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An Engineering Geological Appraisal of the Leakage Problem in Dora-1 Earthen Dam, Tigray: Implications for its Stability

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ABSTRACT

Leakage is one of the major problems facing the functionality and sustainability of dams. It occurs through the embankment body, reservoir, foundation, and abutments. This study was conducted to identify the main causes of the leakage problem at the Dora-1 dam, located in the northern part of Ethiopia. It is an earthfill dam with a height of 43.5 m, crest length of 454 m, and reservoir capacity of 4.67 million cubic meters. Part of the embankment body was wet and swampy up to 20 m high from the ground due to leaking water. Geological investigation, laboratory test of the construction materials (including grain size analysis, specific gravity and water absorption, Atterberg limit, free swell, dispersion, permeability, and shear strength), and electrical resistivity investigation were used to identify and pinpoint the possible causes of the leakage problem. Results of the study show that the favorable geological features responsible for the occurrence of leakage include: (a) geological contact between sandstone and moderately to highly weathered basalt unit at the left abutment, (b) the gravelly sand deposit at the central foundation and (c) dyke outcrop at the river course within the reservoir running in the upstream-downstream direction. Results of laboratory tests for clay core show medium to high compressibility, good to poor workability, and semi-pervious to impervious permeability when compacted. The water absorption and the percentage finer of the filter material don’t satisfy the filter criteria and the shell material was found to be semi-previous. The anomalous in the resistivity survey result confirms the situation. Slope stability analysis of the embankment showed instability conditions at full reservoir level. Close follow-up and a downstream stabilization structure, including rock and gravel support, were recommended.

Keywords: Construction material, Embankment dam, Site investigations, Ethiopia.

1. INTRODUCTION

The Federal Government of Ethiopia initiated a rural development strategy, with the main objective of attaining food security at household level, and bringing about an overall socio-economic development (Haregeweyn et al., 2006). Thus, a number of dams have been constructed to overcome the recurrent drought, which is caused by highly erratic and variable (spatial and temporal) rainfall. However, most of the dams didn’t bring continuous economic growth due to technical challenges faced after the construction of the porjects. This is due to, among others, the reason that most dams are constructed without detailed engineering geological investigations. It was reported by Berhane et al. (2016a); and Abdulkadir (2009)

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that the sustainability of dams in Tigray is affected by many problems, including construction of the dams without being supported by detiled investigation. Kebede (2009) also indicated that, systematic study, design and construction of embankment dams requires full understanding of the geological, engineering geological and geotechnical properties of the foundation and construction materials. On the other hand Abay and Meisina (2015) stated that, the planning and execution of water resource development projects has a number of constraints, due to the engineering geological problems posed by the various foundation rocks.

Dora-1 dam is one of the dams constructed by Tigray Water Resource Bureau (TWRB) to harvest run-off water for irrigation and other domestic uses. This paper is aimed at identifying the main causes of leakage and assessing the impact of leakage on the stability of the dam. In addition, it is aimed at assessing the quality of the construction materials used for the construction of the dam and its consequence on the presence of continuous leakage problem.

1.1. Regional Geological Setting

The regional geology of the Dora area is part of the northern province of Ethiopia which is characterized by rocks of varied composition, which include Mesozoic sedimentary units, volcanics and Quaternary deposits. The northern Ethiopia is mainly underlain by weakly metamorphosed rocks capped by sedimentary and volcanic rocks. After this work, several authors start to investigate the geology of Ethiopia in general and northern Ethiopia in particular (Alene et al., 2000; Alene et al., 2006; Beyth, 1972; Bossellini et al., 1997; Dow et al., 1971; Gebreyohannes et al., 2010; Kazmin, 1972; Tadesse, 1996; Tadesse et al., 1999; Teklay et al., 1998). According to these authors, northern Ethiopia is covered by variety of rocks, varying in age and genesis. Based on stratigraphic sequence, the northern Ethiopian stratigraphy is classified (from the youngest to the oldest) as flood basalt volcanics, Amba-Aradam Formation, Antalo Supersequence, Transitional Unit, Adigrat Sandstone Formation, Enticho Sandstone and Edaga Arbi Tillites, and Upper Complex Metamorphic (Basement) rocks.

1.2. Description of the Site

Dora dam is located in the southeastern administrative zone of Tigray Regional State, particularly in Hintalo-Wajerat Woreda (district) near Adi-Keyh and Debub towns (Fig 1). It is found at 82 km south of Mekelle City across Weynat River. Adi-Keyh town (at 80 km from Mekelle City) is accessible through the Mekelle–Addis Ababa asphalt road. The specific dam site is accessible through a 2 km gravel road. The physiography of the dam site and its vicinity varies from an elevation of 2100 to 2800 m above mean sea level. It is the result of both volcano–tectonic and surface (erosion) processes. The area drains toward Raya valley and Afar basin. The salient features of the dam are presented in table 1.

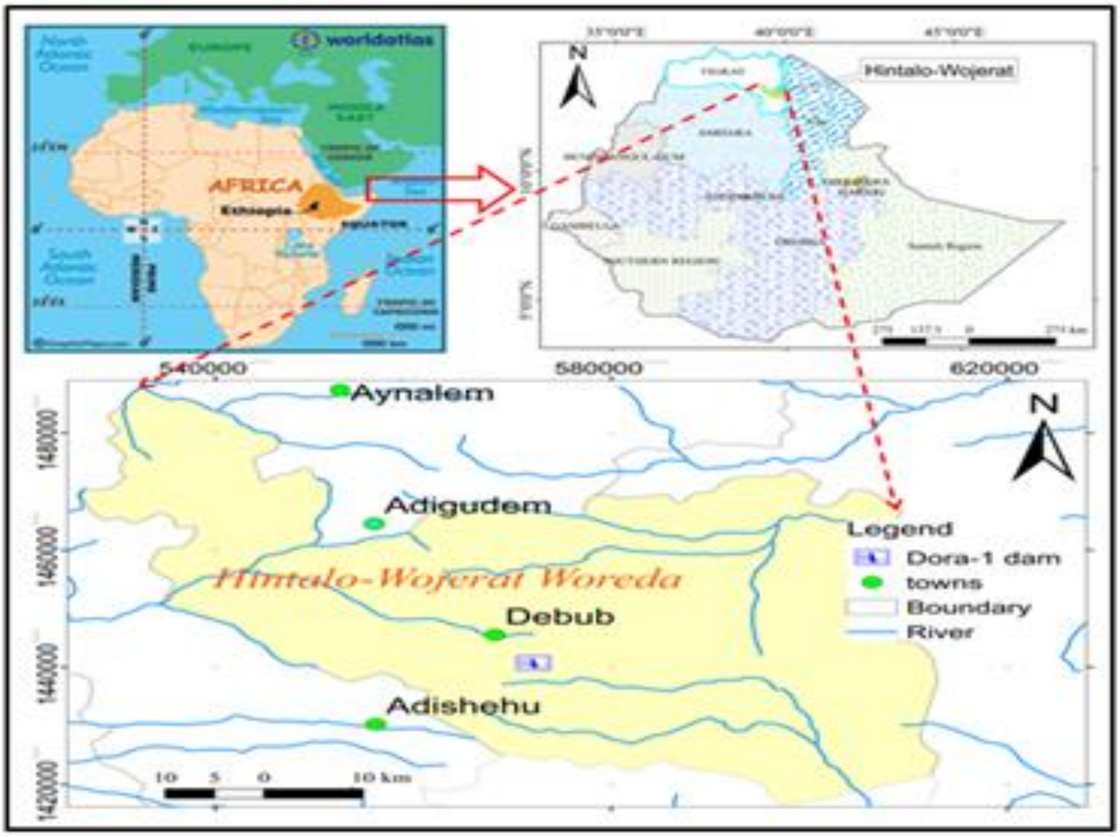

Figure 1. Location map of the Dora-1 dam with reference to Africa (modified from https://www.worldatlas.com/webimage/countrys/africa/et.htm), Ethiopia (from Ethio-GIS datasets), Tigray Regional State and Hintalo–Wojerat Woreda (~district).

Table 1. Salient features of the Dora-1 dam.

Dam features	***Dora–1 dam***	***Classification criteria based on ICOLD (1990)***	***Dora-1dam classification***
Dam crest length (m)	454	>500m (large dam)	
Dam height (m)	43.5	>15 m (large dam)	Large dam
Reservoir capacity (Mm^3)	4.67	>3 Mm3 (large dam)	Large dam
Dam type	Zoned earth-fill	-	-
Embankment volume (m^3)	98,056,440	-	-
Irrigable land (ha.)	265	-	-
Catchment area (km^2)	27.93	-	-
Year of construction	2014	-	-

2. METHODOLOGY

In general, field descriptions of soil, rock and discontinuities, and laboratory tests were carried out according to the methods suggested by the American Society for Testing and Materials (ASTM) and the International Society for Rock Mechanics (ISRM, 1981, 2007).

2.1. Field Study

Before the start of fieldwork, literature review was conducted from existing published and unpublished documents, journals and books related to dam and leakage problem. Secondary data, including engineering geological reports of the dam, electrical resistivity data (profiling and vertical electrical sounding, VES) and dam design documents were collected from TWRB. The geophysical survey of the Dora-1 dam was carried out when the leakage problem was appeared after construction completion in 2014. The location for the starting and end points for *Profile one* are 0572126mE; 1440560mN and 0571858mE; 1440364mN respectively. Similarly for *Profile two* the points are 0572188mE; 1440509mN and 0571979mE; 1440386mN. The leakage problem was experienced starting from the first reservoir filling. In this research, geophysics was used to detect leakage causing geological features. The electrical resistivity survey was carried out at the crest and the berm. The height of the berm from the lowest river is about 24m.

A total of 10 VES, five along the dam crest and the other five at the berm parallel to the dam axis, were conducted with Schlumberger array. In addition, two electrical resistivity profiling, one at the dam crest and one at the berm, were conducted with Wenner array. For the VES “AB/2” ranges from 45 to 100m, while for the profiling survey “a” varies from 10 to 45m and the suvey length was 330m for profile one and 260m for profile two. Direction of survey or AB direction was in the northeast-sourthwest direction along the direction of the dam axis. The VES data were analyzed by IPI2win software (Bobachev, 2002). Primary data were collected from direct geological investigation of the dam site, reservoir and from laboratory tests. Close observation was conducted at the foundation, abutments, reservoir, embankment body, reservoir rim and the spillway parts. Since the dam was already constructed data were collected from downstream and upstream toe of the dam and its surroundings and interpretation of VES and resistivity profiling survey data. Five test pits with a depth that varies from 2 to 3m were excavated at the downsteam toe of the dam for visiul inspection. Schmidt hammer or rebound test (L-type) was carried out to estimate the strength of intact rocks found near the reservoir area. The Schmidt hammer rebound data collection and interpretation were conducted as per the ISRM suggested methods (Aydin, 2008) and ASTM D5873 procedures. Moreover, weathering description and classification of rock mass was executed as per the guidelines and suggestions of BS 5930:1981 (Anon, 1981).

2.2. Laboratory Tests and Procedures

The construction materials for the dam were obtained from borrow areas near the dam site. The purpose of the sampling was to evaluate the borrow materials and samples were disturbed to simulate the specific purposes. Sample locations are indicated in figure 2. Report by TWRB (2013) shows description of the construction materials based on visual field observation only. But, field observations alone wouldn't fully characterize the construction material quality. It should be supported by field and laboratory tests. Low performing construction materials can cause leakage via embankment body. All the laboratory tests were carried out at the Department of Civil Engineering, Mekelle University, except the permeability test which was carried out at TWRB Geotechnical Laboratory. The laboratory tests were conducted in accordance to the ASTM standards, except the free swell and linear shrinkage test in which the standard from the Geological Survey of Ethiopia (2017) was adopted. Finally, the generated data were processed and analyzed using softwares (e.g. ArcGIS10, Global Mapper11, Surfer10, CorelDRAW, IPI2win, Geostudio-2007, Google Earth and MS Excel).

3. RESULT AND DISCUSSION

3.1. Geology

The geology of the Dora-1 dam catchment area comprises of Quaternary Deposit, Basalt and Sandstone rock units (Fig 2).

3.1.1. Quaternary Deposit

It covers flat to gently sloping areas, found at downstream part of the dam, at the reservoir area and at upstream area near the river. It consists of alluvial and colluvial sediments. The colluvial sediment consists of angular pebble to cobble size basaltic rock fragments, and sandstone fragments of boulder size. It shows variable thickness, degree of compactness, texture and color. The maximum thickness reaches up to 7m at the site. The alluvial deposit is exposed along the stream courses, and it consists of fluvial origin of rounded to sub-rounded pebbles and boulders, and poorly sorted sediments of clay, silt, sand, and pebbles.

3.1.2. Basalt

This unit is exposed almost in all directions and most parts of the catchment. The dominant varieties are aphanitic and porphyritic basalt. The porphyritic basalt is characterized by porphyritic texture. It has mineral phenocrysts of olivine, pyroxene, and plagioclase.

3.1.3. Sandstone

This unit is found in the elevated areas forming rugged terrain. In areas where the sandstone is exposed at the elevated areas the capping volcanic rocks are eroded away and subjected to faulting and folding.. This shows existence tectonic activity and surficial geological processes in the past. The sandstone unit is characterized by medium to coarse grained, white in color, rounded to sub-rounded, and commonly composed of quartz conglomerate.

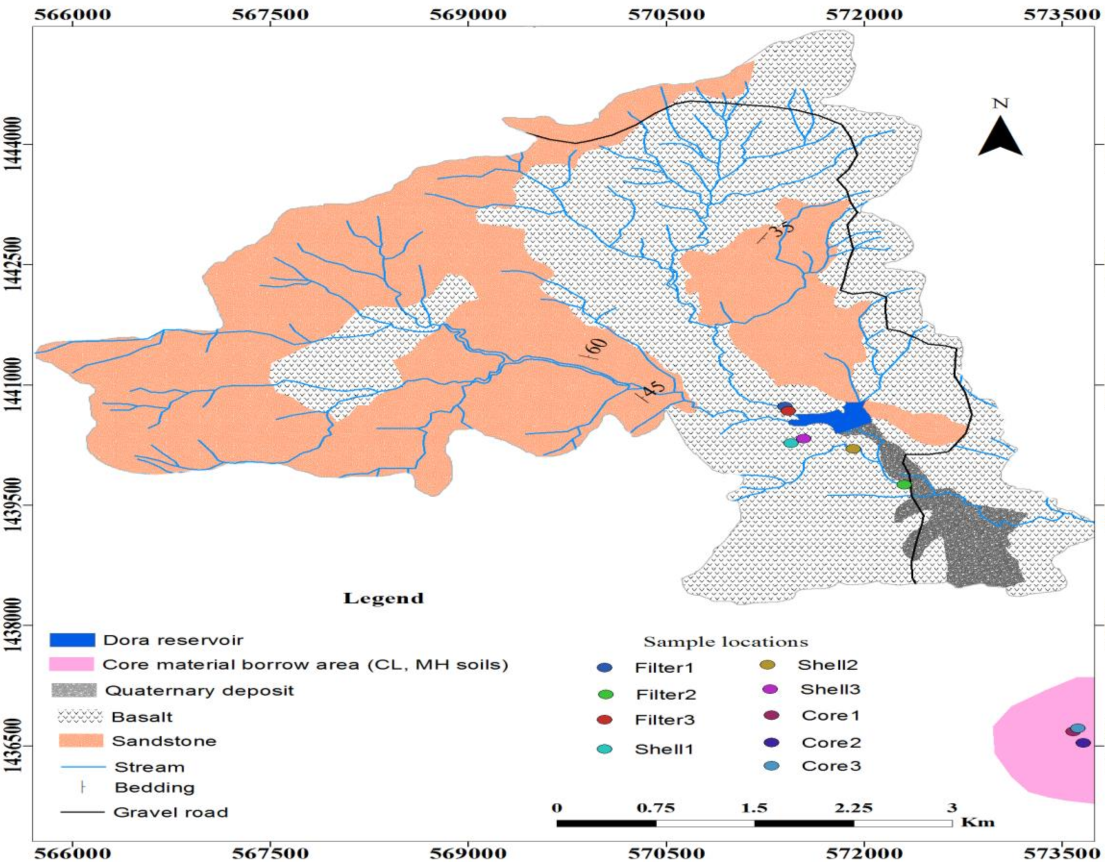

Figure 2. Geological map of Dora-1 dam and its catchment area.

3.2. Engineering Geology of the Dam Site and the Reservoir

Dora-1 dam is one of the dams located in Tigray Regional State which was constructed without an adequate geological and geotechnical investigations. In this research, the rock masses found at the abutment, reservoir rim and the spillway parts of the dam site were characterized based on their origin, degree of weathering, spacing and orientations of the discontinuities and the intact rock strength.

3.2.1. Central Dam Foundation

The dam is founded at a river valley on alluvial deposits and residual soils which are underlain by slightly weathered basalt. The central foundation of the dam site is covered by river channel fill deposits of gravelly sand (TWRB, 2013). As it is already described in

TWRB (2013), the deposit is about 6 to 7m thick, pervious, non-plastic and very loose. Subsurface water flow was observed at the test pits in the central foundation (Fig 3).

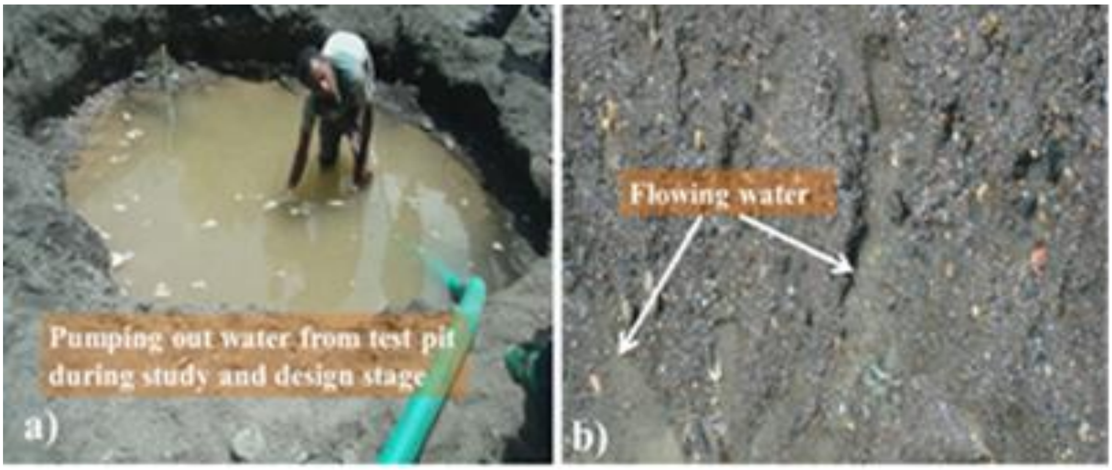

Figure 3. a) Subsurface water inflow into the test pit and pumping out. b) Foundaton materials are very pervious and loose. Photographs are taken from TWRB (2013).

3.2.2. Dam Abutments

The right abutment is covered by a moderately to highly weathered and fractured basalt unit overlaid by residual soil. The spillway is located at the right abutment side. At the right side of the spillway excavation, moderately to highly weathered and fractured basalt rock unit is exposed. This unit is cross-cut by a dyke dipping at an angle of 54° to the upstream direction (Figs 4a & b). The geology at the left side of the excavation is not the same with the right side of the excavation. The left side comprises shale, moderately to highly weathered basalt and pyroclastic rock units stratified one over the other, and is dipping at an angle of 36° to the downstream direction (Figs 4c & d). Two dykes which have width of 0.8m each and spaced at 46m are exposed at the left side of the excavation. The dykes are massive and dipping to the upstream direction (Figs 4a & b), so they can act as barriers.

In left abutment basalt and sandstone units are exposed. The contact between the two units runs across the dam axis. Leaking water was observed during field observation along this area. This geologic feature is found to be favorable for water leakage from the reservoir. According to TWRB (2013), the recommended depth of excavation for the foundation was shallow, only 5m at the abutments and 9m at the central foundation. There was no concrete data regarding the actual construction or excavation depth at different part of the foundation. It was observed that the depth of weathering is beyond a depth of 5 m at the abutments and their surrounding. The strike of the dykes at the spillway and the geologic contact at the left abutment is presented in figure 5.

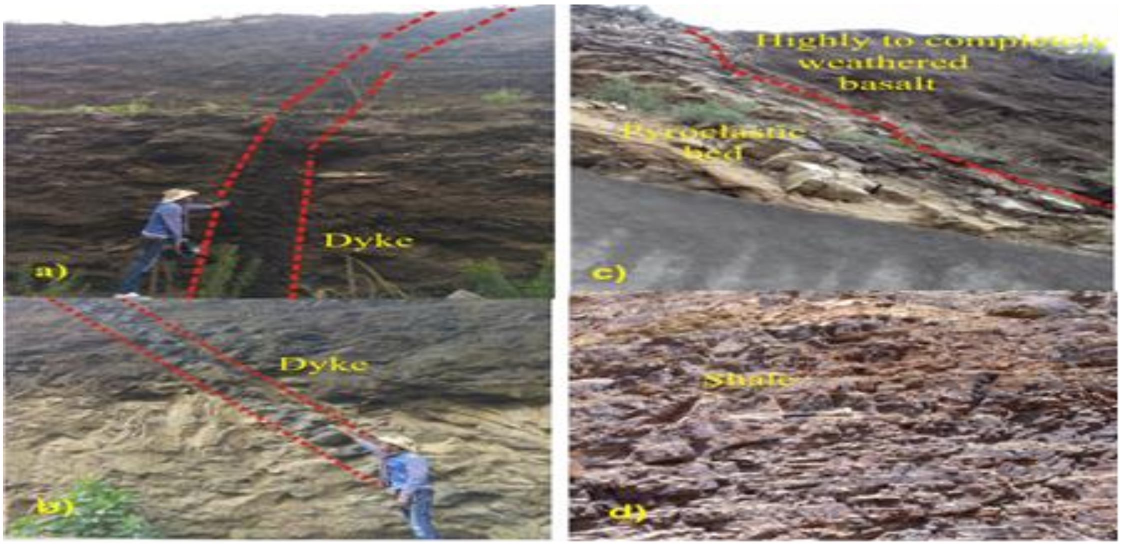

Figure 4. Rock units and structures exposed at the spillway, a) Dyke at the left of the spillway excavation, b) Highly to completely weathered basalt overlaying pyroclastic bed, c) Dyke at the right of the spillway excavation, d) Shale rock unit at left of the spillway excavation. All photographs taken by the second author in 2018.

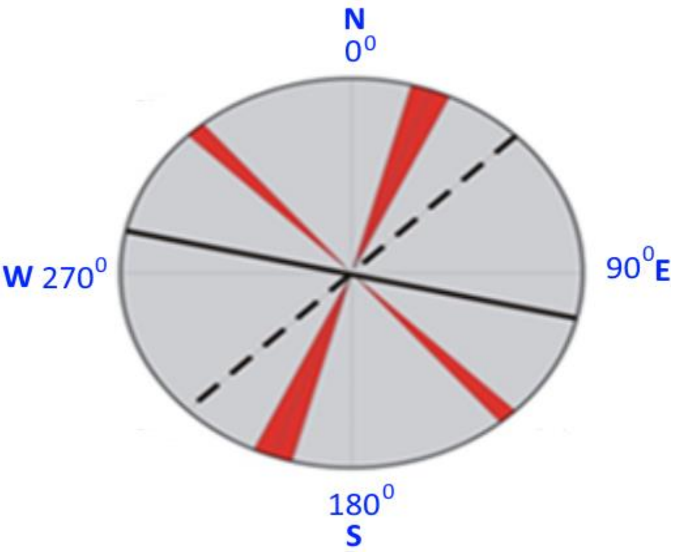

Figure 5. Rose diagram showing the strike of the 3 dykes (shaded plot) found at the spillway area and the geologic contact (solid line) at the left abutment in relation to the direction of the dam axis (broken line arrows pointing towards the center color of the circle.

3.2.3. Reservoir Geology

During the research work, the reservoir area was found to be partially filled by water (Fig 6a) and by sediment derived from the catchment. From the TWRB (2013) report, the reservoir area is mainly covered by alluvial deposit and residual soil. From the field observations, the alluvial deposit found at the downstream of the embankment is a mixture of sand and gravel with minor cobble to boulder sizes. In addition, a massive and late coming basaltic dyke is observed at the river course in the reservoir area (Fig 6b) which extends towards the right abutment (TWRB, 2013). The basaltic unit trends toward the downstream part. This geological feature (contact between the dyke and surrounding basaltic rock) could be a possible leakage path. The basalt rock unit is moderately to highly weathered and the discontinuities are closely‒spaced (Fig 6c). The rim of the reservoir is comprised of basalt and sandstone rock units. At the upstream side, the basalt is covered with residual soils and the sandstone unit is found exposed at the steep slope. The sandstone unit at the left abutment side was excavated at steep angle (nearly vertical). This can lead to sliding of rock blocks in to the reservoir during full impoundment. The sandstone unit is slightly weathered and is characterized by the presence of moderately‒spaced discontinuities (Fig 6d). Simplified engineering geological map of the dam site and reservoir area is depicted in figure 7.

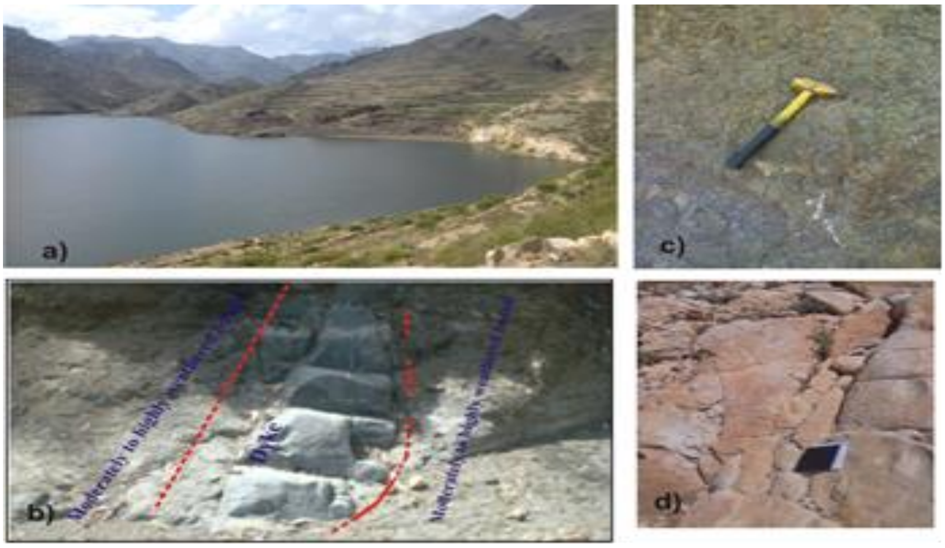

Figure 6. a) Over view of the rim of the reservoir, b) Basaltic dyke at the upstream river course of the reservoir (photograph taken and modified from TWRB (2013), c) moderately to highly weathered basalt at the rim of the reservoir, and d) Fractured sandstone unit at the rim of the reservoir. All photographs except b taken by the second author in 2018.

3.3. Geophysical Investigation on the Embankment Body

In embankment dams, resistivity surveying is important to detect potential weaknesses zones, anomalous seepage and to verify the safety of the dam (Sjodahl, 2006). The resistivity survey of Dora-1 dam was carried out by TWRB (2013). The leakage problem was experienced during construciotn phase when reservoir was started to impound water while the height of the dam reached 37m. Electrical resistivity raw data containing the profiling and VES measurements were collected from the bureau. This data were analyzed and interpreted by integrating with the new engineering geological map and other data collected during the present research.

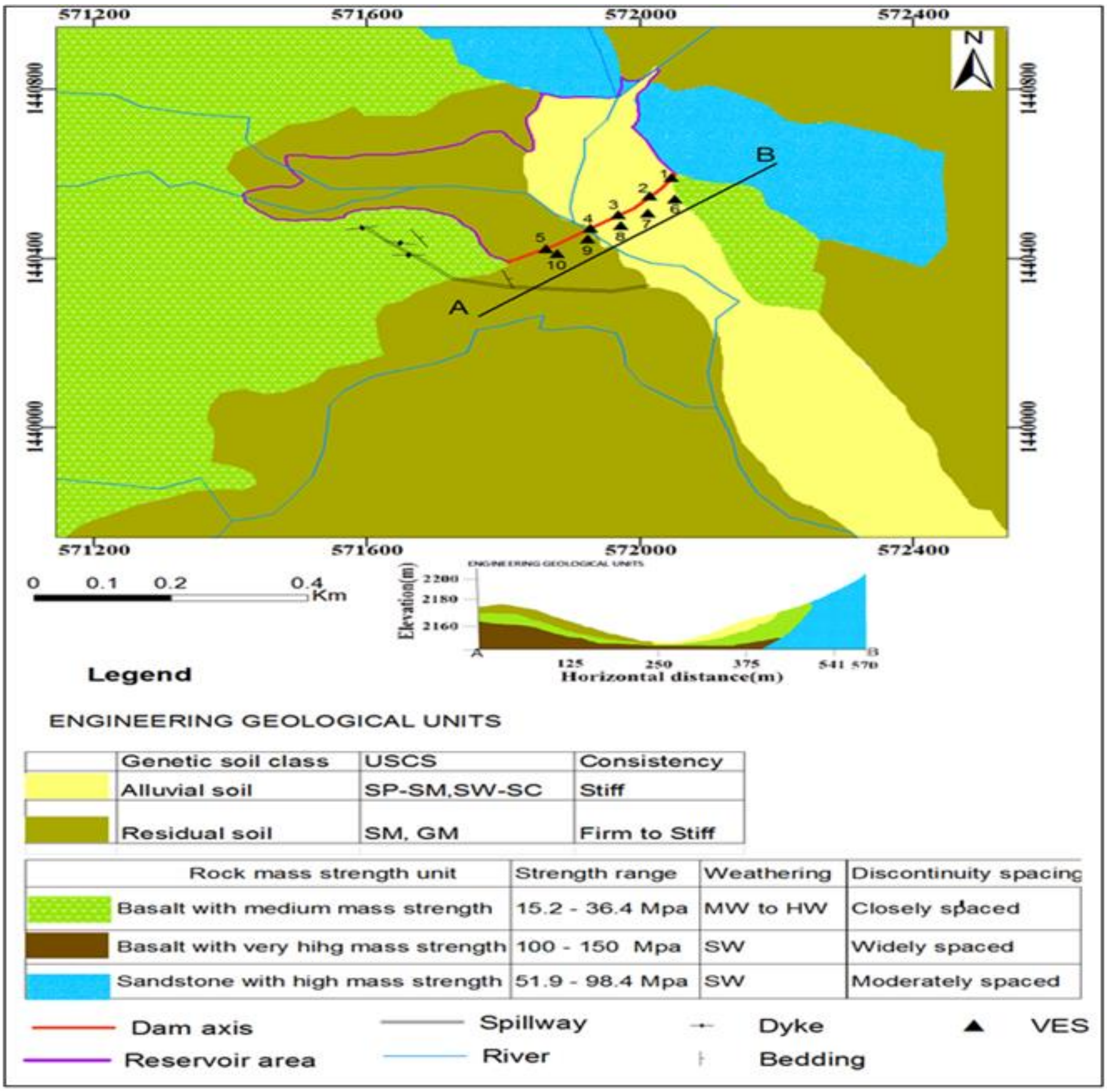

Figure 7. Engineering geological map of Dora-1 dam reservoir area and its environs with cross-section along the direction of the dam axis.

3.3.1. Vertical Electrical Sounding (VES)

VES 1 to 5 were conducted at the crest of the dam and VES 6 to 10 at the berm of the dam. The individual VES data gives information about the vertical resistivity variation of the subsurface beneath the VES point. To interpolate the data throughout the section between the VES points, the resistivity data were analyzed and presented in terms of apparent resistivity pseudo-sections constructed along selected VES points. Interpretations were made based on dam profile, field observation and resistivity pseudo-sections. The low resistivity values within the embankment body and natural ground were interpreted as the presence of defects, compaction difference during construction and weak zone.

The survey for the pseudo-section (Fig 8) was conducted along the center of the dam crest. The center of the dam crest is the core material. The resistivity variation detected within the single material (core material) could be interpreted as the result of presence of defects, compaction difference, and moisture variations. The relatively low resistivity value (<19.31 Ωm) found at a horizontal distance of 25 m infers to be the contact zone between the embankment body and the natural ground and the presence of geological defects. In the section starting from the horizontal distance of 150 m the resistivity decreases gradually from the top up to a depth of penetration by the current electrode spacing (AB/2) of 10 m, and again increases from AB/2 of 10 m up to AB/2 of 45 m. This variation in resistivity for a single zone (core material) indicates the presence of layering or stratification of the core fill material as a result of construction deficiencies (poor bondage between successive lift) and/or the presence of defects that could enhance leakage through the embankment body.

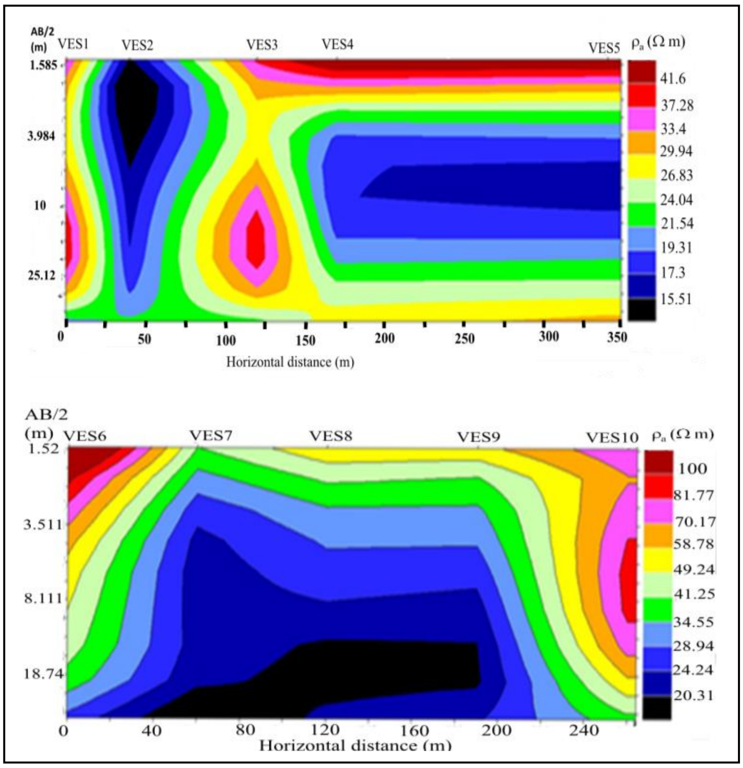

Figure 8. Apparent resistivity pseudo-sections (Ohm-meters) along VES1, VES2, VES3, VES4 and VES5 points at the dam crest, and VES6, VES7, VES8, VES9 and VES10 points at the dam berm starting from the left abutment to the direction of the right abutment.

The pseudo-section (Fig 8) is constructed from the sounding points that lie along the dam berm. The height of the berm is 24 m from the general foundation level. The pseudo-section shows a variation in resistivity of the embankment fill material with space and depth. Portion of the embankment starting from the left abutment up to a horizontal distance of 200 m shows a relatively low resistivity value (Fig 8). This low resistivity value could be the result of moisture due to the leakage, compaction deficiencies and lack of treatment of the foundation. This interpretation was confirmed by field observations where the outer portion of this section (the downstream shell material) was found to be wet and dripping (Fig 9).

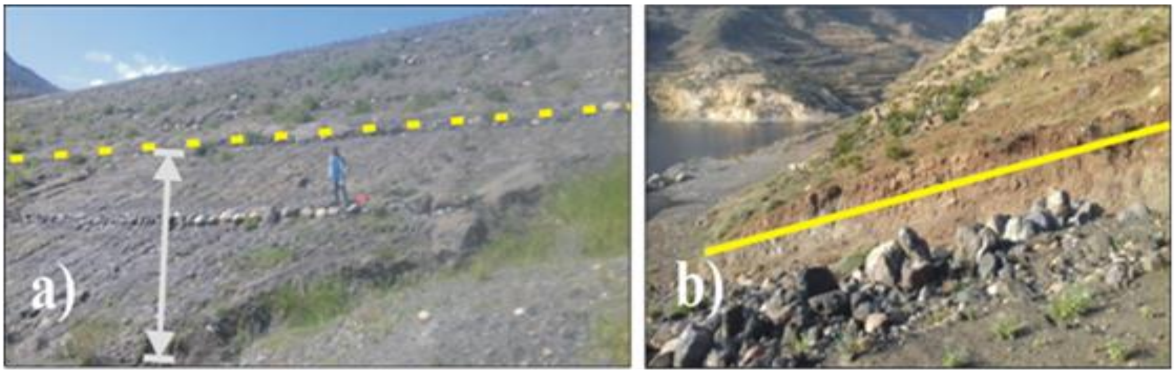

Figure 9. a**)** Field photo illustrates the wet portion of the embankment body (double arrow); b) Field photograph showing the contact between the basalt and sandstone units at the left abutment. Solid line shows the trend of the contact. Part of the reservoir (water) is visible in upper left side of the photograph. Photographs were taken by the second author in 2018.

3.3.2. Electrical Resistivity Profiling (ERP)

The two profiles were aligned in the NE-SW direction (left abutment to right abutment). The first profile (ERP1) which was conducted at the crest of the dam with a=15, 25, 35, and 45 m, while the second profile (ERP2) was executed at the berm of the dam with a=10 and 20 m.

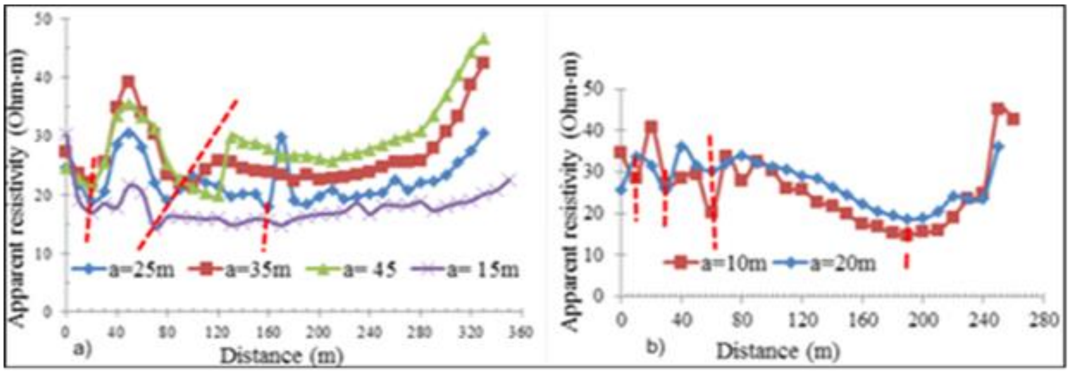

Figure 10. Graphical plot of the electrical resistivity profiling a) along the dam crest (profile one) and b) along the dam berm (profile two). The broken lines indicate interpreted as geological defects and variation in degree of compaction during construction.

According to Kirsch (2009) as cited in Berhane et al. (2016b) the presence of fracture zones and the degree of saturation of the ground can be determined using electrical resistivity profiling. As indicated in figure 10a, the resistivity varies laterally along the dam crest. This variation in resistivity was inferred as presence of geologic features favorable for leakage. The low resistivity value at around 20 m distance was interpreted as a result of the contact zone between the embankment and the natural ground. Low resistivity values at distances 60-80 and 160 m were interpreted as a result of geologic defects, variations in degree of saturation or the result of less (improper) compaction during the construction time.

The electrical resistivity profiling along the dam berm also shows lateral resistivity variations (Fig 10b). A relatively low resistivity values are observed at the horizontal distance of 10, 30, 60, and 80ms indicated by broken line (Fig 10). The low resistivity at the horizontal distance10 m could be interpreted as a result of the contact zone, while those at 30, 60, and 80 m were interpreted as a result of defects/cracking, variation in degree of saturation due to improper compaction during the construction time. At a horizontal distances of 100–220 m the resistivity values decrease progressively. As observed during the field campaign, part of the embankment body below the dam berm was wet. This direct observation serves as a confirmation for the resistivity data interpretation. The apparent resistivity pseudo-section along the dam berm (Fig 8) and the graphical plot of electrical resistivity profiling along the dam berm (Fig 10b) show low resistivity values for this section of the dam body. This is the result of saturation of the embankment fill materials due to leaking water. The left abutment of the dam axis is founded on a sandstone and basalt units. The field photograph in (Fig 9b) shows the contact zone. The contact between the rock units crosses the dam axis. Discontinuities that intersect the dam axis, dipping toward downstream are the most promising features for leakage of water from reservoirs. So, the contact at left abutment of Dora-1 dam could be one contributing cause for the occurrence of leakage.

3.4. Geotechnical Condition of the Embankment Body

Leakage is severed problem at this project to the extent that water is leaking directly through the embankment body. Portion of the embankment at the downstream face up to a height of 20 m was found to be saturated and wet (swampy) when the reservoir water level was at around 25 m. When the reservoir level was dropped the extent of the wet area was also dropped. Generally, as observed in the field the height of wet portion of the embankment varies with the fluctuation of the reservoir water level. Such phenomenon and observations are clear indications that the safety of the embankment is under question. The danger signs of

Dora-1 based on the U.S. Society on Dams (2011) guidelines are listed in table 2. In addition, field photographs that show the danger signs are presented in figures 9 and 11.

Table 2. List of danger signs for an embankment dam (U.S. Society on Dams, 2011) and their occurrences in Dora-1 dam.

S. No.	***Danger signs of an embankment dam.***	***In case of Dora-1 dam***	***Localities***
1	Erosion of the outer slopes or of the abutments	Observed	D/S & U/S slope of embankment (Fig. 12)
2	Wet or saturated areas along the downstream slope	Observed	D/S embankment up to 20m high from valley bottom (Fig. 10a)
3	Seepage emerging on the downstream slope or from abutments and foundations	Observed	D/S slope at the toe (Fig. 12a)
4	Changes in seepage rate or in the pore pressure distribution within the dam	Observed	Variable rate with reservoir level at D/S
5	Seepage carrying fines	Observed	D/S embankment toe
6	Cracks	Observed	Embankment crest, D/S, U/S slopes

At Dora-1 dam, the leakage which is observed in the form of springs (Fig 11) was observed carrying fine soil particles. To check the probable source of the fine particles, dispersion test was conducted for the core materials. However, the laboratory test result showed non-dispersive character (Table 4). Therefore, the possible source of the fine materials could be the shell material and/or the moderately to highly weathered basalt found at the left abutment. The migration of fines via leaking water indicates poor performance of the filter material. Had it been good quality and fulfilled the filter criteria, migration of fine materials would not be observed. Cracks which are parallel to the dam axis (longitudinal) were also observed at the dam crest. The cracks are localized and have an opening up to 5mm wide.

Figure 11. Photographs showing leaking water (a) and erosion features (b) at the downstream face of the embankment. Arrow indicates leaking (flowing) water from the embankment body. Photographs were taken by the second author in 2018.

3.4.1. Index and engineering Properties

3.4.1.1. Grain Size Analysis

The grain size analysis results for the filter, shell and core materials are presented in (Fig 12). The primary purpose of a filter material is to provide a safe drainage and prevent migration of fine particles from the protected zone. To achieve these purposes filter criteria is checked and fulfilled.

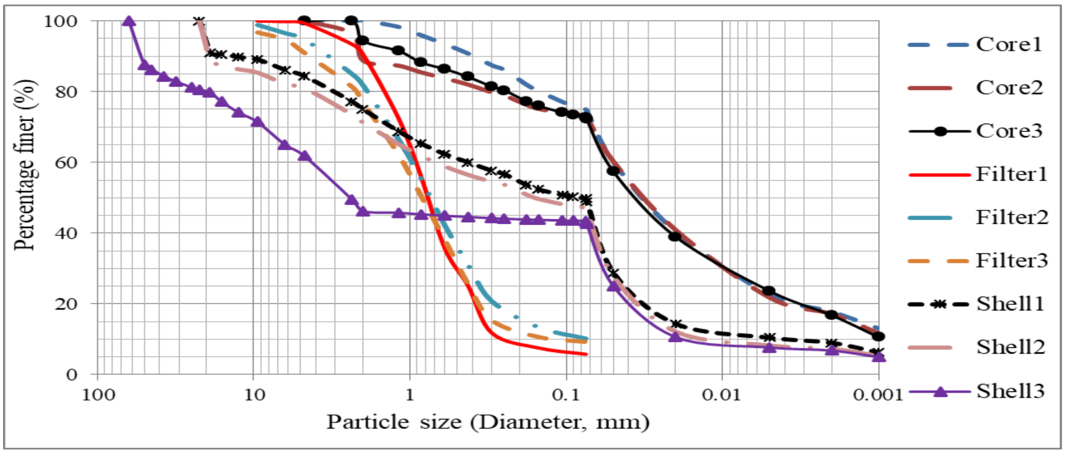

Figure 12. Grain size distribution curve of the embankment fill material.

(A) Terzaghi Criterion (1996) (Terzaghi et al., 1996)

The Terzaghi criterion ($\frac{D15\ (F)}{D85\ (B)} < 4$) addresses the retention requirement. For the present research, the test result was 0.55, which satisfies the criteria. For the second Terzaghi criterion ($\frac{D15\ (F)}{D(B)15} > 4$) the result was 56, which satisfies the criteria. Other requirements in the Terzaghi criterion for a good filter are:

- ✓ The gradation curve of the filter material should be approximately parallel to the gradation curve of the protected soil (core material), especially in the finer range. This criterion is satisfied as can be seen in figure 12.
- ✓ Filters should not contain more than 5% fines and fines should be cohesionless to ensure that the filter is pervious and prevent cracking. This criterion is not satisfied. Because, the percentage of fines of the filter material ranges from 5.8 to 9.3%.
- ✓ The filter should not contain particles larger than 75 mm to minimize segregation. This criterion is satisfied.

B) Sherard’s Criterion (Sherard and Dunnigan, 1989)

According to this criterion, the filter is considered as good filter if it fulfills the following.

I. $\frac{D15\ (F)}{D85\ (B)} < 9$, is satisfied because the value for this ratio is found to be 0.55.

II. The coefficient of permeability (cm/s) of dense filter should be in the range of k = 0.2 to 0.6 $(D_{15})^2$ (mm) with average value of 0.35 $(D_{15})^2$ mm.

For this criterion the permeability test results of the filter material are summarized in table 3.

Table 3. Evaluation of the filter material as per the Sherard's permeability criterion.

Filter Samples ID.	***Permeability (cm/s) of the filter Material obtained from the laboratory***	***Permeability range obtained to evaluate the fulfillment of Sherard's criterion (K=0.6 $(D_{15})^2$ to 0.2$(D_{15})^2$)***	***Remark***
Filter1	$1.14*10^{-2}$	0.06936–0.2	Out of range
Filter2	$1.48*10^{-3}$	0.024–0.2	Out of range
Filter3	$1.46*10^{-3}$	0.054–0.2	Out of range

The permeability of filter material is categorized in to pervious as per USBR (1998). However, all of the samples were not with in the recommended range of Sherard's permeability criterion (Table 3). The filter material doesn't fulfill all the quality requirements. The percentage of fines (particles passing #200 sieve 0.075mm) obtained in the laboratory test ranges from 5.8–9.3% which is above the permissible value. According to ASTM C 33 (1999), the fines content of fine aggregate should be less than 3 percent. The presence of higher amount of fines can result clogging of the filters and drains. In addition, the filter doesn't fulfill the second (II) criteria of Sherard.

Sample Shell1 and Shell2 of the shell material are classified as SM (Silty sand with gravel) and sample Shell3 is classified as GM (Silty gravel with sand). As it is portrayed in the grain size distribution curve (Fig 12), the shell material is consist of higher amount particles finer than #200 sieves (0.075mm) and it ranges from 43.5–49.3%. Obviously, the presence of higher amount of fine particles in the shell material can also lead to migration of fines from the shell material in to the filter material when water seeps in to the filter. This can result clogging of the filter. The purpose of shell material is to support the embankment (stability), and it should be pervious. But, actually the shell material used in constrcting the dam has excess fines content, this can result clogging of the filter which in turn can result pore pressure and triggers leakage via the embankment and detorirate its stabilty. The soil classification indicates that sample Core1 of the core material classified as CL and samples Core2 and Core3 as MH. As per USBR (1998), CL (Inorganic clays of low to medium plasticity) soils are ranked as 3rd based on the relative desirability of the soil as core material for embankment (suitable material). But, the MH (Sandy elastic silt) soils are characterized by fair to poor in their shear strength when saturated, highly compressible, and poor workability as a construction material. So, these soils are considered unsuitable material as impervious core.

3.4.1.2. Specific Gravity and Water Absorption

Water absorption gives an idea about the strength/durability of aggregates. Aggregates having high water absorption are more porous in nature and are considered unsuitable. According to ASTM C128 (2012); and Kosmata et al. (2003), the absorption value for fine aggregates should not be more than 2%. The water absorption of the filter materials of the present research resulted in the range of 3.72 to 4.25%, while the specific gravity was about 2.9 (Table 5).

3.4.1.3. Free Swell and Linear Shrinkage

According to Holtz and Gibbs (1956), soils are grouped in to non-expansive, intermediate and expansive soils based on their degree of expansiveness. Swell value of less than 50% are non-expansive, 50–100% are considered as intermediate and greater than 100% are grouped in to expansive soils. The free swell value of the core material ranges between 65 &78.4% (Table 5), and for the shell material it ranges from 50 to 60%. All the results fall in the intermediate class. Intermediate soils are not considered as sever, but such soils could be potential for some problems.

3.4.1.4. Atterberg Limit

Atterberg limit tests were conducted for the core and shell materials show low liquid limit. Test results are summerised in table 5 and in the plasticity chart (Fig 13).

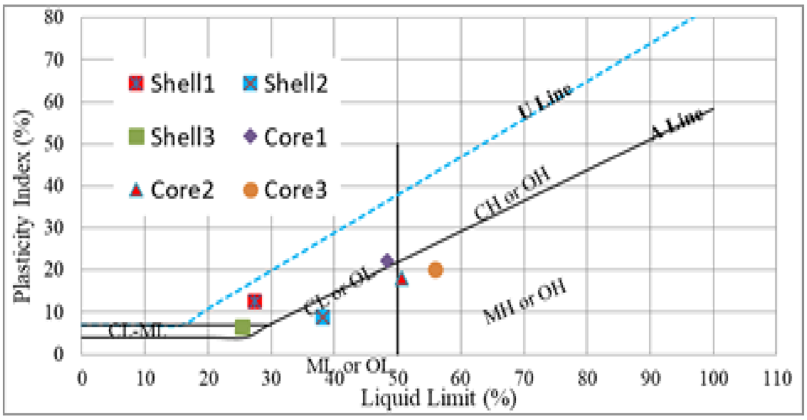

Figure 13. Classification of the core and shell materials using plasticity chart.

3.4.1.5. Dispersivity of Core

Bell and Maud (1994) cited in Fell et al. (2014) indicated that, soils with > 50% dispersion are regarded as highly dispersive, 30–50% moderately dispersive, 30 to 15% slightly dispersive, and < 15% non-dispersive. For the present research all the core materials fall under the non-dispersive soil type (Table 4).

Table 4. Summary of the double (dispersion) hydrometer test results.

Sample ID.	***% passing 0.005mm (ASTM D 4221, 1999)***	***% passing 0.005mm (ASTM D 4221, 1999)***	***Dispersion (%)***	***Classification (Bell and Maud, 1994)***
Core1	2.1	22.6	9.3	Non-dispersive
Core2	1.9	21.0	9.04	Non-dispersive
Core3	1.9	23.6	8.05	Non-dispersive

3.4.1.6. Permeability Test Results

The permeability results from moulded samples are summarized in table 5. According to USBR (1998), soils with permeability value <1×10^{-6} cm/s are impervious, 1×10^{-6}cm/s to 1×10^{-4}cm/s) are semi pervious and > (1×10^{-4}cm/s) are pervious. The permeability results for the filter material fall in the previous and both the core and shell materials fall in the semi previous. Generally, the shell material is supposed to be pervious or at least it permeability should be different from that of core material. Otherwise, the embankment shall be homogenous types. This is not the case for the present dam.

3.4.1.7. Shear Strength Test Results

In this research, unconfined compression strength test (UCS) and direct shear test were conducted for the core and shell materials. The shear parameters were used in the slope stability analysis (Table 5).

3.4.1.8. Stability Analysis of the Embankment Slope

The stability analysis was conducted for three selected reservoir water levels: at a full level of the reservoir (40.5 m), at 25 m (the maximum reserve water level that the dam was reached in the years of 2017 and 2018) and at 20 m. For the analysis the embankment fill material's shear strength parameters were used as input.

From the analysis results, the slip surfaces and the calculated factor of safety for the reservoir level of 25 m and 20 m are presented in figure 15, and for the full reservoir water (40.5m) in figure 14. The slope stability analysis was conducted using SLOPE/W model, one of the GeoStudio-2007 software products. The calculated factor of safety for the reservoir levels of 20 m and 25 m are 2.162 and 1.909 respectively. This shows stable condition of the embankment. But, the most critical condition of embankment occurs if the reservoir is fully impounded. The minimum factor of safety obtained at a full reservoir level is 0.835 (Fig 14). The dam is therefore, unstable at a full reservoir water level.

Table 5. Classification of the soils used as construction material based on their index properties as per the Unified Soil Classification System (USCS).

Sample Code	Specific Gravity	Water Absorption (%)	Free swell (%)	Linear shrinkage (%)	Cohesion (c) (kN/m^2)	Angle of shear resistant,Ø	Coefficient of Permeability K (cm/s)	Atterberg limit (%)			Grain sizes distribution (%)				Classification according to USCS
								LL	PL	PI	Gravel	Sand	Silt and Clay		
Filter1	2.90	4.52	-	-	-	-	1.14×10^{-2}	-	-	-	0.6	93.6	5.8		SP-SM, Poorly graded sand with silt.
Filter2	2.87	3.95	-	-	-	-	1.48×10^{-3}	-	-	-	5.3	84.5	10.2		SW-SC, Poorly graded sand with clay.
Filter3	2.92	3.72	-	-	-	-	1.46×10^{-3}	-	-	-	5	85.7	9.3		SW-SC, Poorly graded sand with clay.
													Silt	Clay	
Shell1	2.55	-	60	5.9	46.0	9.3	2.40×10^{-4}	27.4	15	12.4	15.6	34.6	39.3	10.5	SM, Silty Sand with Gravel
Shell2	2.74	-	55	5.9	34.7	9.3	3.44×10^{-4}	38.2	29.5	8.7	19.1	33.8	38.8	8.3	SM, Silty Sand with Gravel
Shell3	2.79	-	50	3.7	44.5	11.4	4.85×10^{-4}	25.4	18.9	6.5	38.2	18.3	35.8	7.7	GM, Silty Gravel with Sand
Core1	2.94	-	78.4	16.1	84.45	0	1.26×10^{-6}	48.4	26.2	22.3	0	25.1	52.3	22.6	CL, Sandy Lean Clay
Core2	2.86	-	65	14.07	69.4	0	2.59×10^{-6}	50.6	32.6	18	0	26.8	51.4	21.8	MH, Sandy Elastic Silt
Core3	2.83	-	70	15.2	76.7	0	2.34×10^{-6}	56	35.9	20.1	0	27.2	49.2	23.6	MH, Sandy Elastic Silt

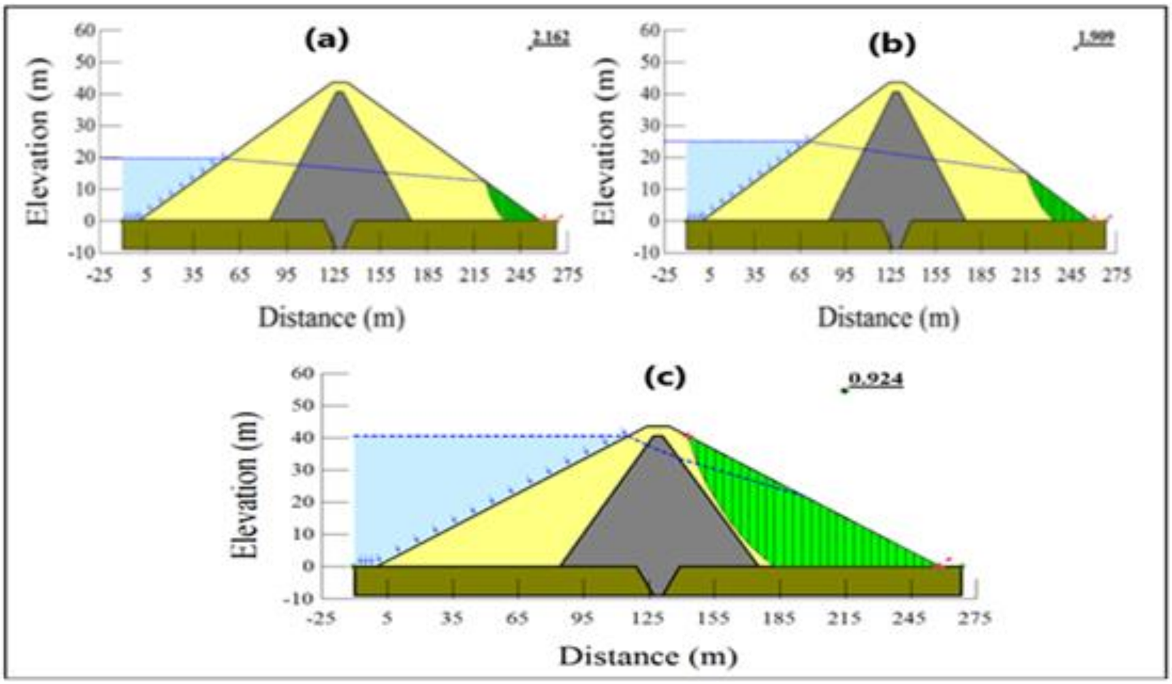

Figure 14. Stability analysis results for a reservoir level of (a) 20 m, (b) 25 m; and (c) for a full reservoir water level.

4. CONCLUSION AND RECOMMENDATION

The engineering characteristics of the rocks/soils and geological structures at the dam foundation, reservoir area, and the abutments favor for the occurrences of leakage. Water is leaking along the contact between sandstone and moderately to highly weathered basalt units at the left abutment. The foundation and reservoir of the dam site is covered by gravelly sand and loose residual soils. Field observations and analysed data showed that part of the embankment in the downstream side is wet and saturated. With respect to the quality of the construction materials, some of the embankment materials were found unsuitable (filter with high percentage of fines, permeability of core and shell materials). The permeability of the core material falls under semi-previous category. The water absorption (above 2%) and the percentage of fines of the filter material don't satisfy the filter criteria. The presence of higher amount of fines can result clogging of the filters and drains and can result pore water pressure. The resistivity results showed strong variations for the same embankment material. This variation was interpreted as the presence of leakage triggering features, such as defects, layering of the embankment fill material due to compaction differences during construction. From the stability analysis conducted the factor of safety at a full reservoir level was 0.835. The dam is, therefore, unstable at a full reservoir water level. A layer of clean compacted gravelly sand/rock which can act as a drain is recommended at the downstream toe of the embankment to prevent excessive pore pressure and improve stability. A close flow-up and warning system during the reservoir filling toward its full level is recommended. Routine embankment slope protection measures (grassing–over, stone riprap, etc.) can prevent sheet and rill erosions at the down–and upstream slopes.

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6. CONFLICT OF INTERESTS

There is no conflict of interests.

7. REFERENCE

Abay, A & Meisina, C. 2015. Engineering geological properties of carbonates and shale: their implication for dam construction in Mekelle, Northern Ethiopia. *Momona Ethiopian Journal of Science,* **1**: 64-84.

Abdulkadir, M. 2009. Assessment of micro-dam irrigation projects and runoff predictions for ungauged catchments in Northern Ethiopia: PhD thesis, University Munster, Germany, https://d-nb.info/1000437884/34.

Alene, M., Ruffini, R & Sacchi, R. 2000. Geochemistry and geotectonic setting of Neoproterozoic rocks from northern Ethiopia (Arabian-Nubian Shield). *Gondwana Research,* **3**: 333-347.

Alene, M., Jenkin, G., Leng, M & Darbyshir, F. 2006. The Tamben Group, Ethiopia: an early Cryogenian (Ca. 800–735 Ma) Neoproterozoic sequence in the Arabian-Nubian Shield. *Precambrian Research,* **147**: 79-99.

American Society for Testing and Materials (ASTM). 1999. Standard specification for concrete aggregates. *Annal book of ASTM standards,* ASTM C33-99.

American Society for Testing and Materials (ASTM). 1999. Standard test methods for dispersive characteristics of clay soil by doublehydrometer. Annal book of ASTM standards, ASTM D 4221 – 99.

American Society for Testing and Materials (ASTM). 2012. standard test methods for fine aggregate density & absorption test proficiency. *Annal book of ASTM standards*, ASTM C128-12.

Anon. 1981. BS 5930:1981: Code of Practice for Site Investigations (formerly CP 2001), *British Standards Institution*, London.

Aydin, A. 2008. ISRM Suggested Method for Determination of the Schmidt Hammer Rebound Hardness: Revised Version. In: R. Ulusay (ed.), The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring (2007–2014), DOI: 10.1007/978-3-319-07713-0.

Berhane, G., Gebreyohannes, T., Martens, K & Walraevens, K. 2016a. Overview of micro-dam reservoirs in Tigay, Northern Ethiopia. *Journal African Earth Science,* **123**, 210-222.

Berhane, G., Kebede, S., Gebreyohannes, T., Martens, K., Van, M & Walraevens, K. 2016b. An integrated approach for detection and delineation of leakage path from Arato micro-dam reservoir, northern Ethiopia. *Bulletin of Engineering Geology and the Environment*, **75(1)**: 193–210, DOI:10.1007/s10064-015-0750-9.

Beyth, M. 1972. Paleozoic-Mesozoic Sedimentary Basins of Mekele Outlier, Northern Ethiopia. *Association of American Petroleum Geologists Bulletin*, **56**: 2426-2439, https://doi.org/10.1306/819A422A-16C5-11D7-8645000102C1865D

Bobachev, A. 2002. IPI2Win Windows software for an automatic interpretation of resistivity sounding data. Russia, Moscow State University.

Bossellini, A., Russo, A., Fantozzi, P., L., Getaneh, A & Solomon, T. 1997. The Mesozoic succession of the Mekelle Outlier (Tigre Province, Ethiopia). *Memoir Science Geology*, **49**: 95-116.

Dow, B., Beyth, M & Hailu, T. 1971. Paleozoic glacial rocks recently discovered in northern Ethiopia. *Geological Magazine*, **108**: 53-59.

Fell, R., MacGregor, P., Stapledon, D., Bell, G & Foster, M. 2014. Geotechnical Engineering of Dams. 2nd edition, eBook ISBN9780429220609, CRC Press, 1382p, DOI: https://doi.org/10.1201/b17800

Gebreyohannes, T., Smedt, F., Miruts, H., Solomon, G., Kassa, A., Kurkura, K., Abdulwassie, Hussein., Jan, N., Hans, Bx., Jan, M., Jozef, D & Mitiku, H. 2010. Large-scale Geological Mapping of the Geba Basin, Northern Ethiopia. Tigray Livelihood Paper No **9,** ISBN 978-90-8826-134-3., VLIR –Mekelle Univ., IUC Program, 46p.

Geological Survey of Ethiopia (GSE). 2017. Technical standards for engineering geological mapping and site investigation, Geological Survey of Ethiopia, Addis Ababa (Unpubl.).

Haregeweyn, N., Poesen, J., Nyssen, J., De Wit, J., Haile, M., Govers, G & Deckers, S. 2006. Reservoirs in Tigray, Northern Ethiopia: characteristics and sediment deposition problems. *Land Degradation and Development,* **17(2)**: 211-230.

Holtz, G & Gibbs, J. 1956. Engineering properties of expansive clays. *Transactions of ASCE,* **121**: 641-677.

International Commission on Large Dams (ICOLD). 1990. Conventional methods in dam construction. *Bulletin 76*. Paris.

ISRM. 1981. Suggested methods for determining hardness and abrasiveness of rocks. In: E.T. Brown (ed.), Rock characterization, testing and monitoring: ISRM suggested Methods. Oxford: Pergamon, p 95-96.

ISRM. 2007. The complete ISRM suggested methods for rock characterization, testing and monitoring:1974–2006. In: Ulusay and Hudson (eds.) Suggested Methods Prepared by the Commissionon Testing Methods, International Society for Rock Mechanics; 2007.

Kazmin, V. 1972. Geological map of Ethiopia. Geological Survey of Ethiopia, Addis Ababa, Ethiopia.

Kebede, T. 2009. Engineering geological assesment of granular material from weathered Adigrat Sandstone as filter material, special consideration to Shumbrit dam, Western Amhara. M.Sc. thesis, Addis Ababa University, Ethiopia (Unpubl.)

Kosmata, S.H., Kerkhoff, B & Panarese, W. C. 2002. *Design and control of concrete mixtures*. EB001, 14th edition, ISBN0-89312-217-3, Portland cement association, 358p.

Sherard, J. L & Dunnigan, L. P. 1989. Critical Filters for Impervious Soils. *J. Geotechnical Engineering,* ASCE, **115(7)**: 927-947. http://dx.doi.org/10.1061/(ASCE)0733-9410.

Sjodahl, P. 2006. Resistivity investigation and monitoring for detection of internal erosion and anomalous seepage in embankment dams. PhD thesis, Engineering Geology, Lund University, https://lucris.lub.lu.se/ws/files/5949674/546337.pdf.

Tadesse T. 1996. Structure across a possible intra-oceanic suture zone in the low-grade Pan-African rocks of northern Ethiopia. *Journal of African Earth Sciences,* **23(3)**: 375-381.

Tadesse, T., Hoshino, M & Sawada Y. 1999. Geochemistry of low-grade metavolcanic rocks from the Pan African of the Axum area, northern Ethiopia. *Precambrian Research,* **99**, 101-124.

Teklay, M., Krone, A., Mezger, K & Oberhansli, R. 1998. Geochemistry, Pb-Pb single Zircon ages and Nd-Sr isotope composition of Precambrian rocks from southern and Eastern

Ethiopia: implications for crustal evolution in East Africa. *Journal of African Earth Sciences*, **26**: 207-227.

Terzaghi, K., Peck, R. B & Mesri, G. 1996. *Soil mechanics in engineering practice*. 3rd edition, ISBN 0-471-08658-4, John Wiley & Sons, Inc., 592p.

Tigray Water Resources Bureau (TWRB). 2013. Engineering geological report of Dora-1 dam site. Unpub. Technical Report, Mekelle, Ethiopia.

U.S. Dept. Interior, Bureau of Reclamation (USBR). 1998. Earth manual part 1, third edition. United States government printing office, Denver.

U.S. Society on Dams. 2011. Materials for Embankment Dams. Printed in the United States of America, ISBN 978-1-884575-49-5, Denver.