Geological, geophysical and engineering geological investigation of a leaky micro-dam in the Northern Ethiopia

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Abstract: The study was conducted to assess the main causes of leakage problem in the Hashenge micro-dam, located in the Tigray regional state, northern part of Ethiopia. The micro, dam is a 19 m height earth fill dam with the length of 387 m and reservoir capacity of about 2.3 million cubic meters at maximum water level. Geological, geophysical and engineering geological investigations were conducted in the abutment and reservoir area to assess and pinpoint the main causes. The dominant lithologic units include limestone-shale-marl intercalation, dolerite and recent soil deposits. Vertical electrical sounding was used to locate geotechnical boreholes and to know vertical and lateral variability of geological materials. Geotechnical and engineering geological investigation including drilling of three boreholes and packer testing along with detail measurement and analysis of discontinuity parameters was conducted. Analysis of the data showed that the sedimentary succession, limestone-shale-marl intercalation was the leaky unit and responsible to the water harvest failure of the scheme. The hydraulic conductivity of the leaky unit was estimated from packer test results and discontinuity data in the order of 10^{-3} m/s. This study revealed that detail subsurface investigation in cyclic sedimentary sequence should be a critical prerequisite in water harvesting planning.

Keywords: boreholes, Ethiopia, Hashenge, micro-dam, reservoir, Tigray

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1 Introduction

1.1 Background

Like most civil engineering structures, bridges, tunnels, etc., earth dams/reservoirs require detailed knowledge of geological, geotechnical and engineering geological properties of the foundation, abutment and the materials used for construction.

Site selection for engineering projects like dam sites, natural and induced hazards such as landslides, flooding, groundwater conditions, active faulting and erosion creates considerable problem on the safety and cost of the project. Hence, for planning, designing, construction and maintenance of hydraulic structures, basic geotechnical and engineering geological investigation is very crucial. Moreover such an investigation is very important to assess the cost and safety of proposed structure, to assist in the selection of technically sound site and appropriate type and method of construction, to ensure long life span and to aid during operation and maintenance.

Geotechnical and engineering geological investigation and mapping mainly focus towards understanding the interrelationships between the geological environment and the engineering situation; the nature and relationships between the geological components, the active geodynamic processes and the prognosis of processes likely to result from the changes being made (UNESCO, 1976). From this perspective, investigation or research of soils and rocks of a failed hydraulic structure, as a material that is used to build with or on and also as a material of the environment that may act in combination with other forces of nature (geodynamic processes) to affect landforms, structure in terms of water harvesting condition or water-tightness is extremely important.

Hashenge earth dam was constructed by Commission

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for Sustainable Agriculture and Environmental Rehabilitation in Tigray (CO-SAERT) in the years 1996 and 1997 for the purpose of irrigating about 130 ha of land. But after the completion of the construction the reservoir failed to harvest or store water as per the design.

This research is therefore intended to identify the problem of water harvest failure of this structure. In light of the above point the present research is aimed at assessing and evaluating the engineering geological and geotechnical conditions of the project area and to provide important engineering geological data that helps to plan, design and maintenance of this structure.

1.2 Previous work

The first recorded geological work in the northern provinces of Ethiopia was done by Blanford (1870) cited in Beyth (1971), who divided the Trap Volcanics of the Ethiopian highlands into two units, a lower entirely basaltic series, and an upper Magdala series which contained many intercalation's of trachyte. Then Dainelli and Marinelli (1912) and Merla and Minucci (1943) as cited in Beyth (1971) proposed the transgression-regression phenomena to explain the sedimentary history of the whole of the Horn of Africa, including Ethiopia. In 1970, Levitte studied the geology of Mekele (central part of sheet ND37-11) and divided the rocks in the area into four major units: Basement complex, Paleozoic-Mesozoic sedimentary sequence, Cenozoic Trap volcanics and sediments of the Ethiopian Rift. Beyth (1971) did detailed mapping of Northern Ethiopian provinces (central and western Tigray). According to this work the history of the sedimentary basin in Tigray, Mekele Outlier in particular, began in either the Ordovician or Carboniferous and probably ended in lower Cretaceous before the eruption of the Trap Volcanics.

Very little or none is known about engineering geological and geotechnical condition of the area and its environment. The only work to be mentioned is the work of Yimam Indris (1996) and Gebremedhin Berhane (1999). These work classified the rocks and soils of the area based on their lithology and origin. Moreover, simplified geological and engineering geological mapping were also included. These works were used as baseline information to this research work.

1.3 Regional stratigraphy

In the northern part of the country, Tigray and its surroundings, the major lithologic units are of metamorphic or basement rocks, sedimentary, extrusive volvanics, intrusive granitoids and sub-intrusive dolerites.

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1.4 Regional structure and tectonics

Levitte (1970) investigated the structure and tectonics of the Mekele area (central part of Sheet ND37-11) and pointed out that faulting and tectonic movements control the structure of the area. The basement structures have the same strike trending N 25^0E with small local deviations. The sediments (in the highland part) are planar and sub-horizontal with dips varying between 3^0 and 9^0 to the northeast. The inclination is due to slight tilting of blocks hinged on northwesterly trending faults.

Three main fault systems exist in the area; two of them are limited to the Ethiopian plateau and one to the rift of the Danakil Depression. The fault systems of the plateau are normal to each other. One system is characterized by vertical faults up to 40 kilometers in length that cut the entire sedimentary section and trend N 25^0E.

The longest of these faults in the area is the Mekele fault which passes about nine kilometers north east of the town and forms a long escarpment which is about 65 kilometers in length. Faulting brings the lower most formation of the Antalo Group against its upper most formation, near the town of Mekele, which means a throw off at least 400 meters (Levitte, 1970).

Beyth (1971) also studied the structure and tectonics of the sedimentary rocks in the Mekele Outlier and in the escarpment. He identified two main fault systems by considering the third fault systems of Levitte as a lineament. The two main fault systems are WNW running fault belts (Wukro, Mekele, Chelekwot and Fuicea Mariam) and Rift Valley fault system formed the escarpment and the Danakil depression.

The Mekele fault belt crosses the present study area, it is about 65 kilometers long and Mekele Dolerite is intruded along it. Figure 1 shows fault map of the outlier and the present study area.

The whole study area is within the Mekele Outlier. The Mekele Outlier is a near circular about 8,000 sq. km in area, where the Mesozoic sedimentary succession has been preserved from erosion.

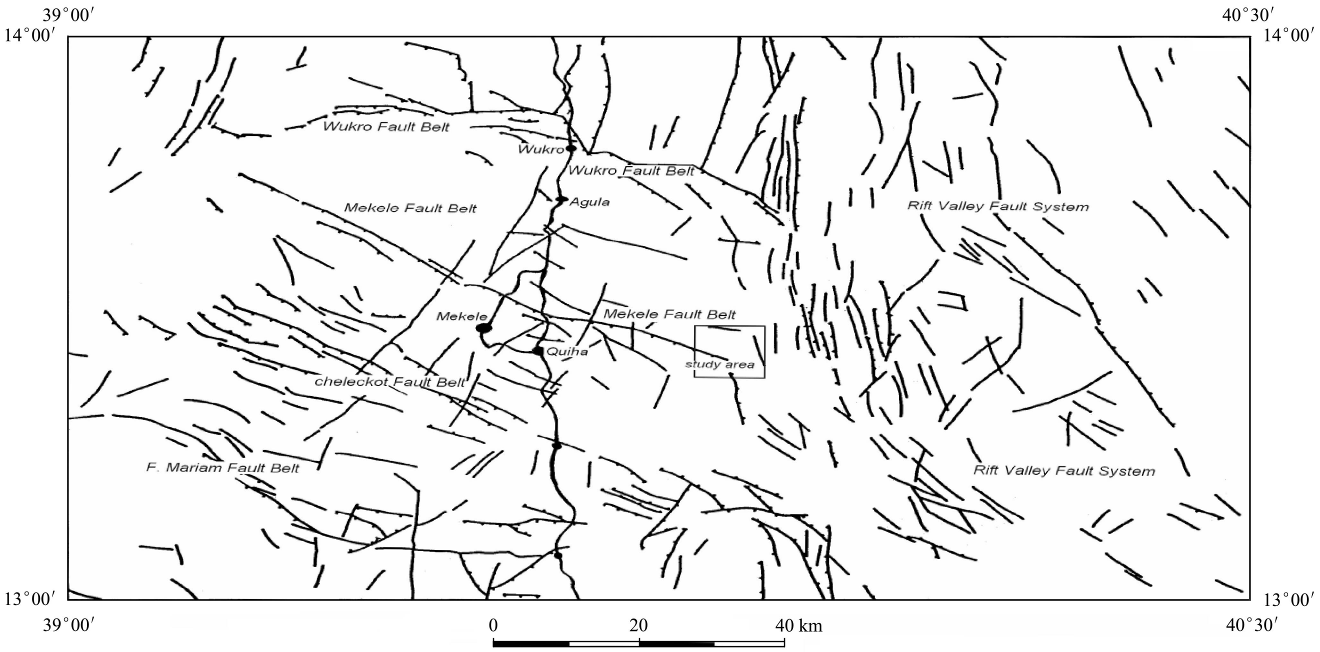


Figure 1 Structural/fault Map of Mekele area with the present study area at the center (modified after Levitte, 1970)

1.5 Problems

All dams produce seepage on different orders of magnitude and quantities. This seepage is not necessarily bad and may not affect dam stability. However, problems may occur when seepage rates increase unexpectedly or become uncontrolled. The rate at which water moves through the embankment, foundation and abutments depends on the type of soil in the embankment, how well it is compacted, the foundation and abutment preparation, and the number and size of cracks and voids within the embankment and natural abutments. Upon first filling of the reservoir numerous leakage areas developed in the left abutment downstream of the dam. Hence the dam/reservoir fails to store water and the land proposed for irrigation has not yet been successful. This research project was then initiated to pinpoint the main reason to the water harvest failure and to propose solution to minimize leakage to an acceptable degree.

1.6 Objectives

The major objective of this research project was to study the engineering geology of the area and identify the main causes of leakage problem. The specific objectives include assess and analyze important engineering geological and geotechnical properties of the soils and rocks of the area with main focus to rock mass permeability.

2 Methodology

2.1 Description of the study area

2.1.1 Location

Hashenge micro-dam is located at 572,850 mE and 1,489,900 mN (Figure 2), situated in the extension of the central highlands of Ethiopia. The altitude of the study area ranges between 1,965 m and 2,420 m above sea level. The area is bounded by rolling mountain ranges in the east and north and Chechat reservoir or flat landform in the west side.

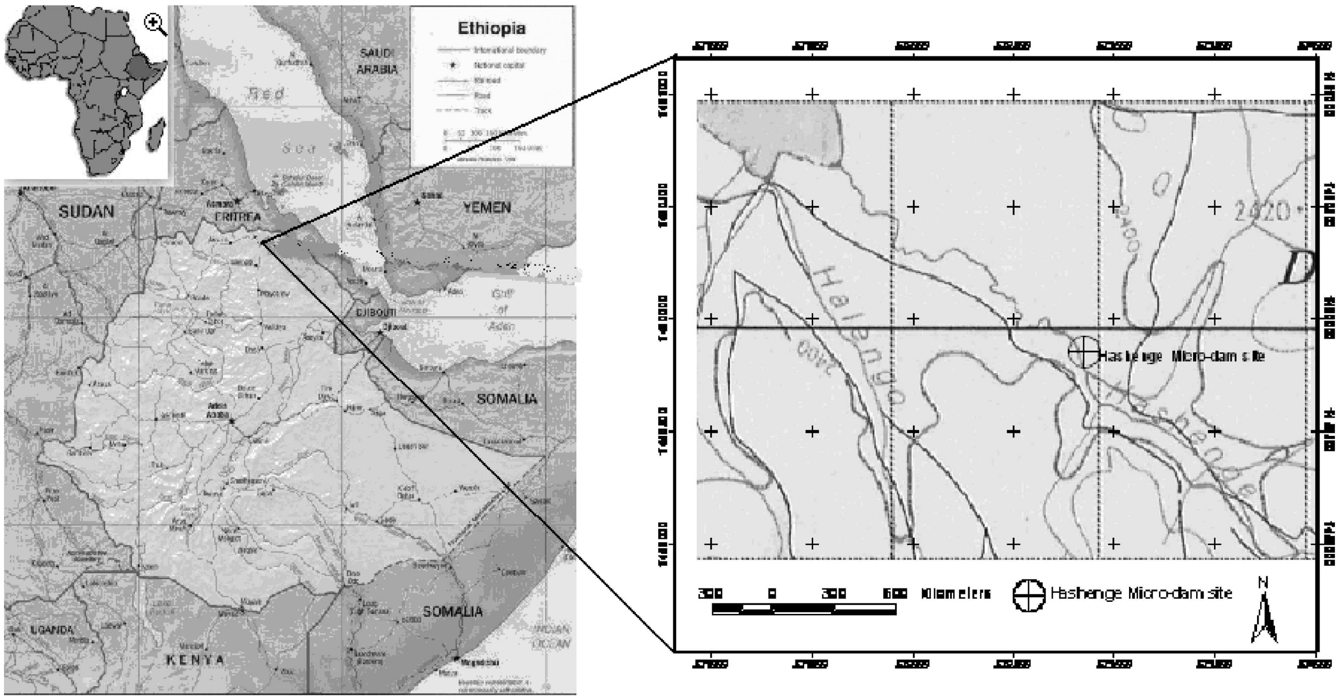


Figure 2 Simplified location map of study area

2.1.2 Local geology

The major lithologic units found in the Hashenge area are the limestone-shale-marl intercalations, dolerite and alluvial deposits. Figure 3 shows simplified geological map of the dam site and reservoir area.

1) Limestone-shale-marl intercalations

The sedimentary unit limestone-shale-marl intercalation (Figure 4) covers large portion of the area. Its color varies from place to place and with depth (white, yellowish, brown, etc).

The beds are mostly horizontal, but in places they are inclined mainly due to intrusions and faults. All grades of weathering are observed in these rock units. Near contacts to the dolerite the shale-limestone-marl intercalations are highly disintegrated due to baking effect of dolerite intrusions. Layer of shale within this intercalation is fissile, weak, highly to completely weathered, while the marl and limestone are relatively hard, thickly bedded and moderately weathered.

2) Dolerite

The dolerite in the area is manifested as swarms of sill and dyke network. It is slightly to completely weathered in the form of concohidal/exfoliation (onion's skin like) weathering. It is greenish grey, medium to coarse grained, massive rock. Weathering degree decreases with depth. It is outcropped mostly following weak zones, lineaments and fault zones. It displays both concordant and discordant relationships with the country rocks.

3) Alluvial deposit

Alluvial deposit is found mainly on the command area or downstream of the dam and along the reservoir floor. Its thickness is generally variable, but thicker near the river course and becomes thinner toward the steep sides of abutments and reservoir periphery. Clay/silt is the dominant size that constitutes the deposit.

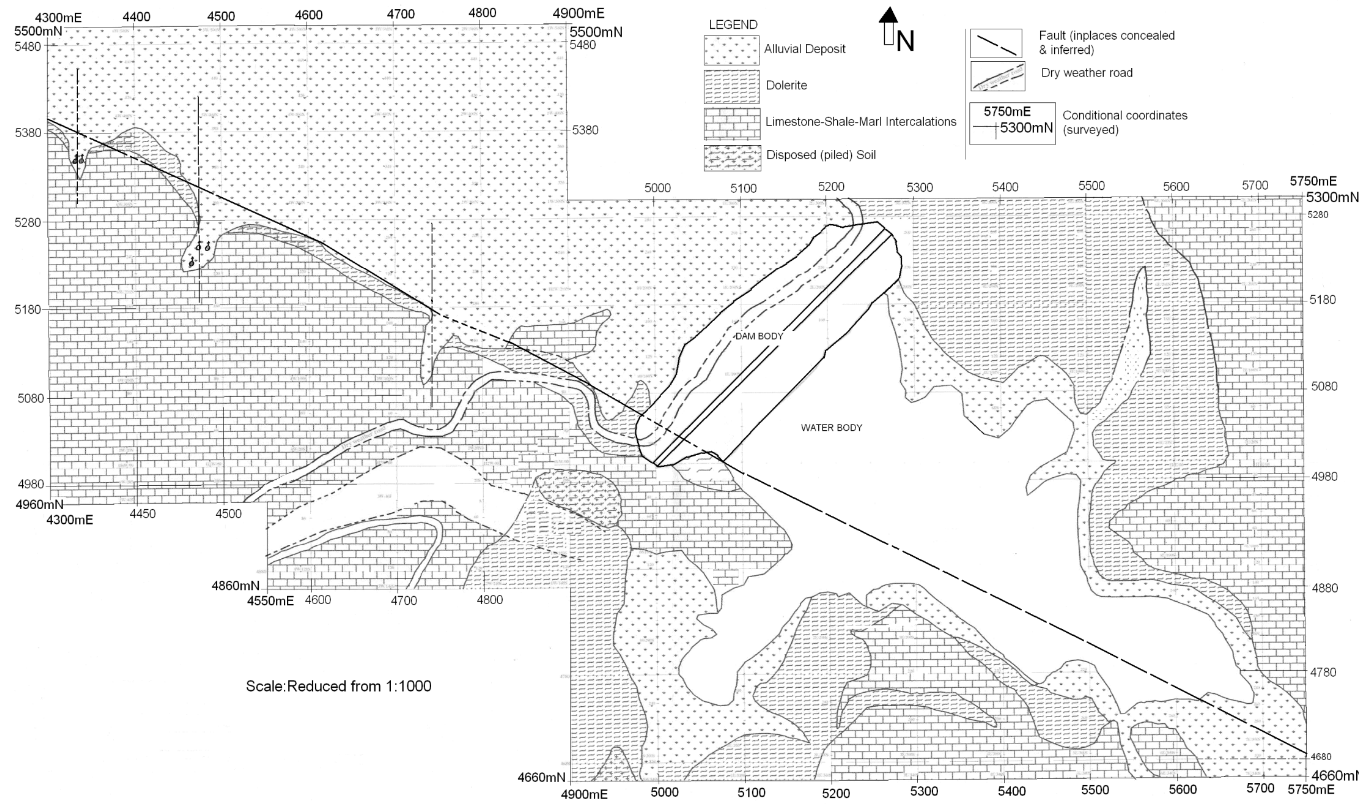


Figure 3 Geological map of Hashenge dam site and its reservoir area

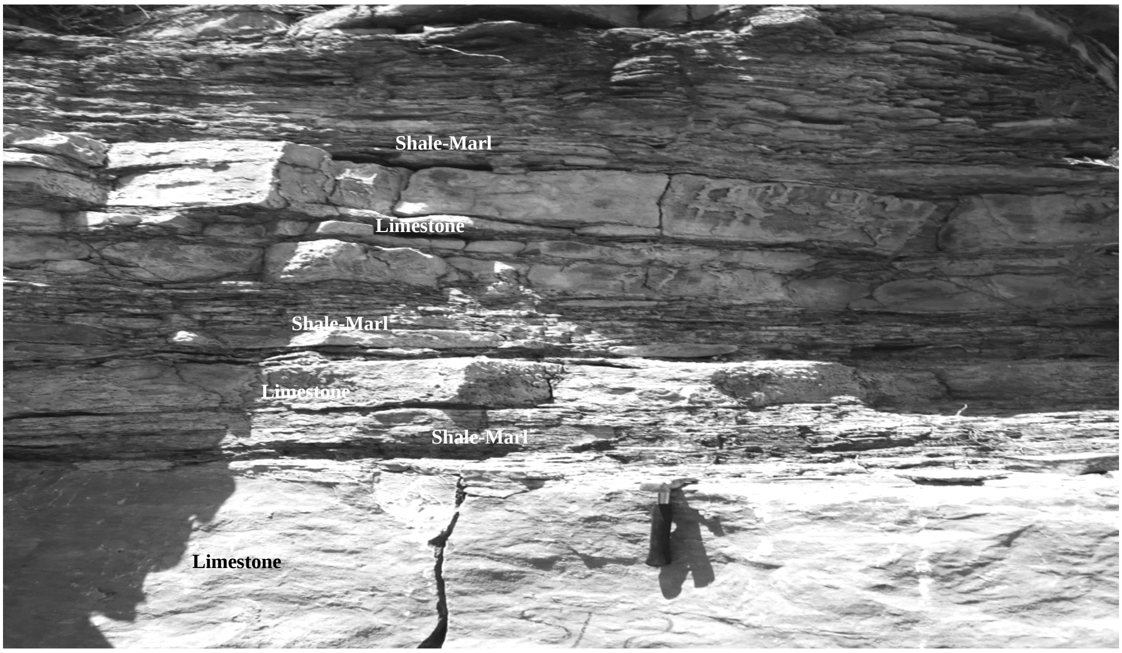


Figure 4 Limestone-shale-marl intercalation unit exposed on the left reservoir side

2.1.3 Local geological structures

The main geological structures observed in the study area are faults, fractures/joints and bedding planes. The major fault in the area is the Mekele fault. It runs or strikes in the range of 300^0 to 315^0 and it crosses the dam site. Joints are the dominant structures in the area, which are generally variable in strike direction. The 285^0 and 45^0 strike joints are the dominant once (Figure 6). Most of the joints observed on the surface are vertical and horizontal. Bedding planes and bedding joints are very common in the sedimentary rock units. The beds are mostly horizontal but inclined in the fault zone and near in gtrusions.

2.2 Methods

The research work involved a number of fieldworks in different seasons (2007 and 2008). A number of field measurements have been conducted to characterize the engineering behavior and engineering parameters of rocks and soils of the area.

Existing geotechnical and engineering geological data were collected from different organizations and individuals and preliminary photo-geological map was produced. The preliminary interpreted photo-geological map was checked by field traverses and changes were made wherever necessary.

In addition continuous rock and soil descriptions, digging of test pits/trenches for in-situ observations, exposure descriptions and discontinuity measurements were conducted during the course of all fieldworks. Moreover, drilling of three boreholes (11.7 to 25 m deep), geophysical survey (six Vertical Electrical Sounding, VES), direct measurements of structural parameters in a subjective and objective survey and traverse along complicated structural and geological features, etc. were carried out. The subsurface investigation was designed to determine the types and distribution, permeability, and sequences of earth materials (soils and rocks).

After completion of the fieldwork, final reinterpretation was made by introducing the field observation and subsurface information. Final maps of geology and engineering geology were produced. To understand the extent of hydraulic conductivity of the rock mass different approaches like graphical method and some empirical equations were used in addition to packer test to estimate mass permeability from the collected data.

3 Results and discussion

3.1 Discontinuity data

Joints in outcrops of the abutment slope were studied. Figure 5 shows location of some measurement stations and Table 1 presents the joint parameters measured in the field. Considerable amount of data was collected from the site, measurements were taken systematically to avoid biasness and emphasis was given to joints with favorable orientation to leakage with respect to alignment of the dam axis and reservoir configuration. Discontinuity sets were identified visually. Accessible surfaces were measured, which may be representative for the joint survey.

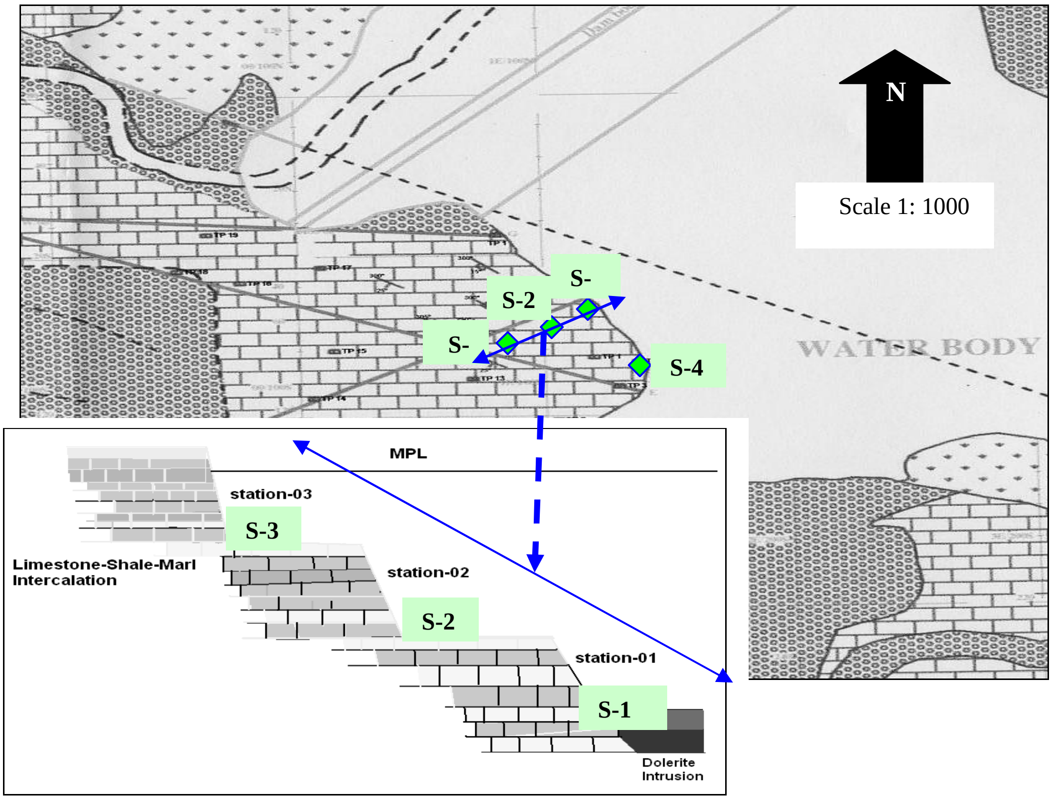


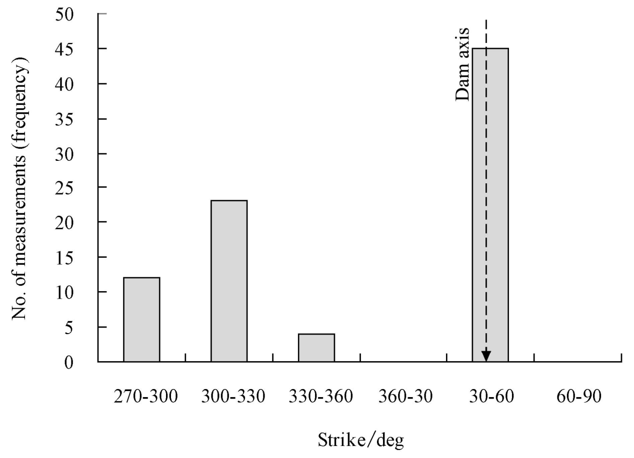
Figure 5 Simplified location of map of station points for discontinuity measurement

Table 1 Summary of discontinuity measurements (left abutment/Limestone-shale-marl unit)

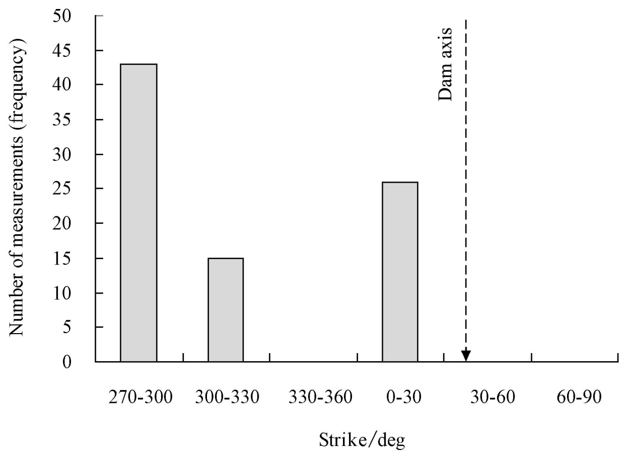
Type	Strike	Dip	Spacing/cm	Aperture/mm	Infill	Continuity	Number of discontinuity
STATION-01 (0572971, 1489868, Elevation 2392 m), Left abutment towards Reservoir Area							
Bedding joint	None	Horizontal	10-30	5	none	continuous	31
Joint/tectonic	45^0	90^0/vertical	50-100	5-20	none	continuous	45
Joint/tectonic	360^0	90^0/vertical	30-50	5-10	clay	continuous	4
Joint/tectonic	280^0	90^0/vertical	20-60	2-5	none-clay	continuous	23
Joint/tectonic	330^0	90^0/vertical	60	2-5	none	continuous	12
STATION-02 (0572939, 1489898, Elevation 2398 m), Left abutment towards Reservoir Area							
Joint/tectonic	285^0	90^0/vertical	50-100	2-20	none	continuous	43
Joint/tectonic	15^0	90^0/vertical	50-100	2-20	none	continuous	26
Joint/tectonic	310^0	90^0/vertical	30-50	5	none	continuous	15
Bedding joint(BJ)	Horizontal	0^0	3-70	0-10	none	continuous	39
STATION-03 (0572903, 1489934, Elevation 2402 m), Left abutment (near top part) towards Reservoir Area							
Joint (JN)	280^0	90^0/vertical	150	5	none	continuous	25
Joint (JN)	30^0	90^0/vertical	100	10	calcite	continuous	25
Bedding joint (BJ)	Horizontal	0^0	4-5	0-40	calcite	continuous	6
Contact (CN) b/n limestone and dolerite	290^0	$65^0/200^0$	-	Tight	calcite	continuous	1
STATION-04 (0572941, 1489884, Elevation 2399 m), Left abutment towards Reservoir Area							
Bedding joint (BJ)	300^0	40^0/SSW	4-25	tight -5	clay, calcite	continuous	33
Joint (JN)	290^0	60^0/NNE	50	1-20	none	continuous	25
Joint (JN)	40^0	90^0/vertical	20-50	2-10	none	continuous	42

Figure 6 and 7 show histogram of discontinuities taken on the left abutment (Table 1). Leakage of water through rock masses usually takes place via the discontinuities, although in some sedimentary rocks leakage through the pores may also play an important role. The joint parameters measurement in the field include joint spacing, opening/aperture, strike and dip, infill material type and amount, continuity and number of joints at the station or exposure extent.

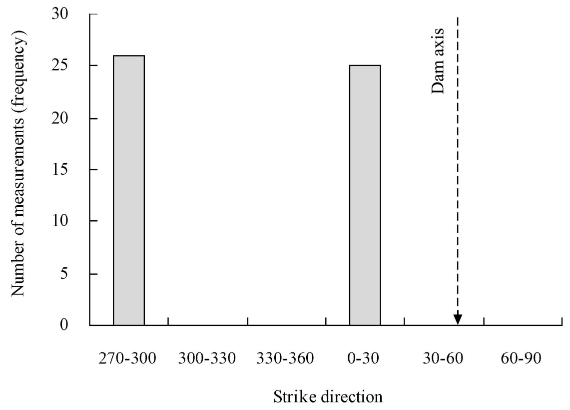
The frequency or spacing of joints (Figure 8) on average ranges from 30 to 45 per meter, i.e. closely to very closely spaced. The joints are generally continuous laterally and in depth urface of joints (wall surface) is smooth with some calcite precipitation. The space between joint surfaces (separation/aperture) is variable from place to place (narrow to wide aperture); many of the measurements show in the order of millimeter to few centimeter.



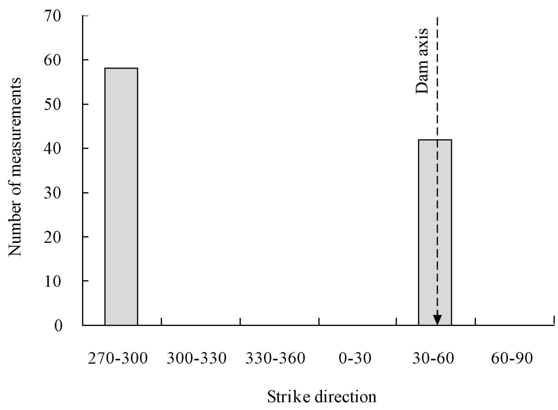
a. Orientation of discontinuities (Station-08-01)



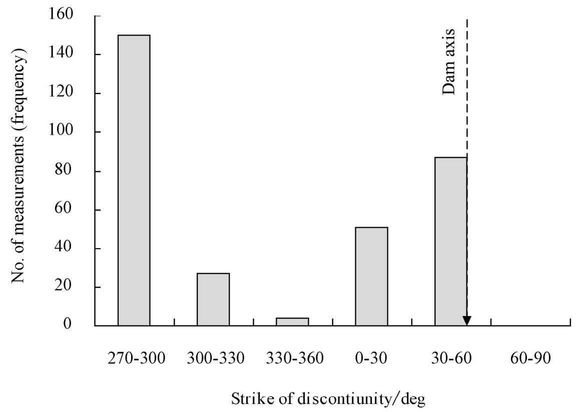
b. Orientation of discontiunity (Station-08-02)



c. Orientation of discontiunity (Station-08-03)

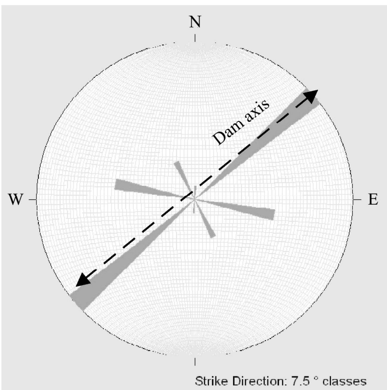


d. Orientation of discontiunity (Station-08-04)

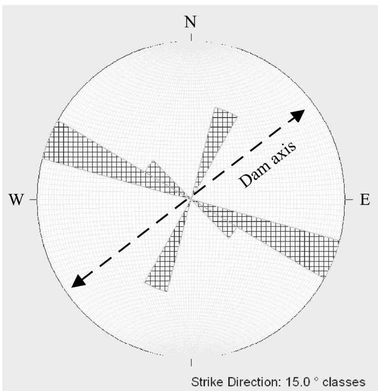


e. Orientation of discontinuities (ST-01, 02, 03 & 04)

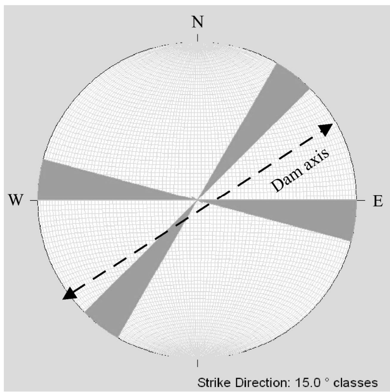
Figure 6 Histogram of discontinuities (left abutment)



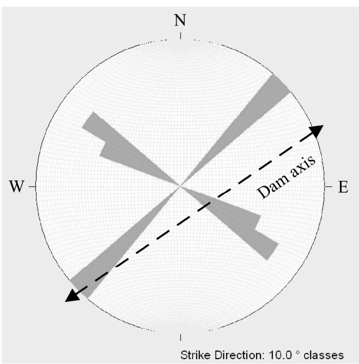
a. Station- 01



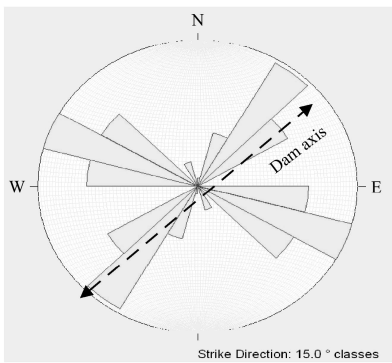
b. Station- 02



c. Station- 03

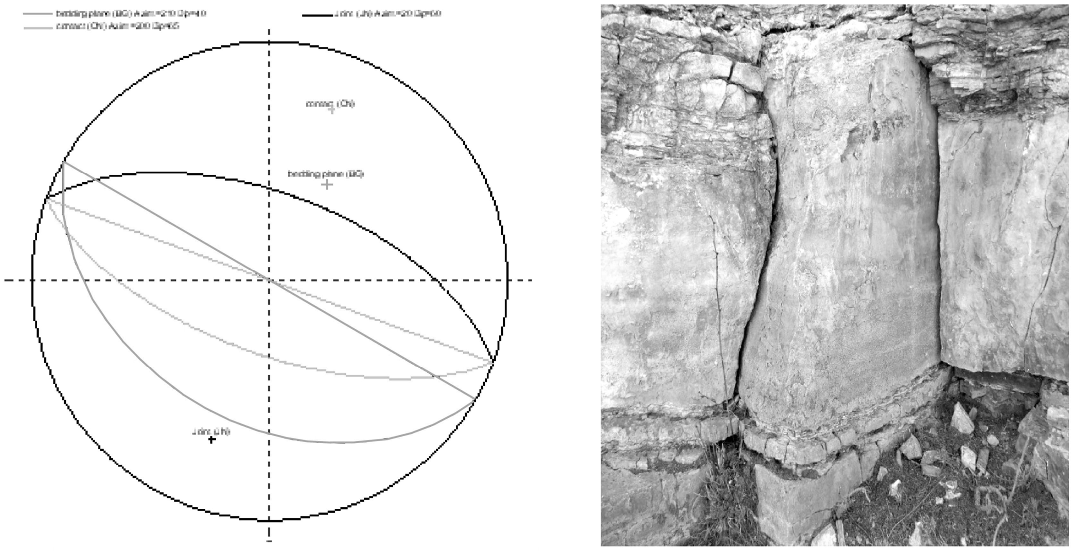


d. Station- 04



e. Station-1, 2, 3 & 4 combined

Figure 7 Stereogram of discontinuities (left abutment), double arrow shows dam axis orientation



a. Stereographic projection b. Field photograph

Figure 8 Bedding and tectonic joints

Permeability of jointed rocks depends on the dimensions and nature of the joints, the closer the spacing and the wider the opening, the higher the permeability is. Joints cause planes of weakness in the rocks and form leakage channels and permit upward pressures below a dam. Joints and other discontinuities are responsible for most of the unsound and permeable rock encountered at the dam abutment and reservoir area. The mass permeability using discontinuity data is estimated in the range of 10^{-1} to 10^{-3} centimeter/second.

3.2 Geophysical survey

On the three VES points, out of six, shallow geotechnical drilling was conducted and the results of VES are interpreted based on the information from borehole (Figure 9).

The resistivity values show an interesting variation in depth and to some extent in space. The variation in depth shows difference in lithology and moisture content. The upper top most part shows higher resistivity value indicating its direr condition. The pattern of the electric sections (Figure 10 to 12) also signifies inclination of the sedimentary beds. The inclination has important geotechnical implication.

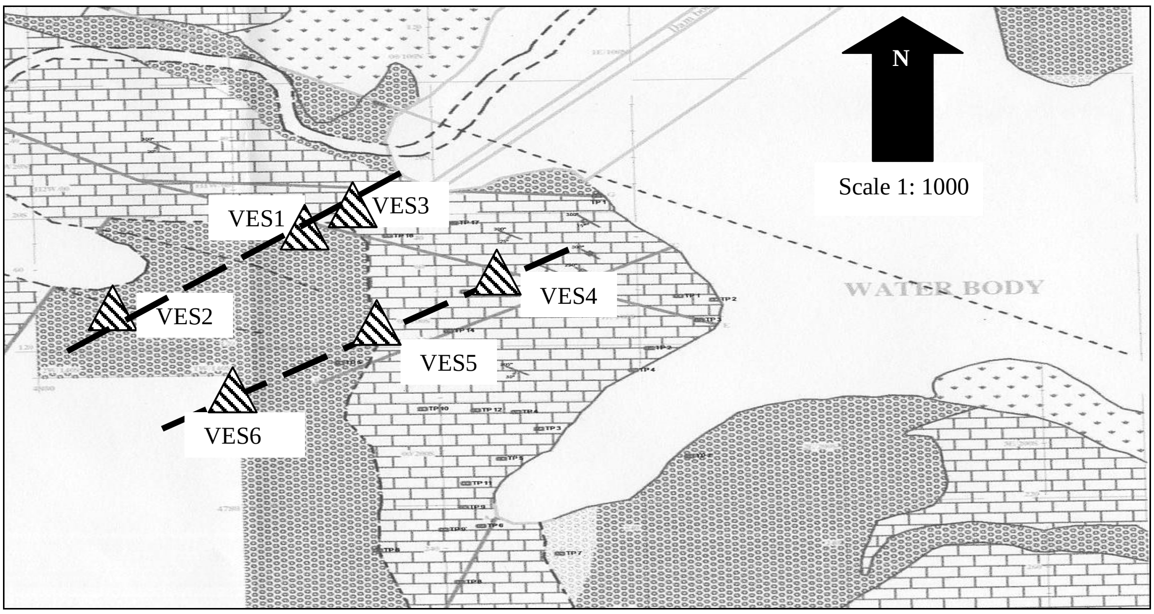


Figure 9 Location of vertical electrical sounding (VES) points

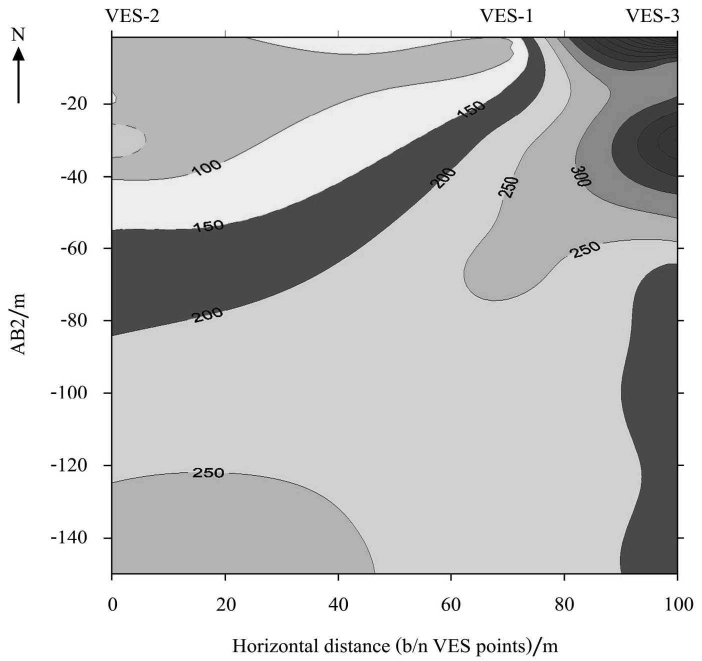


Figure 10 Apparent resistivity psuedosection (Ohm-meters) along VES2, VES1 and VES3

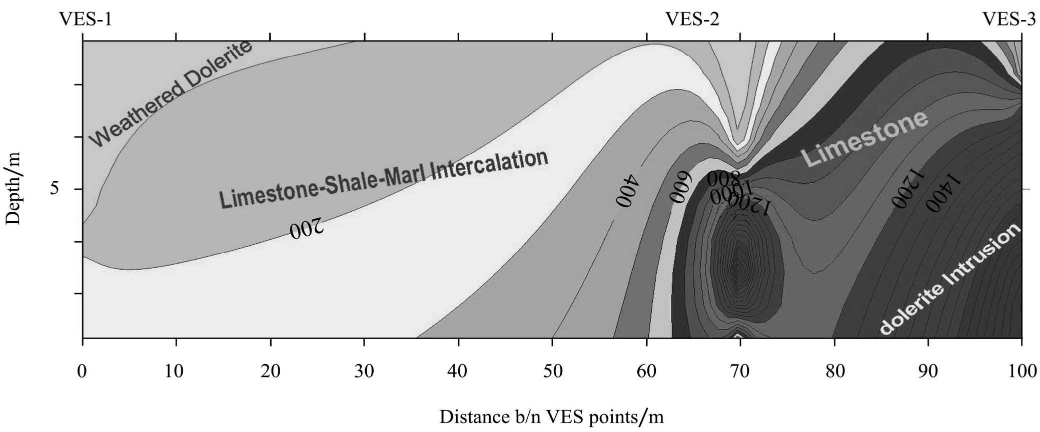


Figure 11 Geo-electrical-section (Ohm-meters) along VES1, VES2 and VES3

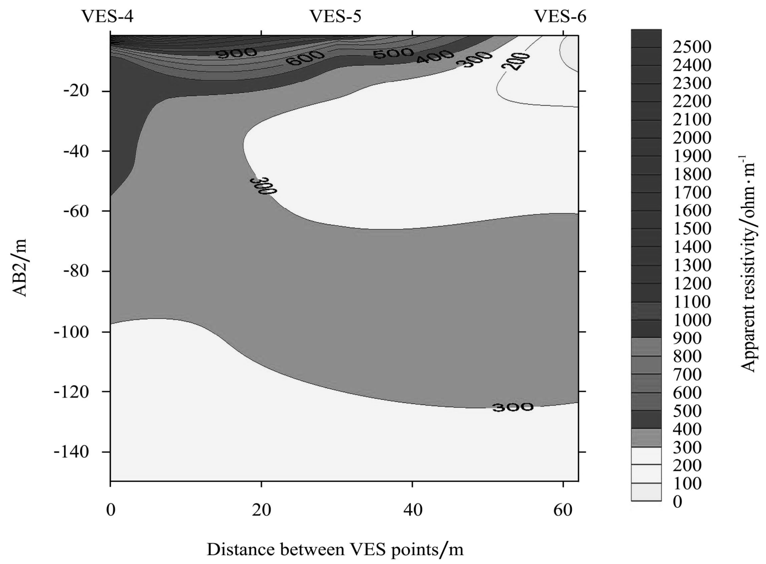


Figure 12 Apparent resistivity psuedosection (Ohm-meters) along VES4, VES5 and VES6

3.3 Engineering geological characteristics/properties of rocks

3.3.1 Shale-limestone-marl intercalations (S-L-M)

It covers the left abutment and part of the reservoir area. This unit shows cyclic sequence (Figure 3) of limestone, shale and marl beds as also revealed from VES results (Table 2). The beds are sub-horizontal to be inclined at different angles. The dominant strike and dip of the inclined bed is 300^0/40SW, but local deviations are also common, dip amount is as steep as 50^0. The strike of the inclined bed is nearly parallel to the Mekele normal fault belt. Bed thickness is variable from thin laminations in shale up to one meter or more thick limestone bed.

Table 2 Summary of vertical electrical sounding results

VES number	GPS Location (mE/mN)	Layer number	Resistivity value/Ω m	Thickness of layers/m	Depth /m
VES-1	0572847/1489935	1	371	0.271	0.271
		2	77.8	6.4	6.67
		3	2779	2.24	8.9
		4	222	-	-
VES-2	0572793/1489889	1	67.9	3.78	3.78
		2	262	2.55	6.33
		3	48.7	9.73	16.1
		4	463	-	-
VES-3	0572864/1489964	1	1.6E+5	0.145	0.145
		2	879	2.65	2.8
		3	92.9	2.19	4.99
		4	1695	5.83	10.8
		5	33.3	18.7	29.5
		6	606	-	
VES-4	0572902/1489876	1	2726	1.74	1.74
		2	361	8.61	10.4
		3	1139	7.98	18.3
		4	236	-	-
VES-5	0572881/1489858	1	1551	0.9016	0.9016
		2	710.2	396	4.862
		3	273.4	29.47	34.33
		4	465	44.31	78.64
		5	198.9	-	-
VES-6	0572848/1489829	1	49.5	6.97	6.97
		2	2049	18.2	25.2
		3	5.66	-	-

Weathering condition of the unit varies with depth and in space. All grades of weathering have been observed in the field (fresh to completely weathered). The rocks are rich in carbonate and shale is inherently weak, so the unit is strongly susceptible to weathering in the presence of moisture.

The unit is highly affected by discontinuities of different type, like bedding joint, contact, tectonic joint, etc. Two major sets of joints are dominant. The NW and NE trending discontinuities are the dominant sets and these discontinuity sets intersect at nearly constant angle forming a system. In addition to the two major sets of discontinuity there are a number of discontinuities with variable trend.

3.3.2 Dolerite

As per the pervious studies the dam foundation and abutments is composed of dolerite and the cut-off is extended to fresh dolerite. This unit covers most part of the reservoir area and extends to south side up to the rim of the reservoir (Figure 13). Concordant and discordant igneous bodies are observed in the area which indicates a dyke and sill pattern. These emplacement mode or nature of intrusive igneous rocks has engineering significance. Massive intrusive bodies such as stocks and batholiths tend to have relatively homogeneous compositions and textures that are three-dimensional throughout. Tabular intrusive bodies such as dykes and sills create more construction or rock-utilization and water harvesting problems than massive intrusives because of the inherent lack of the three-dimensional continuity that is found in massive intrusives.

The weathering grade is variable, fresh dolerite to completely weathered or residual dolerite, but weathering intensity decreases with depth. Joints and fractures are observed here and there in this unit without any set or system of orientation. Joints are very widely spaced and non-continuous spatially (Table 3) and in depth. Surface of the joint is slightly rough and joint wall strength is hard on fresh dolerite. Joint separation is generally tight and weathering is slightly intensive along joints. Observations on test pits and trenches near reservoir water body shows that there is no difference in moisture content along joints and other part of the rock mass.

All the above engineering geological features lead to signify that this unit is relatively impermeable, i.e. due to homogeneity of the dolerite and absence of closely spaced and open joints (Figure 13). The upper top part of the unit is affected by weathering and hence pervious.

Figure 14 and 15 show cross-sections along selected lines to portray the subsurface condition.

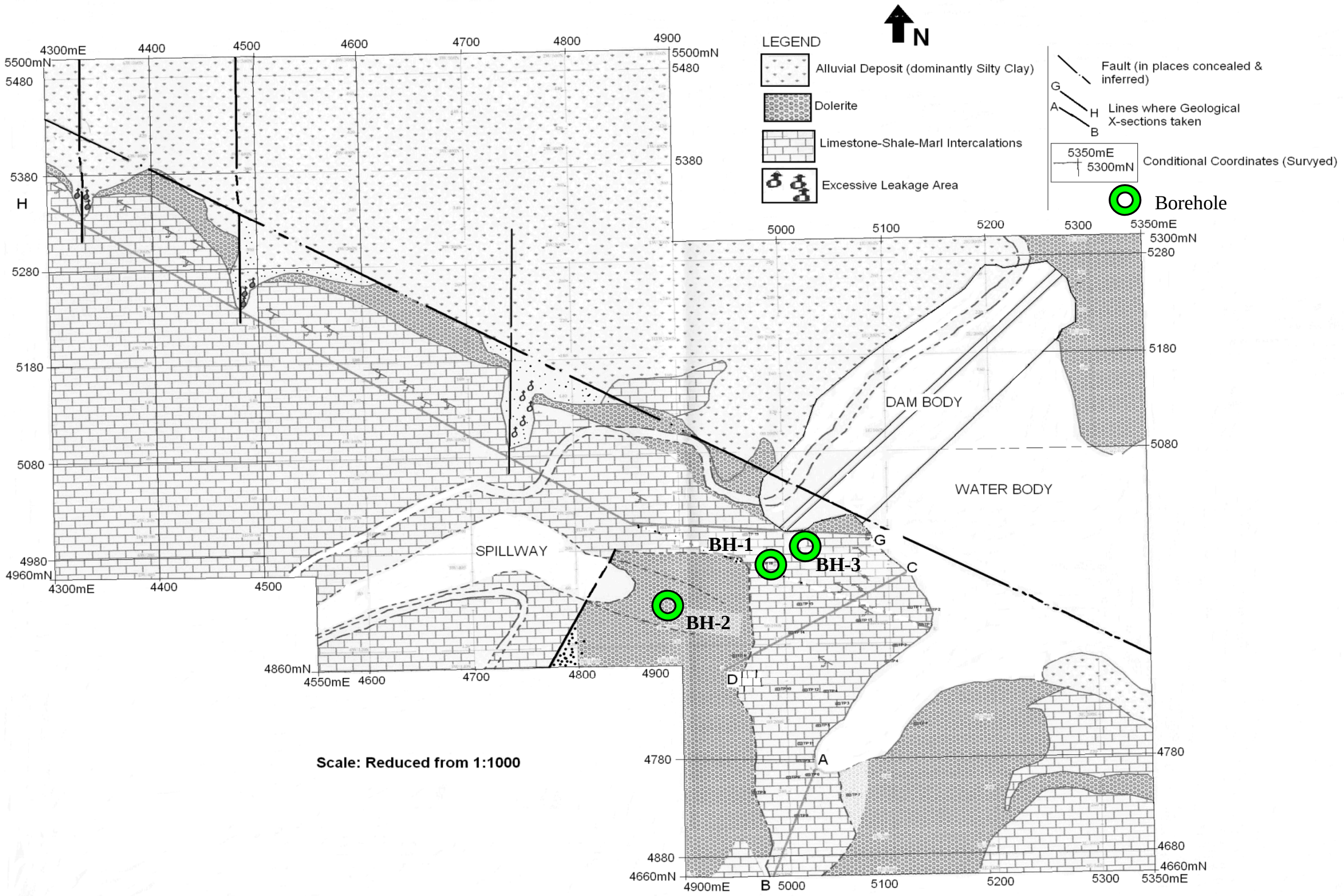


Figure 13 Detail engineering geological map of Hashenge dam site and its reservoir

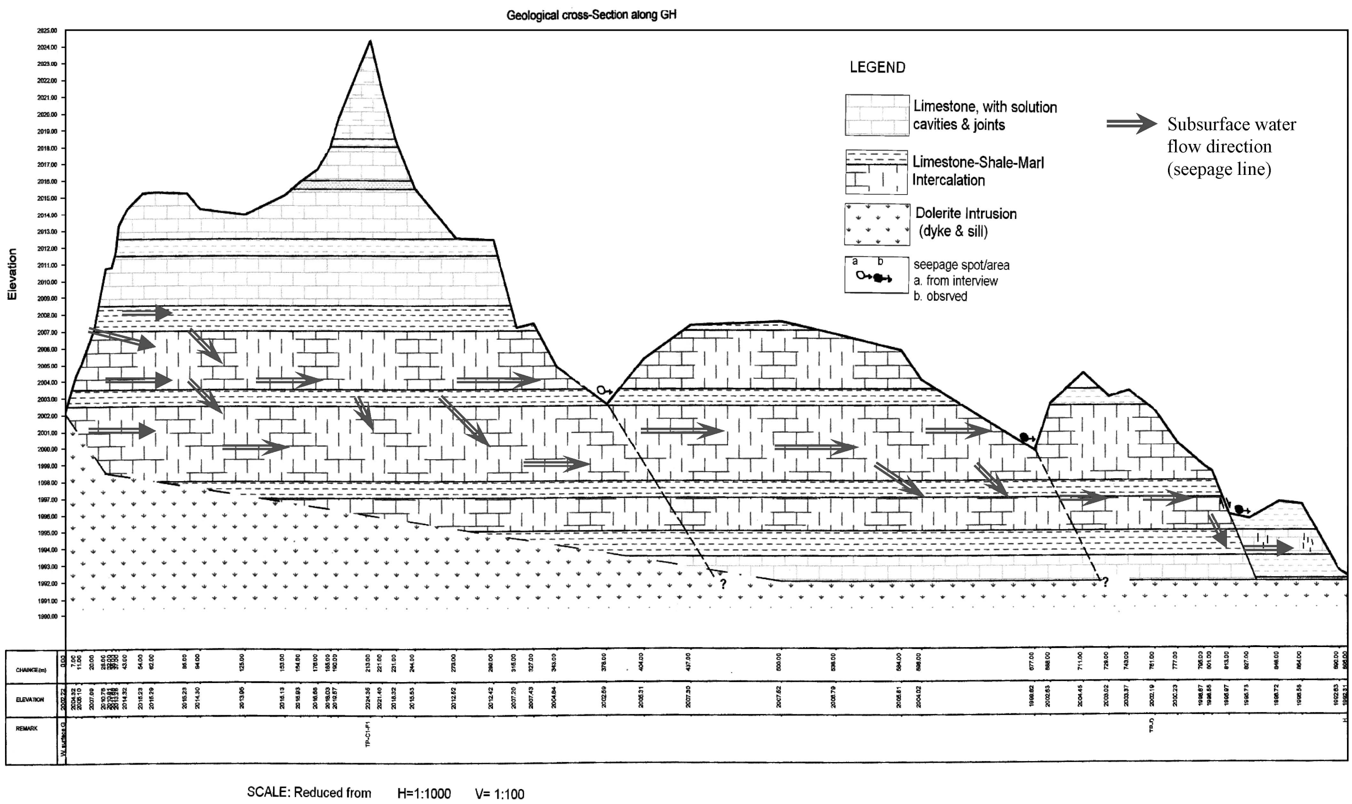


Figure 14 Engineering geological cross-section (Upstream to down stream side along the left abutment (Arrows show flow direction/leakage)

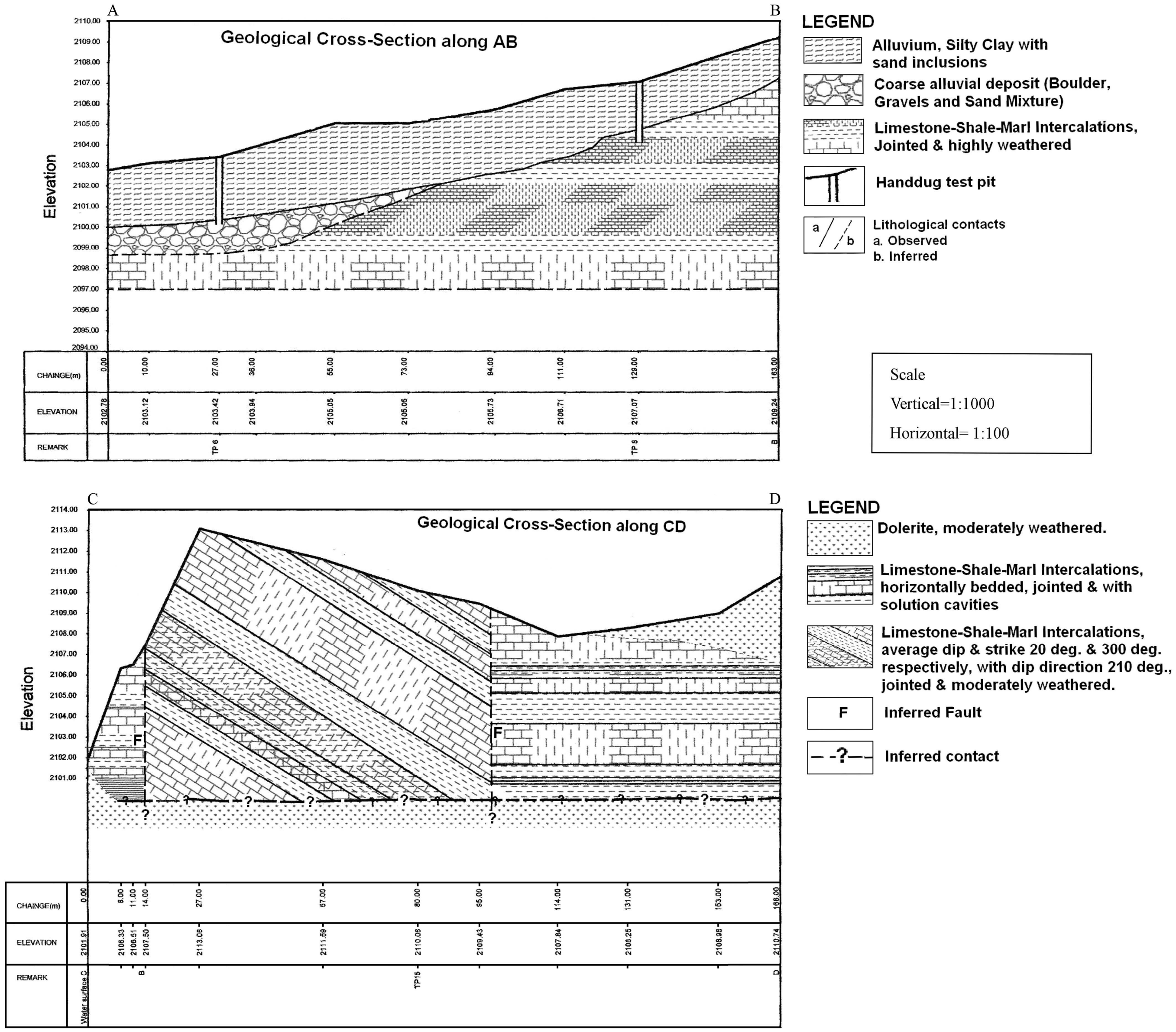


Figure 15 Engineering geological cross-section along AB and CD

Table 3 Summary of discontinuity measurements on right abutment (dolerite)

STATION-Right Abutment (0573142mE & 1,490,212 mN, Elevation: 2401), Right abutment towards Reservoir Area

Type	Strike	Dip	Spacing/m	Aperture/mm	Infill	Continuity	Length/m	No. joints
Joint (JN)	280^0	90^0	2	tight	none	discontinuous	20	3
Joint (JN)	340^0	90^0	3	tight	none	continuous		4
Joint (JN)	30^0	40^0/SE	0.3-1.0	tight	none	continuous	3m	14

3.4 Geotechnical drilling and test pits

Careful exploratory work must be carried out in all phases of a dam project. By far the most important step in the study of a site for dam is the exploration conducted for determining the jointing, zone of weathering, shearing, faulting and other adverse features at the site. This process of work consists of geologic mapping, digging of test pits and trenches and drilling.

3.4.1 Purpose

The purpose of geotechnical drilling at the left abutment of Hashenge micro-dam site was to:

1) Secure samples of soil and rock for visual examination and for laboratory testing.

2) Characterize the subsurface soil and rock conditions from water tightness perspectives.

3) Obtain information on groundwater level condition.

4) Tconduct pressure test and understand the role of joints, bedding planes and other geologic features to hydraulic conductivity of the rock mass.

5) Predict line or zone of leakage path.

3.4.2 Planning

A review of the available information including geological map, topographic maps, and site reconnaissance and feasibility report, location and direction of seepage/leakage areas were used to plan drilling sites and additional test pits. During the geotechnical drilling plan site inspection and close review of previous documents and result of surface geological maps was used in selection of borehole positions. Based on the existing information from hand dug test pits, surface geology, geophysical survey and topographic situation three drilling sites were selected two on the left abutment and one at the spillway route (Table 4 and Figure 13)

Table 4 Location of boreholes

BH No.	GPS	Elevation (a.m. s. l.)	Relative location	Depth drilled/m	Remark
BH 1	0572842mE & 1489933mN	2402	Left abutment	25	Final depth Interrupted with discussion
BH 2	0572786mE & 1489885mN	2401	Spillway route	11.7	Final depth Interrupted due to hole collapse
BH 3	0572866mE & 1489946mN	2404	Left Abutment (near dam body)	15.5	Final depth Interrupted due to hole collapse

3.4.3 Drilling operation

Drilling operation was carried out in the weathered near surface part using auguring while in bedrock rotary coring. Drilling in the upper top weathered material was successful and many disturbed samples were collected for visual inspection. Drilling in bedrock was successful at one borehole (BH1), but drilling on the remaining two boreholes was interrupted due to collapse. Due to this condition drilling was conducted to a depth of 11.7 m and 15.5 m in BH2 and BH3 respectively.

3.4.4 Drilling results

Figure 16 shows log of the three boreholes drilled on the left abutment and spillway route of the dam. A close inspection of the core samples indicates variation in lithology, weathering grade, fracturing and thickness of beds with depth and space. The drilling operation and samples recovered further confirmed the presence of high permeable layers or beds, perhaps cavities.

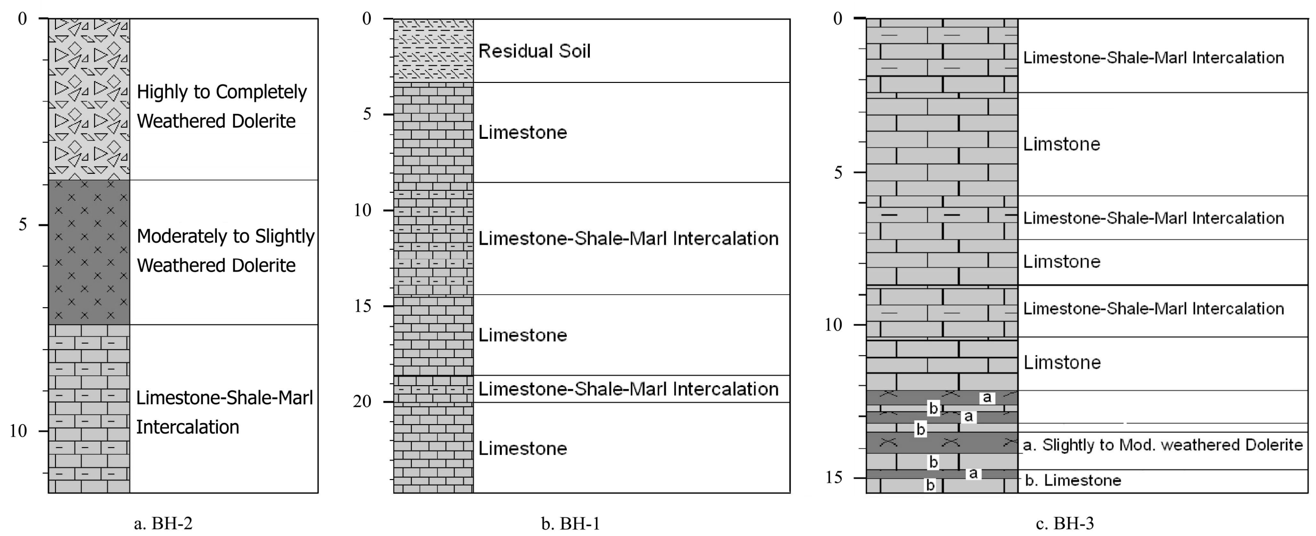


Figure 16 Simplified lithological log of the three boreholes

Three of the boreholes show almost similar geological units with variation in fracturing and weathering. The main units include limestone, shale and marl, but at BH-2 and 3, a dolerite unit is also encountered. Their thickness is variable and generally it occurs in a cyclic fashion or sequence. At BH-2 dolerite extends to a depth of 7.4 m, below this depth a sedimentary sequence of shale and limestone are the dominant units.

Similarly at BH-3 trace of dolerite sill starts at a depth of 12.11 m and continues at a depths of 12.84, 13.95, 14.10 and 14.7 m. From these drill holes it is clear that limestone is the dominant rock unit and governing factor with respect to the hydraulic conductivity of the rock mass.

In addition to log and joint description of the drill holes packer/pressure test was also conducted at BH-1 within the depth interval of 12.4 m to 13.4 m. Water/packer testing is necessary for evaluating seepage potential and for determining whether grouting is necessary or practical. Water testing for designing a grout program is often secondary to the main purpose of the water testing program, which is to determine permeability for seepage evaluation or control.

The test was conducted in three stages at different pressures. Calculation of the permeability of the rock mass shows in the order of 10^{-3} cm/sec. A bar chart (Figure 17) showing the relationship of test pressure and Lugeon indicates a continuous reduction in Lugeon value as test pressure increases. This condition is related to filling of void or fractures by finer materials during the course of testing.

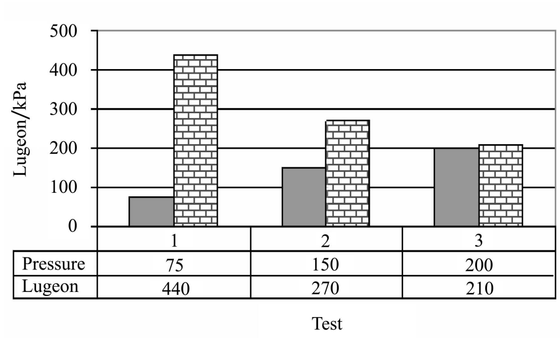


Figure 17 Bar chart showing relationship of test pressure and Lugeon value

Synthesis of the different surface and subsurface information collected during the course of this research work leads to develop a comprehensive geological cross-section or model (Figure 18). The model helps to understand the leakage phenomena and assist in proposing and implementation of mitigation measures.

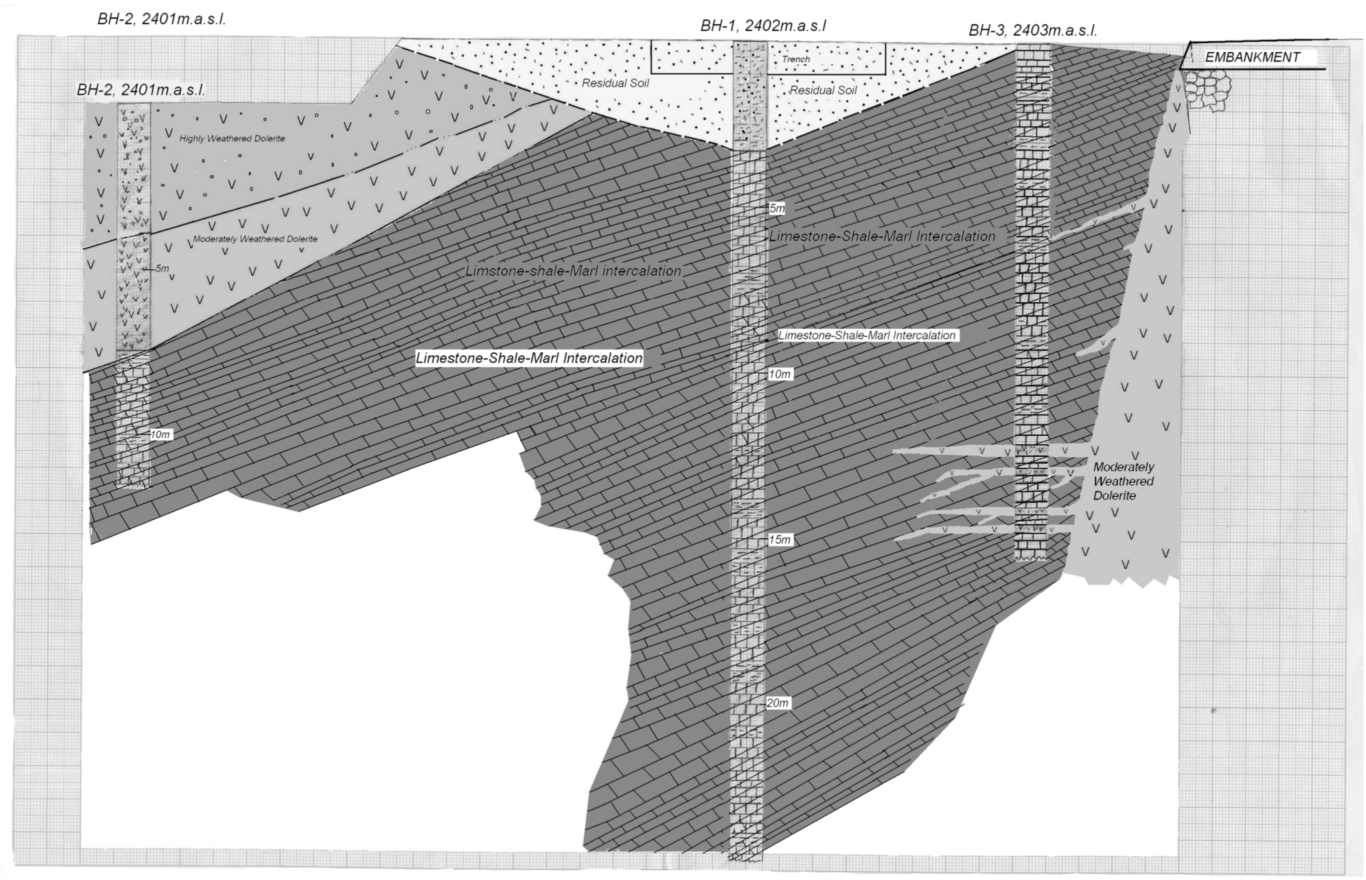


Figure 18 Engineering geological cross-section along the three boreholes (model)

4 Conclusions

The geotechnical drilling information, geophysical survey, geological mapping, etc show the possible leakage path which leads to the failure of storage. The geological setup, structures and geotechnical/engineering properties of the rocks make up the left abutment favors excessive leakage. The packer test result and assessment of joints and fractures in terms of spacing and opening or separation are in close correlation. Both the information/data shows moderately to highly permeable nature of the sedimentary sequence in the left abutment.

The Limestone-shale-marl intercalation unit exposed on the left abutment has continuity beneath the dolerite on the spillway route. This geotechnical condition, where presence of hard impervious dolerite overlying soft and permeable sedimentary sequence indicates an open cut-off trench, is impractical as a mitigation measure. It is shown how the site geology, type and extent of rock defects, and degree and extent of weathering influence greatly the rock mass permeability and other engineering properties.

The dolerite which is exposed on the foundation and part of the abutment and spillway route does not have any connection which acts as a barrier, if any, the connection is as deep as the 25 m and this depth is well below the reservoir floor.

This research work reveals that the sedimentary succession (Limestone-shale-marl unit) is pervious, due to fracturing/joints, bedding planes, fault and impact of intrusions. Dolerite is found to be impervious to semi-pervious with respect to degree of weathering and fracturing. So, it is clear that part of the reservoir, foundation and abutment which is covered by the sedimentary succession is leaky. Any mitigation strategies should then consider this geotechnical and engineering geological condition of the reservoir and foundation/abutment in to account.

Acknowledgment

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