engineering geological foundation map after removal of the top alluvial soil.

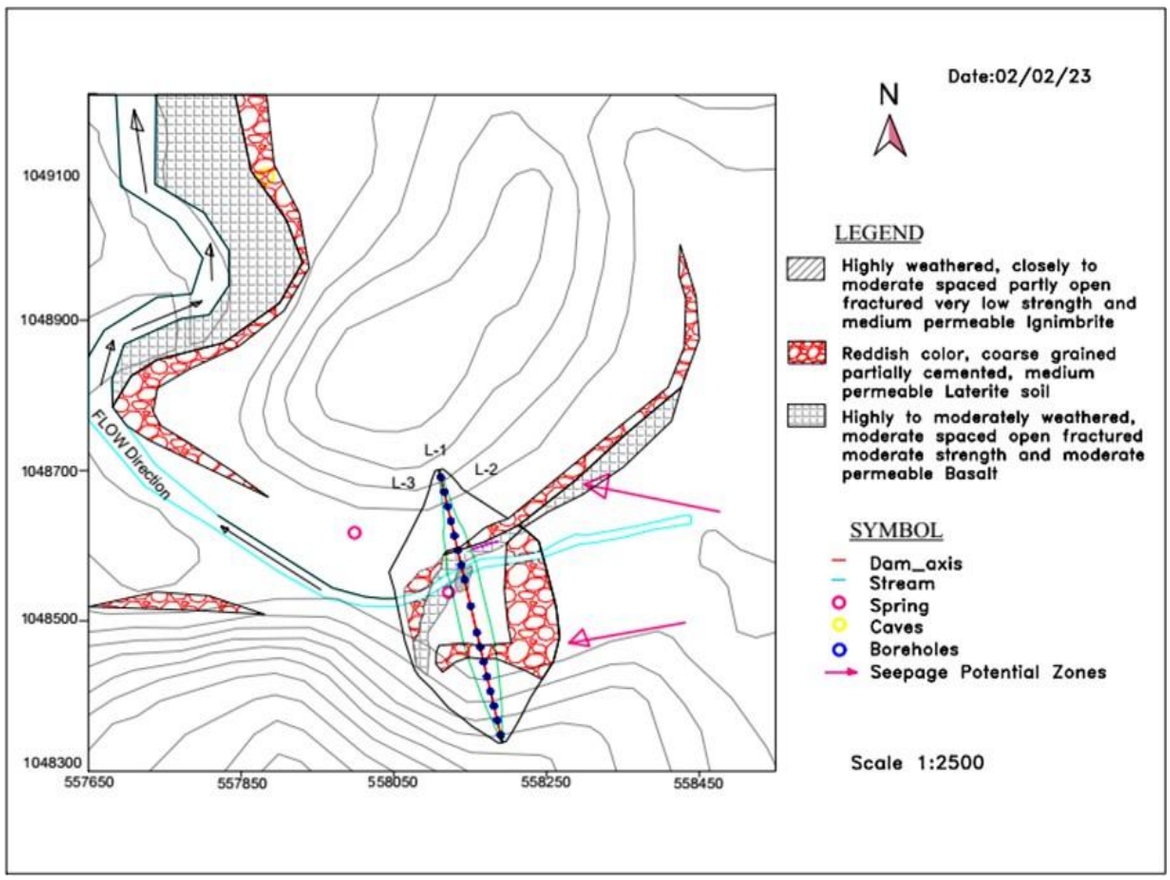


Figure **20**. Seepage potential zones through the pervious units.

5. DISCUSSION

5.1. Surface and Structural Geology

5.1.1. Lithological Units

The study area is covered by five lithological units, ignimbrite (approximately 45% of the dam foundation area), tuff (25%), basalt (15%), alluvium (10%), and andesite (5%). The thickness of ignimbrite ranges from 15-45m (mean 32m), while alluvium thickness averages 2-3m with a maximum of 5m in the valley floor.

Basalt rock in the study area is exposed near the stream bed and characterized by a dark gray color, fine-grained in texture, and clay-infilling columnar jointing with a slightly to moderate degree of weathering. The area covered by columnar basalt have relatively good strength, resistance to weathering, less erodible, and durable. While tuff rock has less strength and more erodible relative to basalt rock. Andesite rock unit has a gray color, fine-grained in texture, and intensively fractured rock. Andesite rock have good durability and strength for this dam site. Furthermore, the area covered by laterite soil need proper attention with respect to seepage and stability, because by nature it is porous, low shear strength, and high compressible. According to borehole data, the thickness of ignimbrite tuff is about 32m and its degree of physical weathering is characterized by fresh at depth to moderately weathered at the top (Fig. 4.).

5.1.2. Discontinuity Survey

The presence of the above geological structures has negative impact on the dam site with respect to seepage/leakage and dam stability. Since, the presence of faults on the dam site causes for path of water flow and increased seepage.

Moreover, the perpendicular orientation of fault with the dam will cause the deformation or failure of dam. Natural openings or caves are also observed at the right abutment downstream slope face within the laterite soils. The presence of cave on laterite soil at downstream will cause geological hazard (Fig. 5). Those caves will cause ground water flow path and for internal erosion of the surrounding soil and rock. These internal erosions may weaken the slope stability and may case for slope failure, land slide or mass movement.

Totally the presence of these caves may cause dam instability and leakage/ seepage problems.

For this study, engineering geological data was collected from both surface and subsurface investigations. Surficial data include rock outcrop data, weathering grade of rocks, topography and

other. Sub-surface data includes borehole data (core sample data and packer test data), test pit data, and SPT data were collected.

To characterize the surficial properties of the rock, discontinuity surveying, weathering grade, and RQD were determined. Under discontinuity surveying, orientation, spacing, persistence, surface condition, aperture, and nature of the filling material were performed. These data have been measured dominantly joints from the stream right bank and right abutment foot surface exposure which has two main joint sets. In addition to this, one major fault was also observed. Joint 1 orientation $62^0/058^0$, Joint 2 orientation 850/0260 and fault orientation $68^0/184^0$, respectively. Both joint set orientations are towards the northwest which is nearly along the stream flow direction, whereas the fault is aligned towards the west.

5.2. Subsurface Geotechnical Properties (Borehole Data)

The discontinuity data were analyzed using “Dips” which is based at the dam site, a total of nineteen (19) boreholes were drilled with a total depth of 633m, out of which seventeen (17) boreholes were at the dam foundation. The drilling was made to conduct field or in situ tests such as Lugeon or Packer tests to determine rock quality designation (RQD) values, and to collect rock samples for laboratory testing. The seventeen (17) Boreholes were drilled during a detailed field investigation.

5.2.1. Uniaxial Compressive Strength (UCS) of Rocks

The uniaxial compression test is a laboratory test used to derive the uniaxial compressive strength (UCS) of a rock material. The UCS values of foundation rocks at the Ajima dam site are categorized as very low to high strength rocks (Table 2). UCS values tells us the study area covered by rocks which have different strength. The dam site is covered by very low and low rock strength that will cause for dam foundation instability or deformation and shortage of construction material (riprap, aggregate, concrete). While, medium strength rock will have good foundation stability, and it will be used for construction material.

Furthermore according to Bieniawiski, (1989) it is a fundamental parameter in rock mechanics, representing the maximum axial compressive stress and a rock can sustain without failure. Its values obtained from laboratory tests are crucial for classifying the rock mass and assessing its suitability

for a foundation and construction material (Hoek, (2007)) at the Ajima dam site. For foundation stability assessment, the classification of foundation rocks at the Ajima dam site grouped into very low, low, and high-strength directly dictates the required foundation treatment (Pells et al, 2000). Let's see one by one.

Very Low to Low-Strength Rocks (UCS < 25 MPa):- These rocks, typically classified as very weak, highly susceptible to deformation, excessive settlement, and potential shear failure under the high structural loads imposed by a dam, particularly an earth dam (Fell, 2005: Cooke,1984).The presence of such weak zones may lead to foundation instability and must be meticulously evaluated. Foundation improvement techniques, such as grouting (cement or chemical) to fill fractures and increase overall stiffness, or excavation and replacement with higher-strength concrete or compacted fill, may be necessary to ensure safety and serviceability.

Medium-Strength Rocks (25 MPa to 50 MPa):- Rocks in this range are generally considered moderately strong and can provide good foundation stability for most civil engineering structures, including earth dams (Fekadu, et al., 2025; Geertsema, 2000). It offers adequate bearing capacity and lower deformability, minimizing the risk of excessive settlement and ensuring the long-term integrity of the dam structure.

Suitability for Construction Material:-UCS is also the primary indicator for evaluating the suitability of rock for essential construction materials. Riprap, Aggregate, and Concrete.

Construction materials like riprap (for erosion protection), aggregate (for concrete and filter zones), and concrete itself require rock sources with high strength and durability (Khodadad, 2022). Medium-strength rocks are often suitable for these purposes, provided they also meet requirements for durability (resistance to weathering/abrasion) and specific gravity. Strong rocks are very suitable for earth dam foundation.

5.2.2. Rock Quality (RQD & RMR)

Rock Quality Designations (RQD) of Rocks

Rock quality designation (RQD) is a standard technique for qualitative and quantitative assessment of rock quality and degree of jointing in a rock mass which has been evaluated by calculating the drill core logs of boreholes drilled along the dam axis using (Eqn 3.1). The presence of high frequency

fracture will cause for rock deformation, high permeable, difficult for excavation and rock fall/landslide. Moreover, the reverse is true for low frequency rock. In addition to qualitative and quantitative assessment of rock quality listed above it is also crucial on the degree of jointing (fracturing) within a rock mass. RQD provides a quick, widely accepted initial classification of the rock mass quality (Zhang, 2016; Shen, et al., 2023).

Table 8. Rock quality designation (RQD) and its standard

RQD (%)	Rock Quality Description
90–100	Excellent
75–90	Good
50–75	Fair
25–50	Poor
0–25	Very Poor

Table 2 in result part is classified based on Table 6 and it demonstrates, high fracture frequency (Low RQD) typically below 50%) indicates a highly jointed, poor to very poor quality rock mass (Fig.7). This condition is linked to several adverse geotechnical issues. Such as, rock deformation/instability, high permeability/leakage and difficult Excavation.

While, Low Fracture Frequency (High RQD) classically above 75% indicates a more massive, competent, and strong rock mass, offering a better foundation. This rock has low permeability, is less prone to deformation, and requires less intensive support or treatment (Fig.7.).

The shallower depth of bedrock at the right abutment compared to the left abutment and the valley floor is that, primarily due to geological asymmetry (the dipping direction of at the right abutment is away from the river and difficult to deep excavation), geomorphological processes, differential Weathering and Erosion processes.

Rock Mass Rating

According to the above data, the quality of the rock grouped under poor rock mass rating at the valley floor and right abutment, and fair rock mass quality at right abutment. (Fig. 8).

According to RMR value indicate, the valley floor needs great attention. Since it has low RMR value and it will cause for leakage, seepage, deformation, less resistance for weathering and erosion. While

the right abetment has relatively good engineering properties. Likewise, The RMR classification categorizes the rock mass quality, directly influencing engineering properties and required foundation treatments. The RMR score, ranging from 0 to 100, correlates to specific rock classes and engineering parameters. According to Bieniawiski, (1989) classification, (Table7.) summarized the value, class and descriptions and linked with (Fig. 8).

Table 9. Rock mass rating and description

Score	Rock Quality	Description
81–100	Very Good	Extremely strong, virtually unweathered rock with widely spaced joints.
61–80	Good	Strong rock with moderate jointing and favorable discontinuity orientation.
41–60	Fair	Moderately strong, moderately jointed rock; can require support in excavations.
21–40	Poor	Weak, highly jointed, and often weathered rock with unfavorable discontinuity conditions
0–20	Very Poor	Very weak, heavily fractured, or highly weathered rock; requires substantial support

5.2.3. Weathering grade

Weathering is a significant process that influences the mechanical characteristics of rock material and rock

mass at shallow depths. It is challenging to quantify weathering because it is described qualitatively. However, it is basic to relate the weathering state of rocks to their engineering properties. Highly weathered rock have poor engineering properties and it leads to foundation instability, seepage, leakage, and other hydrological and geological hazards. But, fresh rocks have good engineering properties and it is suitable for dam construction.

5.3. Soil Properties (Laboratory Tests)

5.3.1. Classification & Atterberg Limits

The soil sample was classified as a silt sand soil group, whereas the laterite soil (AJLa-2) was categorized as well graded sand (Table 3 and Fig.19.). Furthermore, more than 50% of the weight of the alluvial soil passes in sieve No.200, it is classified as fine-grained soil.

The Atterberg limit test result of 5 soil samples was silt and clay soil. Liquid limit and plastic index Values of the alluvial soils ranges from 50 to 69% and 22 to 33.7% respectively which have medium to high plasticity. Hence, the alluvial soil which covered most of the reservoir area is characterized by medium to high plastic silt clay (Table 3). Coarse grain soil and high plastic soil may have negative impact with respective of permeability and deformability of dam site, respectively. While, well graded soil, silt and clay soil with medium plastic nature have good engineering properties. However, well graded soil has greater amount of sand and gravel. Therefore, it will cause for potential flow path of water or increase permeability.

5.3.2. Permeability test results

The alluvial soil (silt and clay) has permeability less than ($1.3*10^{-8}$ m/s which is categorized as impervious soil, whereas the laterite soil has a permeability of about 10^{-5} m/s and is grouped under pervious soil (Table 4.).

5.4. In-Situ Field Test Results

5.4.1. Standard Penetration Test (SPT)

The Standard Penetration Test (SPT) is a widely accepted in-situ dynamic method used to assess subsurface soil properties and consistency according to ASTM D1586 standards. By recording the resistance to penetration (N-value), engineers can empirically estimate relative density, shear strength, and allowable bearing capacity (Meyerhof, 1956). This test is fundamental for verifying if the foundation can safely sustain the dams calculated stress loads without failure**.**

A Standard Penetration Test (SPT) was performed to determine and estimate the strength of soils and weak rocks. The dam load stress at the center is about 1.154 MPa. Three soil sample bearing capacity value is < 1.1 Mpa and this tells us unsafe bearing capacity of the dam foundation.

Unsafe or low bearing capacity soil needs great attention, like Comprehensive geotechnical investigation, engineering analysis, and proper design. Otherwise, it will be cause for foundation instability, reservoir leakage/seepage, structural failure and other problems. But, starting from 1.6 Mpa to 8.1 Mpa tells us the bearing capacity of dam foundation is safe (Fig. 9).

5.4.2. Borehole permeability of foundation rocks

The standard process for determining the permeability of rocks penetrated by boreholes is called Packer or Lugeon testing (Ia and Falae, 2018). According to Kasenow, (2002), Permeability is a crucial physical property in hydrogeology and geotechnical engineering. It describes the ease with which water (or other fluids) can flow through the interconnected void spaces (pores, joints, fissures) within a material. Coefficient of Permeability (Hydraulic Conductivity, (K) is a quantitative measure, typically expressed in units like meters per second (m/s). It depends on the fluid properties and the material's properties (Andrén, 2021).

The Lugeon test, developed by Maurice Lugeon, and it defined as a field method for estimating the average hydraulic conductivity of rock masses Houlsby (1976). Interpretation involves analyzing the Lugeon values to assess the rock mass quality, the nature of the discontinuities, and the necessity for ground improvement like grouting and measured by lugeon unit (Lu).

Permeability is the concept while, Lugeon is the practical field measurement unit for fractured rock. 1 Lu is defined as a water loss of 1 liter per minute per meter of test zone at an over-pressure of 1 MPa. To convert Lu to m/s recommend to applying Darcy's Law for flow through a porous medium, using water at ~20°C, this specific flow rate converts to a hydraulic conductivity (permeability) of roughly 1×10^{-7} m/s. 1 Lugeon (Lu) $\approx 1 \times 10^{-7}$ meters per second (m/s). According to Houlsby (1990).Lugeon Classification summarized in the following table.

Table 10. Lugeon Classification summarized

Permeability	Lugeon Range (Lu)	Approx. Hydraulic	Interpretation

Class		Conductivity (m/s)	
Very Low	< 1 Lu	$< 1 \times 10^{-7}$ m/s	Essentially impervious and grouting generally not required.
Low	1 – 5 Lu	$1 \times 10^{-7} – 5 \times 10^{-7}$ m/s	Minor seepage and selective grouting may be considered.
Moderate	5 – 15 Lu	$5 \times 10^{-7} – 1.5 \times 10^{-6}$ m/s	Permeable, therefore, typically the target range for systematic grouting
High	> 15 Lu	$> 1.5 \times 10^{-6}$ m/s	Highly fractured/porous and requires intensive grouting treatment

Based on the above standard the study area permeability finding at the left and right abutment as well as at the valley floor summarized below.

At the left abutment (Fig. 10), 66% of tests exceed 1 LU; high permeability (Table 8.) continues up to 30m depth. The rock mass is fractured and leaky due to three primary factors. These are, Granular material prone to high seepage and internal erosion, closely spaced joints provide continuous flow paths and weak interfaces act as preferential flow planes. This high permeable rock may posed to structural frailer.

In the valley floor (Fig. 11) 75% of tests exceed 1 LU, with peaks of 75 LU extending to 35m depth. This is the site's most permeable and weathered zone. The loosely welded tuff acts as an erodible granular medium, while the 75 LU readings signify wide-open, interconnected fracture networks. Critical reservoir water loss and significant foundation erosion beneath the dam core. A sharp transition at 35–40m to <1 LU in widely jointed ignimbrite confirms a competent, impermeable foundation base.

Right Abutment (Fig. 12), 76% of tests are < 1 LU, indicating overall low permeability (Table 8.). This is the site's most competent abutment, characterized by a largely intact rock mass. It exhibits moderate permeability in the upper 20m due to weathering. This is a critical interface where seepage could undermine the dam's contact point, leading to erosion and structural instability.

A grout curtain is a continuous, impermeable barrier injected into the ground (soil or rock) to block water flow (seepage), control uplift pressure, and stabilize foundations, crucial for dams, tunnels, and built by

drilling holes and pumping grout like cement or chemical mixtures in overlapping stages to create a solid underground wall (Saif, and Ahmed 2022).

Conceptual design summary

For this project the depth of grouting is extends nearly 30 m, to the low-permeability layer bedrock or specific clay stratum identified in the permeability profile. The raw and spacing is primarily in 2-3 rows with 1.5-2.0 m spacing, staggered. The grout type is stable cement based grout for the main curtain; chemical grout for fine fractures if needed. Furthermore, the refusal achieved at sustained pressure or when specified take <1 L/min per meter is met.

An upstream blanket is a layer of impervious or semi-impervious material placed on the upstream face of an earth dam or the reservoir floor to control the flow of water and reduce seepage through the dam's foundation (Salmasi, and Nouri 2019). Extension up to 30 m from the dam toe, covering the high-permeability near-surface zone. The design looks like 2-3 m thick, trenched and backfill with impervious material, entered into the dam core and natural ground.

The design is hold back based on the dam site vertical and lateral permeability distribution. The 30 m curtain depth targets the competent, low-k stratum that confines seepage.

The 30 m upstream blanket length is optimized to intercept and lengthen the seepage path through the high-permeability shallow alluvium/weathered zone, reducing permeability and under-seepage effectively. This combined system addresses the critical flow pathways visible in the site investigation.

5.5. Geophysical Investigation Results

5.51. VES Interpretation

Electrical profiling contour map shows 15m, 30m, and 50m depth level (AB/3 = 15m, 30m, and 50m) is characterized by heterogeneous resistivity. It shows high resistivity ranging from 17-22 Ohm-m at both corners of the profile line. The subsurface material at this location has relatively low conductivity and high resistivity materials such as rock or compacted soil. While, the resistivity values at the middle of the profile decline from 15-8 Ohm-m. The subsurface material in this area has low resistivity and higher conductivity, which may be clay or water-bearing sediment.

As VES result indicated the subsurface of the dam site is heterogeneous in lithology.

The permeability and seismic resistance is different. This differential permeability will be cause seepage and internal erosion. The other main concerning problem is deferential seismic resistance/response

because the dam site is located on the rift zone. When it will be responded, differential seismic response liquefaction or dam instability will be occurred.

5.5.2. Seismic refraction survey

Geophysical investigation is used to investigate zones of discontinuities, the thickness of overburden, and lithological contact (Gomo et al., 2024; Hamed, et al., 2024; Kargaranbafghi, & Ghalamzan,2018).).Three lines of raw seismic refraction 2D P-wave velocity data at the dam axis were collected. The seismic refraction survey has provided very useful information related to the mechanical and geological conditions of the subsurface.

Line 01/ Center of the dam axis

According to the 2D P-wave velocity tomography the uppermost part of the section with p-wave velocities below 1000m/sec is mostly related to clay associated with rock fragments and silt with sand. The thickness of this top unit varies widely from about a few centimeters to a maximum value of 12m. The next velocity unit is marked by 1000-1500m/sec probably attributed to weathered, closely spaced fractured ignimbrite, highly weathered open fractured aphanitic basalt as compared with BH-10, BH-12, and BH-13 data and silt with sand laterite soil as referred from borehole (BH-6 and BH-7) data. This unit is exposed to the surface around the river and the maximum thickness of this unit is 5 to 10m. Highly weathered and open fracture basalt may cause for decrement of bearing capacity and it will lead for deformation as well as foundation instability.

The other layer is characterized by 1500-2500m/sec p-wave velocity with thickness varies from 20m to 28m. The third unit reflects higher p-wave velocities (2500-3500m/sec) attributed probably moderately weathered to fresh and widely space-fractured Ignimbrite rock. This unit appears uplifted in the central area, to the north of the station, and reflects rock fracturing. Moreover, the bedrock velocities increase continuously with depth reflecting the increased soundness of the rock. Fresh and massive ignimbrite rock characterized by 3500m/sec appears about a depth of 35 to 40m in the central part of the line (Fig. 15).

Line 02 / Dam Upstream Section

The 2D P-wave velocity tomography of the uppermost part of the section with p-wave velocities below 1000m/sec covers the entire line with an average thickness of about 4m and a maximum around station 40. It is also expected to comprise highly weathered and decomposed tuff in the elevated sloppy parts of the line and totally it was removed or excavated. The underlying lithological unit is marked by 1000-1500m/sec probably attributed to highly weathered open fractured aphanitic basalt and silt with sand laterite soil at some places. This unit is uniformly distributed below the top layer having an average thickness of about 3m. The next 1500-2500m/sec velocity unit is related to slightly weathered to poorly welded tuff. Lithological units reflect higher p-wave velocities (2500-3500m/sec) and may be moderately weathered to fresh and widely space-fractured ignimbrite rock and uplifted in the central area. Moreover, the soundness of the bedrock increases with depth and very fresh, sound, massive ignimbrite rock (over 3500m/sec) is observed at a minimum depth of 33m (Fig.16). These highly weathered rocks decrease internal cohesion, increase deformability and leads for structural failure of dam.

Line 03/ Dam Downstream Section

The top velocity unit is characterized by p-wave velocities below 1000m/sec. The thickness of this unit range from 3 to 10m covered by clay associated with rock fragments and silt with sand soils. The presence of clay between rock fragments may important to decrease permeability but it has negative impact on shear strength. Because, when clay interact with water it increases its volume and when it loos water it decreases its volume. These increment and decrement of volume leads for settlement or deformation of dam structure. The underlying unit is marked by 1000-1500m/s and the lithological unit may be highly weathered open fractured aphanitic basalt and silt with sand laterite soil. This unit is mapped along the entire line with thicknesses between 2m and 4m. The next 1500-2500m/s velocity unit is related to slightly weathered to fresh poorly welded tuff. The thickness of this unit attains maximum values in the central part of the line associated with the above zones to 20-22m. The lithological unit reflects higher p-wave velocities (2500-3500m/sec) determined as moderately weathered to fresh and widely space fractured to ignimbrite rock. This unit reflects a wide velocity variation in the central part of the line around stations. Furthermore, the fresh, sound, massive ignimbrite rock characterized by 4500m/sec appears at a minimum depth of 40m around station 220 (Fig. 17).

All datasets (RMR, RQD, UCS, SPT, Lugeon, seismic, and permeability) in a quantitative way and link them gives the following summary and tells us informed decision.

Table 11. Summary of linked result.

Engineering Zone	Lithology	Depth (m)	Vp (m/s)	RQD (%)	RMR Class	Lugeon (Lu)	UCS/SPT	Design decisions
Zone-I (Overburden)	Alluvium / Clay	0–5	< 1000	------	Very Poor	10^{-5} m/s Pervious	N<10 Low	Excavate:- Unsafe bearing capacity (< 1.15 MPa).
Zone-II (Weathered)	Basalt /Ignimbrite	5–15	1000–1500	25–50	Poor (21-40)	15–75 (High)	< 25 MPa low	Grout:-High seepage potential, internal erosion risk.
Zone-III (Transition)	Tuff/ Fractured Ignimbrite	15–35	1500–2500	50–75	Fair (41-60)	5–15 (Moderate)	25–50MPa Medium	Cut-off:- Upstream blanket needed to extend flow path.
Zone-IV (Bedrock)	Massive Ignimbrite	> 35	> 3500	90–100	Good (61-80)	<3Lu (Low)	>50 MPa High	Foundation: - Grout curtain termination depth.

5.6. Seismic zone of Ajima dam site

The Main Ethiopian Rift (MER), which trends SSW from the Afar Depression, is one of the well-developed continental rift segments in East Africa that marks the boundary between the Nubia and Somalia plates (Kibret et al., 2023: Kinde et al., 2011). Ajima dam is located at Zone IV near the rift

margins (Fig.18.). Therefore, it needs great attention during construction and after construction. Because of it has a lot of negative consequences such as foundation instability, ground shaking, potential dam failure, loss of water from reservoir, and totally it will cause for socioeconomic impact.

Moreover, According to Getachew, et al. (2020) the study area found near Seismic Zone Iv and the design accounts for a PGA of 0.20g 475-year RP as per ES8-2015. The soft, heterogeneous overburden (clay with rock fragments, weathered basalt/tuff, Vs ~ 300-600 m/s) overlying stiffer bedrock (Vs > 1500 m/s) creates a significant impedance contrast. Therefore, site-specific amplification factor is up to 2.0 derived from geophysical data. The risks associated with the heterogeneous foundation (clays and weak tuffs) are mitigated through a combination of dental concrete treatment and consolidation grouting, ensuring the foundation remains resilient against differential settlement during a seismic event tied to the Debre Berhan Shear Zone. Using the Seed and Idriss (1971) simplified method, the factor of safety against liquefaction is <1.0 for the upper 5m, indicating potential for ground failure.

Engineering geological mapping of the dam site

Engineering geological map is a particular kind of geological map that offers a generalized representation of the geological environment's elements that are important for land use planning, design, construction, and maintenance related to civil engineering applications (Dearman, 1991). The basis of engineering characterization of the rock mass and soils, and engineering geological mapping of the Ajima dam site was finalized. The rock mass has been classified for mapping purposes based on the principle that the physical and engineering properties of the rock strength, weathering grade, discontinuity characteristics, and permeability. Whereas, the unified soil classification system (USCS) was used to classify the soils around the dam site. The dam site is covered by medium to high plastic silt clay, low permeable alluvial soil, and coarse grained partially cemented medium permeable laterite soil. In addition to this, the area is covered with highly weathered, closely to moderately spaced, partially opened, very low strength, medium permeable ignimbrite rock. Not only this but also the area is covered by moderately to highly weathered, moderately spaced open fracture, moderate strength, and medium permeable basalt rock. Furthermore, in the study area there is spring and caves (Fig. 19 &20).

Figure 19 demonstrates the engineering geological mapping of Ajima dam site at a scale of 1:2500. The area is dominated by three lithological units: highly weathered ignimbrite, basalt with open fractures, and reddish laterite soil along the dam axis. Critically, the mapping highlights seepage potential zones,

particularly within the laterite and contact zones, which correlate with the observed stream flow and borehole locations (L-1, L-2, and L-3). Furthermore, it pinpoints the spatial distribution of the cave, spring, stream, reservoir area dam axis.

6. Conclusion and Recommendations

6.1.Conclusion

The Ajima dam site located in a complex and heterogeneous geological environment characterized by significant engineering challenges, primarily seepage potential, low bearing capacity, and seismic risk.

Lithology and Strength: - The foundation is dominated by tuff, ignimbrite, basalt, and laterite. The upper Zone consists of overburden and highly weathered rock with unsafe bearing capacity < 1.15 MPa, making it prone to deformation under the dam's load.

Permeability: - Seepage is a critical concern while, the reservoir floor is naturally sealed by low-permeability alluvial silt, and the dam axis contains highly fractured zones (especially the valley floor and left abutment) with Lugeon values peaking at 75 LU. Natural caves in the laterite soil further threaten stability via internal erosion.

Rock Quality: - The rock mass generally improves with depth. Surface layers are classified as Poor (RMR Class IV), transition to Fair (Class III), and eventually becoming Good (Class II) massive ignimbrite bedrock below 35m.

Seismic Hazard: -Since the study area located in Seismic Zone IV (Main Ethiopian Rift), the site is susceptible to amplification and differential settlement due to the contrast between soft overburden and stiff bedrock.

Table 12. Integrated framework

Engineering Issue	Geological Data	Geophysical Data	Geotechnical Data	Synthesis
Bearing capacity	Weathering grade, lithology	Seismic velocity	SPT-N, UCS	Weak zone identified (0-5m), FOS <1

Seepage	Faults, fractures, caves	Resistivity anomalies	Lugeon tests, permeability	High permeability zones mapped (>1 LU)
Rock quality	Discontinuity spacing, persistence	Velocity contrast	RQD, RMR	Quality improves with depth, best below 35m
Seismic hazard	Tectonic setting, faults	Vs profile	N-values	Site class D, liquefaction risk

6.2 Limitation of the study

Despite a thorough investigation, the 22-meter borehole spacing and limited laboratory samples mean small scale geological variations might have been missed. Furthermore, the geophysical survey resolutions and inherent data modeling limits could smooth out or misinterpret subsurface features smaller than 5 meters. Even though in situ permeability test was done using disturbed soil samples for permeability lab, the findings may not perfectly mirror real-world, site specific conditions. The short timeframe also made it impossible to track how changing seasons impact local groundwater levels and slope stability over time.

6.3 Recommendations

Dams, especially those made of rock fill, need careful engineering geological investigation. The following suggestions were forwarded based on the findings of the current study to be taken into account while constructing the dam.

Depending on the result of the core drilling and geophysical surveys works, the upper portion of highly weathered decomposed tuff and silt with sand and clay-associated rock fragments (below 1000m/sec) are unfavorable zones. As the SPT test result indicates the bearing capacity of the tuff unit which is the dominant geological unit in the dam foundation does not have sufficient strength. Hence, removal or strip off the top 5 to 6m within the valley floor area (chain-age 0+50 to 0+320m) is advisable to fit the required bearing capacity (load stress imposed by the dam at center=1.154 MPa). In turn, this helps to increase the strength and decrease the permeability of the rocks.

The caves in the right abutment downstream slope within the laterite formation could risk the dam stability

during impounding the reservoir water. Hence, there should be multiple rows of curtain grouting to control seepage through the laterite soil and to avoid liquefaction. In addition, the appropriate grout type for laterite soils is using chemical grouting. The rock mass conditions at the dam foundation have a significant impact on grouting efficiency or groutability. Hence, the pyroclastic rocks of the Ajima dam foundation should be investigated in detail relative to grout type and pattern, water cement ratio, grout stage, and grouting pressure which are important characteristics to prevent hydro fracturing and similar problems during grouting. The Ajima Dam site found in main Ethiopian rift center. Therefore, it needs proper design resistance to seismic activities.

Table 13. Recommendations Basis Table

Recommendation	Data Source	Basis
Excavate 5 - 6m	SPT, UCS, Lugeon	Bearing capacity < 1.154 MPa in upper 5m; Lugeon > 15 LU
30m grout curtain	Lugeon, seismic	High permeability (>1 LU) extends to 30m depth
2-3 rows at 1.5 - 2.0m	Lugeon, RQD	Fractured rock requires multiple rows for effective grouting
Chemical grouting	Cave identification	Laterite soils with caves require chemical (not cement) grout
Upstream blanket 30m	Lugeon, permeability	Shallow high permeability zone requires extended flow path
Seismic design	ES8-2015, Vs profile	Site in Zone IV (PGA 0.20g) with amplification potential

Funding: No funding was received for this research

Declaration: The authors declare no conflict of interest.

References

Anny, N. Z, Rahman, S., Tambi, F., (2020). The importance of enhancing pedagogical skills through continuing professional development. International journal of research in business and social science, 9(4), 121-129.

A Hamed, A., Fat-Helbary, R. E. S., Mohamed, A. M., El-Faragawy, K. O., Gaber, A. A. E., & Meneisy, A. M. (2024). Application of seismic refraction and MASW methods for investigating the Spillway Fault trace along the western side of the Aswan High Dam, Egypt. Acta Geodaetica et Geophysica, 59(1), 27-50. https://doi.org/10.1007/s40328-024-00437-y

A.K., Reddy, K.R., Chore, H.S. (eds) Proceedings of Indian Geotechnical and Geoenvironmental Engineering Conference (IGGEC) 2021, Vol. 1 https://doi.org/10.1007/978-981-19-4739-1_8

Adamo, Sissakian, V.K., N. & Al-Ansari, N. The Role of Geological Investigations for Dam Siting: Mosul Dam a Case Study. *Geotech Geol Eng* **38**, 2085–2096 (2020). https://doi.org/10.1007/s10706-019-01150-2

Adewoye and Esho (2017). Geotechnical Investigation of a Proposed Dam in Adunyin Area Ogbomosho, Southwestern Nigeria. *International Journal of Scientific and Engineering Research*, 879- 905.

American Society for Testing and Materials. (2000). Standard test method for particle-size analysis of soils. D 422– 63 (1998). 2000 Annual book of ASTM standards 04.08:10–17. ASTM, Philadelphia, PA

Andrén, J. (2021). An Overview of State-of-the-art Hydraulic Conductivity Measurements in Coarse Grained Materials.

Annys, S., Ghebreyohannes, T., & Nyssen, J. (2020). Impact of hydropower dam operation and management on downstream hydrogeomorphology in semi-arid environments (Tekeze, Northern Ethiopia). Water, 12(8), 2237.

ASTM D1586: *Standard Test Method for SPT and Split-Barrel Sampling of Soils.*

Ayogu, N.O., Igwe, O. & Onuoha, M.K. Characterization of problematic subsurface soils in Eha-Amufu using integrated investigation approach: implications for earth works. *Discov Geosci* **2**, 38 (2024). https://doi.org/10.1007/s44288-024-00026-0

Barjasteh, A. (2019). Influence of geological structure on dam behavior and case studies. In *Dam engineering*. IntechOpen. https://doi.org/10.5772/intechopen.78742

Belete, D., Chala, E.T., Jilo, N.Z. *et al.* Engineering Geological Investigation of the Katar Dam Foundation and Abutment Slope Stability Analysis, Southeast Ethiopia. *Indian Geotech J* (2024). https://doi.org/10.1007/s40098- 024-01033-1

Bell, F. G. (2013). *Engineering geology and geotechnics*. Elsevier.

Bieniawiski (1978). Determining rock mass deformability: Experience from case histories. 15(5), 237–247. https://doi.org/10.1016/0148-9062(78)90956-7

Birhanu, D., & Tesfa, C. (2023). Geological and geotechnical characterization of Ziragn Dam sitting, northwestern Ethiopia. *Environmental and Sustainability Indicators*, *19*, 100261. https://doi.org/10.1016/j.indic.2023.100261

Bull Eng. Geol Environ 73, 689–706) https://doi.org10100100640140576

Casagrande, A. (1932). The structure of clay and its importance in foundation engineering. Boston Society Civil Engineers Journal.

Cooke, J. B. (1984). Progress in rock fill dams. *Journal of Geotechnical Engineering*, *110*(10), 1381-1414.

Dai, X., Schneider-Muntau, B., Fellin, W., Franco, A., & Gems, B. (2021). Engineering-geological analysis of a subaerial landslide in Taan Fiord, Alaska. *Remote Sensing*, *13*(21), 4258, **https://doi.org/10.3390/rs13214258**

Dam Safety Bureau. (2008). New Mexico Office of the State Engineer

Dearman, W. R. (1991). 2—Principles of engineering geological mapping. In W. R. Dearman (Ed.), Engineering Geological Mapping (pp. 12–18). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-7506-1010-0.50005-X

Deere, D.U., Deere, D.W., 1988. Rock Quality Designation RQD Z . after Twenty Years. US Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Deere, D.U.; Miller, R.P. (1966.) Engineering classification and index properties for intact rock. Ill. Univ. Urbana Dept. Civ. Eng.

Demisie, T., Getahun, E., Jothimani, M., & Qi, S. (2024). Geotechnical Study for Assessing Slope Stability at the Proposed Weito Dam Site in Ethiopia: Implications for Environmental Sustainability and Resilience. *Eng*, *5*(2), 1140-1154, **https://doi.org/10.3390/eng5020062**

Duffaut, P. (2013). The traps behind the failure of Malpasset arch dam, France, in 1959. Journal of Rock Mechanics and Geotechnical Engineering, 5(5), 335-341.

Fan, X., Dufresne, A., Whiteley, J., Yunus, A. P., Subramanian, S. S., Okeke, C. A. & Stefanelli, C. T. (2021). Recent technological and methodological advances for the investigation of landslide dams. *Earth-Science Reviews*, *218*, 103646 https://doi.org/10.1016/j.earscirev.2021.103646.

FAO. (2016). AQUASTAT Country Profile – Ethiopia. Food and Agriculture Organization of the United Nations (FAO).

Fekadu, A., Chemeda, Y. C., Karuppannan, S., & Chala, E. T. (2025). Engineering geological evaluation of Bowa Dayole dam site, North Shewa Zone, Oromia, Ethiopia. *Heliyon*, *11*(1).

Fell, R. (2005). *Geotechnical engineering of dams*. CRC press.

Forzieri, G., Gardenti, M., Caparrini, F., & Castelli, F. (2008). A methodology for the pre-selection of suitable sites for surface and underground small dams in arid areas: A case study in the region of Kidal, Mali. *Physics and Chemistry of the Earth, Parts A/B/C*, *33*(1-2), 74-85 https://doi.org/10.1016/j.pce.2007.04.014

Geertsema, A. J. (2000). *The engineering characteristics of important southern African rock types with emphasis on shear strength of concrete dam foundations*. Water Research Commission.

Getachew, K., Chen, D. H., & Peng, G. (2020). Seismic performance evaluation of RC frame designed using Ethiopian and Chinese seismic codes. *Advances in Civil Engineering*, *2020*(1), **https://doi.org/10.1155/2020/8493495**

Gomo, S., Mutshafa, N., Dildar, J., Manzi, M. S., Bourdeau, J. E., Brodic, B., ... & Durrheim, R. J. (2024). Integration of ground geophysical methods to characterize near-surface aquifer

zones within an active mine. *Near Surface Geophysics*. https://doi.org/10.1016/j.hydres.2024.04.002

Gosschalk, E. M. (2002). *Reservoir engineering: guidelines for practice*. Thomas Telford.

Himi, M., Casado, I., Sendros, A., Lovera, R., Rivero, L., & Casas, A. (2018). Assessing preferential seepage and monitoring mortar injection through an earthen dam settled over a gypsiferous substrate using combined geophysical methods. *Engineering geology*, *246*, 212-221, https://doi.org/10.1016/j.enggeo.2018.10.002

Hoek, E. (2007). *Practical Rock Engineering*

Horton, J., Butler, L., Overton, D. D., & Garcia, D. (2015). Variability of samples from various drilling and sampling methods http://dx.doi.org/10.14288/10314308

Houlsby, G. T., & Jewell, R. A. (1990). Design of reinforced unpaved roads for small rut depths. Geotextiles, Geomembranes and related products, 171-176.

Hudson J. A. and Priest S. D. Discontinuity spacing in rock. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 13, 135-148 (1976).

Ia, O., & Falae, P. (2018). Integrated Geophysical and Geotechnical Methods for Pre-Foundation Investigations. 8, 453 https://doi.org/10.4172/2381-8719.1000453

IACESD 2023. Lecture Notes in Civil Engineering, vol 449. Springer, Singapore. https://doi.org/10.1007/978-981- 99-8505-0_30

IAEG 1981. Rock and soil description and classification for engineering geological mapping. Bulletin of International Association of Engineering Geology, 24, 253-274

Iraji, A., & Motahari, M. R. (2024). Investigation of geotechnical characteristics of Khersan 2 dam

site in exploratory boreholes. *Geomechanics and Geoengineering*, 1–21. https://doi.org/10.1080/17486025.2024.2310008

ISRM. (1981). Suggested methods for the rock characterization, testing and monitoring.

Jabeen, T., Das, M., Sarkar, A. (2024). Assessment of the Impact of Big Dams in the Himalayan Mountain Environment System: Management and Sustainability. In: Borthakur, A., Singh, P. (eds) The Himalayas in the Anthropocene. Springer, Cham. https://doi.org/10.1007/978-3-031-50101-2_4

Kanik, M., & Ersoy, H. (2019). Evaluation of the engineering geological investigation of the Ayvali dam site (NE Turkey). Arabian Journal of Geosciences, 12, 1-13 https://doi.org/10.1007/s10706-019-01150-2

Kargaranbafghi, F., & Ghalamzan, F. (2018). Application of seismic refraction and tomography methods to the assessment of the Sivaki dam site. *International Journal of Engineering & Technology*, *7*(3), 1337-1345. http://doi:org10.14419/ijet.v7i3.12572

Kasenow, M. (2002). *Determination of hydraulic conductivity from grain size analysis*. Water Resources Publication.

Khodadad-Zadeh, M., Fereidooni, D., & Diamantis, K. (2022). An engineering geological assessment for the Darband dam site, NE of Iran, using eight rock mass classification systems. *Innovative Infrastructure Solutions*, *7*(2), 151. https://doi.org/10.1007/s41062-022-00741-y

Kibret, B. A., Ayele, A., & Keir, D. (2023). Crustal structure of the Ethiopian Northwestern Plateau and central Afar from receiver function analysis. *Frontiers in Earth Science*, *11*, 1170907.

Kinde, S., Engeda, S., Kebede, A., & Tessema, E. (2011). Technical Notes: Notes and Proposed Guidelines on Updated Seismic Codes in Ethiopia-Implication for Large-Scale Infrastructures. Zede journal, 28, 91-110

Lamessa, G., Mammo, T. & K.Raghuvanshi, T. Homogenized earthquake catalog and b-value mapping for Ethiopia and its adjoining regions. Geoenviron Disasters 6, 16 (2019). https://doi.org/10.1186/s40677-019-0131-y

Li, F., Zhang, P., Li, Q. *et al.* Decision-making study on risk evaluation of earth and rock dams based on ANP unascertained measurement theory. *Nat Hazards* **120**, 1715–1753 (2024). https://doi.org/10.1007/s11069-023- 06236-y

Lyu, Z., Chai, J., Xu, Z., Qin, Y., & Cao, J. (2019). A comprehensive review on reasons for tailings dam failures based on case history. *Advances in Civil Engineering*, *2019*(1), 4159306. **https://doi.org/10.1155/2019/4159306**

Magnekou Takamte, C. R., Ntomba, S. M., Okomo Atouba, L. C., Bisso, D., & Mvondo Ondoa, J. (2022). Geophysical and geological considerations for characterizing the dam foundation during the Memve'ele dam construction (southern Cameroon): influence on the dam type retained. *Environmental Earth Sciences*, *81*(13), 343 https://doi.org/10.1007/s12665-022-10463-0.

Meyerhof, G. G. (1956). *Penetration tests and bearing capacity of cohesionless soils.* Journal of the Soil Mechanics and Foundations Division. https://doi.org/10.1061/JSFEAQ.0000001

National Research Council. (2006). *Geological and geotechnical engineering in the new millennium: opportunities for research and technological innovation*. National Academies Press.

Olasunkanmi, N. K., Aina, A., Olatunji, S., & Bawalla, M. (2018). Seepage investigation on an existing dam using integrated geophysical methods. *Journal of Environment and Earth Science*, *8*(5), 7. www.iiste.org

Parry, S., Baynes, F.J., Culshaw, M.G. (2014). Engineering geological models: an introduction: IAEG commission https://doi.org/10.1007/s10064-014-0576-x

Pells, P. J. N., MacGregor, J. P., and Poulos, H. G. (2000). *Foundation Engineering*. Australian Geomechanics Society

Raji, W. O., Adeoye, T., & Ibrahim, K. O. (2017). Geophysical investigation of Basement Rock Structures around a proposed Dam site, http://www.adsujsr.com.

Rogers, J. D. (2006). Lessons learned from the St. Francis Dam failure

Saif, A., & Ahmed Sheikh, K. (2022). Design of grout curtain for temporary embankments on rock foundation. Geomechanics and Geoengineering, 17(2), 426-441 Saif, A., & Ahmed Sheikh, K. (2022). Design of grout curtain for temporary embankments on rock foundation. Geomechanics and Geoengineering, 17(2), 426-441. https://doi.org/10.1080/17486025.2020.1778193

Salmasi, F., & Abraham, J. (2022). Geological Considerations in Dam Engineering. *Novel Perspectives of Engineering Research Vol. 6*, 97-125 https://DOI.10.9734/bpi/nper/v6/1786A.

Salmasi, F., & Nouri, M. (2019). Effect of upstream semi-impervious blanket of embankment dams on seepage. ISH Journal of Hydraulic Engineering, 25(2), 143-152 https://doi.org/10.1080/09715010.2017.1381862

Sani, F., Ghinassi, M., Papini, M., Oms, O., & Finotello, A. (2017). Evolution of the northern tip

of Afar triangle: Inferences from the Quaternary succession of the Dandiero—Massawa area (Eritrea). *Tectonophysics*, *717*, 339-357 https://doi.org/10.1016/j.tecto.2017.08.026.

Sari, M., Seren, A., & Alemdag, S. (2020). Determination of geological structures by geophysical and geotechnical techniques in Kırklartepe Dam Site (Turkey). *Journal of Applied Geophysics*, *182*, 104174, https://doi.org/10.1016/j.jappgeo.2020.104174

Sari, M., Seren, A., & Alemdag, S. (2020). Determination of geological structures by geophysical and geotechnical techniques in Kırklartepe Dam Site (Turkey). Journal of Applied Geophysics, 182, 104174 https://doi.org/10.1016/j.jappgeo.2020.104174

Seed, H. B., & Idriss, I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. Journal of the Soil Mechanics and Foundations division, 97(9), 1249-1273.

Shen, W., Ni, W., Yong, R., Huang, L., Ye, J., Luo, Z., & Du, S. (2023). Estimating RQD for rock masses based on a comprehensive approach. *Applied Sciences*, *13*(23), 12855.

Srivastava, H., Tiwari, R.P., Kumar, V., Singh, D. (2022). A Review on Various Geotechnical and Geophysical Investigations for a Dam Rehabilitation Project. In: Agnihotri,

Tabwassah, C. A., & Obiefuna, G. I. (2012). Geophysical and Geotechnical Investigation of Cham Failed Dam Project, Ne Nigeria. Research Journal of Recent Sciences ISSN, 2277, 2502. Available online at: www.isca.in

Taleb, H.A., Guemidi, I. & Charrak, H. Numerical investigation of dam stability in the presence of fissured materials with varying angles. *Nat Hazards* **120**, 5743–5761 (2024). https://doi.org/10.1007/s11069-024-06436-0

Tanchev, L. (2014). *Dams and appurtenant hydraulic structures*. Boca Raton: CRC Press.

Ukpai, S.N. Stability analyses of dams using multidisciplinary geoscience approach for water reservoir safety: case of Mpu Damsite, Southeastern Nigeria. *Bull Eng Geol Environ* **80**, 2149–2170 (2021). https://doi.org/10.1007/s10064-020-01977-7

Wahlstorm. (1974). Dams, Dam Foundations, and Reservoir Sites. Elsevier Scientific Publishing Company.

Xiang, Y., Fu, Z., Liu, C., Zhang, K., Wang, Y., Shen, G. (2024). Dam Safety On-site Inspection and Test. In: On- site Inspection and Dam Safety Evaluation. Hydroscience and Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-97-3987-5_2

Zhan, T. L., Zhan, X., Lin, W., Luo, X., & Chen, Y. (2014). Field and laboratory investigation on geotechnical properties of sewage sludge disposed in a pit at Changan landfill, Chengdu, China. Engineering geology, 170, 24-32 https://doi.org/10.1016/j.enggeo.2013.12.006

Zhang, L. (2016). Determination and applications of rock quality designation (RQD). *Journal of Rock Mechanics and Geotechnical Engineering*, *8*(3), 389-397.